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The influence of the ground parameters' assumptions on the low enthalpy heat pump's energy source simulation's results

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Abstract. In the paper the simulations of the low enthalpy energy source for brine-to-water heat pump using EED software had been presented. Authors indicated the influence of the ground parameters' assumptions on the low enthalpy heat pump's energy source simulation's results. Based on the real borehole geological profile and data available in literature, the ground thermal conductivity coefficients have been calculated making different assumptions concerning the ground thermal properties. The calculated ground thermal conductivity coefficients along with the calculated source sizes, heat pump parameters and the heated building thermal performance served as the input data for the simulation software. The outcomes of the analyses include the temperatures of brine entering the heat pump as well as the brine initial temperature. Outcomes served for the low enthalpy energy source performance evaluation.

1 Introduction

Renewable sources of energy gained the popularity back in the 80s, when the global energy crisis began. Some new buildings' heat supply systems were introduced and ground source heat pumps have been among them. Also already in 80s the research on the introduction of the computer software, enabling analysis of the low enthalpy energy sources for heat pumps, have been performed in the USA and Sweden [1]. The analysis of the simulation outcomes let designers optimize the low enthalpy energy source performance in the subsequent years of the heat pump operation. Earth Energy Designer – the vertical ground heat exchangers' design software is the example of such simulation computer program. Along with the development of the computer software, the need for the analysis input data determination methods, particularly the ground thermal conduction, have increased. There are several methods, like the pilot drilling or Thermal Response Test (TRT), that let determine the ground properties. The pilot drillings let the designers preliminarily asses the ground thermal conduction coefficients. The parameters of the particular layers can be found, based on the created ground profile. The determination of the ground moisture is the greatest issue. The thermal conductivity values of the ground with various level of saturation can be found in the literature. For example the thermal

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conductivity of the dry sand equals 0,4 W/(m·K), while for the saturated one it reaches 2,4 W/(m·K) [2]. The difference of the assumed specific extraction rate of the dry and saturated sand equals 20 W/m. The implementation of wrong assumptions leads to the design faults, that may result with low enthalpy energy source extensive cool down in the first years of the system operation. The second method that let determine the ground heat conduction, the TRT test, is carried out primarily for the bigger installations, because of the small availability and high costs. It is estimated that the TRT test establishment starts to be economically feasible for the systems with 10 or more boreholes, because it enables the proper low enthalpy energy source sizing [3]. The analysis methods of ground parameters are employed only for big installations due to high costs. The common practice is the low enthalpy source sizing on the basis of the assumed unit thermal performance of the ground. This procedure, although consistent with guidelines, may also lead to the low enthalpy energy source overcooling, the heat pump operation in emergency mode and substantial operational costs increase. The system efficiency decrease may be visible already in the first years of the system operation and depend on the difference between the assumptions made and the real ground properties.

2 Analysis method and system description

In the paper the design process and the thermal performance analysis of brine-to-water low enthalpy energy source had been performed based on the geological profile of the ground and taking into account various assumptions concerning the ground thermal properties and design guidelines. The purpose of the analysis was to indicate how those assumptions influence the system sizing and the simulation outcomes.

2.1. The geological profile and assumptions concerning ground properties

In the Fig. 1 the geological profile of the ground on the depth of 100 meters had been presented. Based on the layers description, the thermal conductivity (λ, W/(m·K)) and the volumetric heat capacity (s, MJ/(m^3·K)) of each layer had been assumed in two variants and the weighted average of the thermal conductivity and volumetric heat capacity of the ground serving as low enthalpy energy source had been calculated. The ground thermal conductivity and volumetric heat capacity in the first variant for all ground types excluding granite (clay, gravel and sand) had been assumed as an average between dry and saturated ones and the sand and granite content in the clay had been assumed as 30%. The ground thermal conductivity and volumetric heat capacity in the second variant for all ground types excluding granite had been assumed as for the saturated ground, the sand and granite content in the clay had been assumed the same as in first variant.

Based on the thermal conductivity coefficients it is possible to establish the specific extraction rate of the ground (q, W/m) used for the heat pumps' low enthalpy energy source sizing. There is a number of guidelines that may be used for that purpose [2,4,5] and they do not give the same outcomes. For the purpose of analysis authors decided to use the values recommended by Polish Organisation of the Heat Pump Technology Development (PORT PC – (in polish) Polska Organizacja Rozwoju Technologii Pomp Ciepła) [2] and the Swiss Standard SIA 384/6 (Erdwärmesonden) [5]. The obtained data have been used for low enthalpy energy source sizing and as the input data for the simulation software EED (Earth Energy Designer).

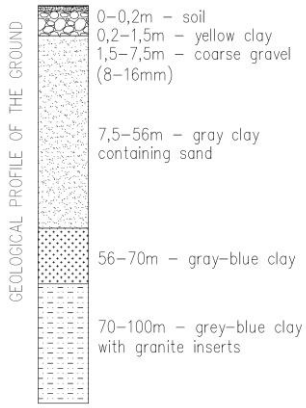

Fig. 1. The ground vertical profile.

2.2. The heat pump system and the building thermal properties description

The energy efficient small size commercial building had been assumed for the purposes of the analysis. The building heat load equals to 16,5 kW and its yearly energy demand is 24 000 kWh, while the heated area is 600 m^2. The building is equipped with the underfloor water heating system with flow temperature of 35°C. The energy demand for each month is given in the Table 1. The energy demand for hot tap water preparation purposes is covered by electric heaters and is not the purpose of this analysis.

Table 1. Monthly energy demand of the office building.

No	Month	Energy demand, MWh	No	Month	Energy demand, MWh
1	January	3.72	7	July	-
2	February	3.55	8	August	-
3	March	3.00	9	September	1.46
4	April	2.38	10	October	2.09
5	May	1.54	11	November	2.81
6	June	-	12	December	3.46

The energy demand for the spatial heating purposes is fully covered by the brine-to-water heat pump, which performance parameters, essential for the purpose of the system analysis, are given in table 2. The low enthalpy energy source for the heat pump consists of the single U-type (PE 32 x 3,0) boreholes, 85-100 m deep. The number and final depth of the boreholes have been calculated assuming four different unit thermal performance values obtained using two thermal conductivity values and two different guidelines. Additionally two other boreholes' numbers and lengths have been assumed using the values of the specific ground extraction rates from tables contained in design guidelines for engineers, without any previous calculations in order to find out how such source would act under heat load conditions for both thermal conductivity values described above. The heat transferring agent had been assumed as monoethylenglycole 25% solution in water. The flow rate had been assumed as 0,24 l/s per borehole and it ensures the turbulent flow in the boreholes and the minimum flow rate for the heat pump.

Table 2. Heat pump technical data (according to EN 14511).

T_H	T_B	-5°C	0°C	5°C	10°C	15°C
35°C	COP_{HP}	3.94	4.44	4.80	5.14	5.56
	Q_{HP}, kW	14.3	16.7	19.2	21.6	24.2
	Q_c, kW	11.0	13.8	16.0	18.0	20.4

2.3. The low enthalpy energy source performance simulation

In order to indicate the influence of the ground parameters' assumptions on the low enthalpy heat pumps' energy source simulation results authors performed the simulations in various variants. The assumptions for the simulations are gathered in Table 3.

In variants from 1.1 to 1.4, first the thermal conductivity had been calculated, according to the assumptions, and then the specific extraction rates of the ground (q, W/m) have been established according to different standards. Based on the established specific extraction rates and the heat pump cooling capacity, the demanded number and depth of the boreholes have been calculated, assuming that the average thermal conductivity of the ground does not change if the borehole length is in range of 85 to 100 m. Afterwards the systems performance have been simulated in EED (Earth Energy Designer) software, which is proven to give the results being in good accordance with the measurements [6].

In variants from 2.1 to 2.4 the specific extraction rates have been assumed (range used most often by designers), and then the sources were sized for two assumed values, without considering the ground thermal conductivity. The simulations in EED software have been carried out assuming two different values of thermal conductivity and volumetric heat capacity for both source sizes.

Table 3. The assumptions made for the simulation variants.

Variant no	Thermal conductivity λ, W/(m·K) and volumetric heat capacity s, MJ/(m^3·K)	Specific extraction rate of the ground, (q, W/m) assumptions
1.1	dry and saturated soil average	according to PORT PC
1.2	dry and saturated soil average	according to SIA 384/6
1.3	saturated soil	according to PORT PC
1.4	saturated soil	according to SIA 384/6
2.1	as in variants 1.1 and 1.2	20 W/m
2.2	as in variants 1.1 and 1.2	40 W/m
2.3	as in variants 1.3 and 1.4	20 W/m
2.4	as in variants 1.3 and 1.4	40 W/m

The input data for the simulations were: thermal conductivity of the ground, volumetric heat capacity of the ground, ground surface temperature, geothermal heat flow, boreholes' characteristics (number, configuration, depth, distance, diameter, heat transfer agent flow and U-pipe diameter and material), heat transferring agent properties, the thermal load of the building (as given in table 1) as well as the number of simulation years and the month of the heat pump system operation begin. The simulation outcomes are the average brine temperatures at the end of each month in 1st, 2nd, 5th, 10th and 25th year of system operation.

Thermal conductivity and volumetric heat capacity and the source size were implemented according to assumptions and calculations. The other properties are common to all system variants. The ground surface temperature assumed for the area of town Jelenia Góra t_g = 6,9°C; the geothermal heat flow q_{gr} = 0,06 W/m^2; boreholes distance b_{ds} = 6,0 m; ground heat exchanger material and diameter PE DN32 PN10 (32 x 3,0 mm). Heat transferring agent properties are: thermal conductivity λ_{br} = 0,48 W/(m·K), specific heat capacity c_p = 3795,0 J/(kg·K), density ρ_{br} = 1052 kg/m^3, viscosity η_{br} = 0,0052 kg/(m·s) and freezing point t_f = -14°C. All simulations have been performed for 25 years and the system starts in September.

3 Analysis, results and discussion

In following section the results of performed calculations, analyses and simulations are discussed in details. First the design process undergoes the basic analysis, than the low enthalpy energy sources' simulation results are analysed and discussed.

3.1. Thermal properties of the ground and boreholes sizing

Calculated thermal conductivity and established unit thermal performance of the ground is presented in table 4 along with the assumed thermal conductivity coefficients of the particular layers. The values described with subscript 1 concern the variant where ground parameters were assumed as an average for dry and saturated ones and the values described with subscript 2 concern the variant where ground parameters were assumed as for saturated ones. The values of the thermal conductivity for particular ground types (gravel, clay and sand both saturated and dry, as well as granite) have been taken as recommended values form the EED software database.

Table 4. Thermal conductivity coefficients and unit thermal performance of the ground.

No.	Depth, m	Ground type	Share in the structure	λ_1, W/(m·K)	λ_2, W/(m·K)
1	2,0 – 7,5	Coarse gravel (8-16 mm)	5.5/100.0	1.10	1.80
2	7,5 – 56,0	Gray clay with 30% of sand	48.5/100.0	1.12	1.84
3	56,0 – 70,0	Gray-blue clay	14.0/100.0	1.00	1.60
3	70,0 – 102,0	Gray-blue clay with 30% of granite	32.0/100.0	1.72	2.14
Weighted average λ coefficient, W/(m·K):				**1.3**	**1.9**
Specific extraction rate of the ground (PORT PC guidelines), W/m [2]:				35	41
Specific extraction rate of the ground (SIA 386/4 standard), W/m [5]:				23	32

The simulation of heat pumps' energy source in EED software requires the volumetric heat capacity of the ground as an input data. They have been calculated using the same assumptions and method as for thermal conductivity and are equal to: $s_1 = 2{,}0$ MJ/(m^3·K) and $s_2 = 2{,}4$ MJ/(m^3·K).

It can be seen that the designers, who have the data concerning the geological profile of the ground, but make different assumptions concerning the ground moisture content will calculate the thermal conductivity coefficients that vary a lot (around 46% in analysed case). Moreover if they use different standards concerning the relationship between the thermal conductivity coefficient and specific extraction rate of the ground the established values show even greater difference (in analysed case values differ almost twice).

The boreholes number and depth have been calculated for established and assumed ground specific extraction rates. The heat pump cooling capacity have been taken from table 2 for the brine temperature $T_B = 0$°C and the heating agent flow temperature $T_H = 35$°C. The calculation outcomes are given in Table 5.

Table 5. The demanded boreholes depth and quantity.

Variant no	Unit thermal performance of the ground, q, W/m	Demanded length of the ground heat exchanger	Calculated number and depth of boreholes
1.1	35	394 m	4 · 99 m
1.2	23	600 m	6 · 100 m
1.3	41	337 m	4 · 85 m
1.4	32	431 m	5 · 87 m
2.1 and 2.3	20	690 m	7 · 99 m
2.2 and 2.4	40	345 m	4 · 87 m

The length and quantity of boreholes have been sized in the way that fits most precisely to the demanded summary length of the heat exchanger. As expected, the sizes of the low enthalpy energy source also vary greatly, depending on the assumptions made. Those values have direct impact on the low enthalpy heat source investment cost, but also on the source performance during long years of operation.

3.2. The low enthalpy energy source simulation outcomes

As mentioned before the simulations of the heat pump's low enthalpy heat source performance have been executed for two design approaches. In first one ground heat exchanger sizes are the effect of geological profile analysis and specific extraction rates established based on the approved standards. In second one the heat source sizing is based on the assumed specific extraction rates (taken from design guidelines) without considering the geological profile. The outcomes are gathered and discussed in following subsections.

3.2.1. The simulation variants 1.1 to 1.4

The outcomes of the low enthalpy energy source simulation are presented in the Fig. 2 and Table 6. The differences among the variants are only due to the assumptions made by authors while calculating the thermal conductivity coefficient of the ground and while assuming the specific extraction rates of the ground, which affected the source size.

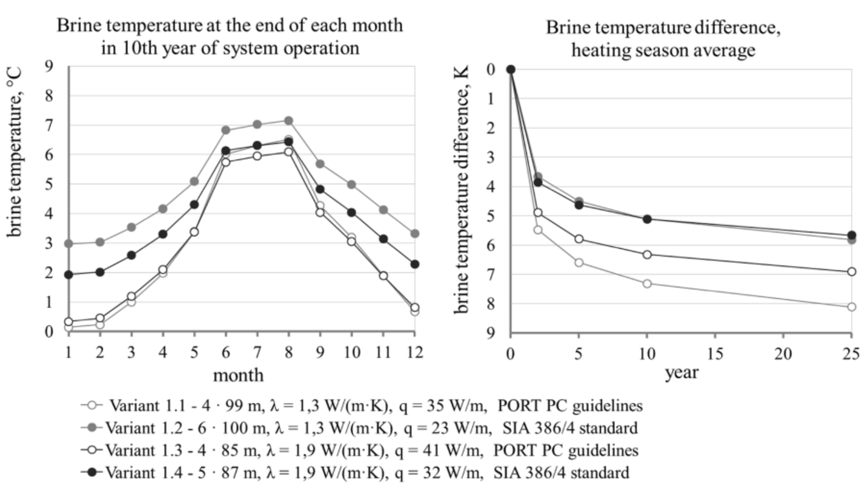

Fig. 2. The outcomes of the system variants 1.1 to 1.4 simulation in EED software.

On the left side of the Fig. 2 the brine temperature values at the end of each month in 10^{th} year of the heat pump system operation for each simulation variant are presented. The difference in brine temperature, depending on the variant, is about 3 K in winter and about 1 K in summer. Those temperature changes are due to the various boreholes thermal load (various source sizes) bud also due to different brine initial temperatures among variants. On the right side of Fig. 2 the difference between the brine initial temperature (before the installation commissioning) and the seasonal average brine temperature are shown. The temperature differences for variants 1.2 and 1.4 (SIA 386/4 standard) are aligned, and those for variants 1.1 and 1.3 (PORT PC guidelines) are divergent. This means that the relationship between the thermal conduction coefficient of the ground and its specific extraction rate proposed in SIA 386/4 standard, which is not linear [5], assigns such specific extraction rates to the different thermal conductivity coefficients that cause similar boreholes performance (similar cool down). The relationship proposed in PORT PC (linear one [2]) assigns such values that for smaller thermal conductivity coefficients give greater brine cool down. Table 6 brings the additional information about the brine initial temperature for each variant, the temperature of the brine in the end of January (the middle of heating season) and in the end of August (just before the heating season, after source self-regeneration during summer) in 25th year of heat pump operation as well as the difference between the initial and operational values. The difference in the initial brine temperatures are due to different boreholes' depth and thermal conductivity coefficients of the ground. The brine temperature in the heating season determines one of the proper sizing conditions, and the temperature difference between the initial and end of summer temperature (which approximately corresponds to the global ground cool down) determines other proper boreholes' sizing condition.

Table 6 Brine temperatures and temperature changes after 25 years of operation.

Simulation	V 1.1	V 1.2	V 1.3	V 1.4
t_{begin}	9.2	9.2	8.2	8.3
t_{25} (January)	-0.7	2.2	-0.3	1.4
Δt_{25} (January)	9.9	7.0	8.5	6.9
t_{25} (August)	6.5	6.5	5.5	5.9
Δt_{25} (August)	2.8	2.8	2.7	2.4

Although all sources are designed according to the approved standards, the outcomes differ one from another. First of all it should be noticed that despite the different assumptions concerning ground moisture, and obtaining different ground thermal conductivity coefficients, as well as despite concerning different relationships between thermal conductivity coefficients and specific extraction rates, all outcomes confirm the source proper sizing. The temperature difference between the initial and the end of summer value do not exceed 3 K. The temperature of the brine in the end of January, which is the lowest value, in case of applying SIA 386/4 standard for specific extraction rates determination, is above 0°C, and in case of applying PORT PC guidelines the brine temperature only slightly drops below 0°C. PORT PC guidelines allow for the smaller (cheaper) source sizing, so the source slightly worse performance was to be expected, because the source is more heavily loaded (especially when thermal conductivity is lower).

Assuming that the calculated thermal conductivity coefficient is the same as real one, the effects described above will be probably true not only while simulating the heat pump's energy source, but also for real installations, because the EED software results proved to be close to the measurements [6]. It is also interesting to find out what will happen if the thermal conductivity is unknown, and the source is designed based on rough assumptions.

3.2.1. The simulation variants 2.1 to 2.4

The outcomes of the simulations are given in in Fig. 3 and Table 7. It has been assumed that both designed sources (for 20 W/m and 40 W/m specific extraction rates) performance will be simulated for the ground with thermal conductivity coefficients of 1,3 W/(m·K) and 1,9 W/(m·K).

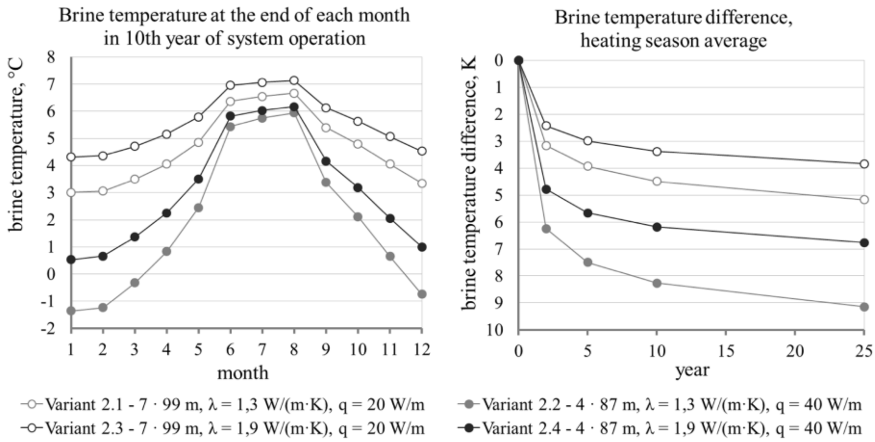

Fig. 3. The outcomes of the system variants 2.1 to 2.4 simulation in EED software.

Table 7 Brine temperatures and temperature changes after 25 years of operation.

Simulation	V 2.1	V 2.2	V 2.3	V 2.4
tbegin	9.2	8.9	8.5	8.3
t25 (January)	3.0	-2.3	3.8	-0.1
Δt25 (Januray)	6.2	11.2	4.6	8.3
t25 (August)	6.7	5.1	6.7	5.6
Δt25 (August)	2.5	3.8	1.8	2.7

In Fig. 3 the brine temperature values at the end of each month in 10th year of the system operation are presented for each variant, as well as the difference between the brine initial temperature (before the installation commissioning) and the seasonal average brine temperature. It can be noticed, that for variants 2.1 and 2.4, which somehow corresponds to the design guidelines, the installations work properly. As it was expected, in case where the designer assumes high extraction rate (40 W/m) and the ground conditions are poor (1,3 W/(m·K)), like in variant 2.2, the low enthalpy energy source will get overloaded, and may freeze. Variant 2.3 is interesting, because one could expect much better performance of the system, in which the low enthalpy energy source is oversized. The simulation results indicate however that the brine temperatures are only slightly higher that for the variant 2.1, and the ground cool down is only a bit smaller.

4 Conclusion

The assumptions made while sizing the brine-to-water heat pump's low enthalpy energy source influence the simulation outcomes, which vary in wide range. Those differences may influence further decisions, including one concerning the installation realization.

While sizing the low enthalpy energy source size, it is important to combine various methods of the data concerning the ground properties gathering; pilot drilling, TRT test and computer simulations; as each of them may indicate some inaccuracy. The knowledge of soil parameters and the appropriate design guidelines selection enables the correct operation of the installation in subsequent years. The analysis based on the computer simulations is the tool that let verify the proper low enthalpy energy source performance.

The change of ground's thermal conduction value and the boreholes depth influence initial, calculated (EED software) brine temperature, strictly related to the unloaded ground temperature. The disproportion between assumed ground specific extraction rate and one resulting from the ground thermal conductivity value is visible in simulation results.

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