ENERGY PERFORMANCE ANALYSIS OF THE FIRST RESEARCH-ONLY GROUND COUPLED HEAT PUMP IN ROMANIA

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Abstract: - One laboratory belonging to Energy Engineering Faculty is heated with a ground-coupled heat pump (GCHP) system having two types of ground heat exchangers: a vertical one and a horizontal one. This paper presents, at first, several coefficients of performance that can be defined for heat pumps together with their usability. Then, an energy efficiency model is set specially for CGHP systems. In this paper the simulation of energy performances is done only for the vertical heat exchanger (borehole heat exchanger) consisting of a double-U pipe inserted into a borehole of 75 m depth, and a horizontal one – SCSO - consisting of 4 pipes laid down into a 75 m long trench, on two layers (1.8 m, respectively 1.2 m depth). Because of manifold headers the system is capable to separate the individual brine circuits. Any GCHP system has three main subsystems (Fig. 1): • underground subsystem; • heat pump subsystem; • consumer subsystem. In order to analyze the efficiency of the whole system, all component subsystems must be successively studied as in the end will result the GCHP energy performance.

Key-Words: - Ground coupled heat pump, energy efficiency, performance, simulation

1 Introduction
University of Oradea developed a sustained research activity in the field of renewable energy sources [1,2,3]. In this framework, a ground-coupled heat pump (GCHP) system was installed in 2008, having two types of ground heat exchangers (SCS): a vertical one - SCSV - (borehole heat exchanger) consisting of a double-U pipe inserted into a borehole of 75 m depth, and a horizontal one – SCSO - consisting of 4 pipes laid down into a 75 m long trench, on two layers (1.8 m, respectively 1.2 m depth). Because of manifold headers the system is capable to separate the individual brine circuits. Any GCHP system has three main subsystems (Fig. 1):

2 Modeling the energy efficiency of a GCHP
Literature defines several coefficients of performance [4] for heat pumps (HP), starting with the theoretical ones and going to real ones, some of them related to power, and some related to energy. For a monovalent GCHP the expression of seasonal performance factor (SPF) is given by equation (1):

$$SPF = \frac{Q_{cons}}{W_{PC} + W_{aux}}$$  \hspace{1cm} (1)

Table 1 – Coefficients of performance for heat pumps

<table>
<thead>
<tr>
<th>Coefficient of performance</th>
<th>Expression</th>
<th>Application factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretic of the sources</td>
<td>(\text{COP}_{ts} = \frac{T_2}{T_2 - T_1})</td>
<td>• control value; • not practical; • theoretic;</td>
</tr>
<tr>
<td>Theoretic of the cycle</td>
<td>(\text{COP}<em>{tc} = \frac{T_c}{T_c - T</em>{ev}})</td>
<td>• control value; • not practical; • theoretic;</td>
</tr>
<tr>
<td>Moto-compressor group</td>
<td>(\text{COP}_c = \frac{\dot{Q}_2}{P_c})</td>
<td>• doesn’t offer a clear idea about real performances; • given by some manufacturers;</td>
</tr>
<tr>
<td>Global of HP</td>
<td>(\text{COP}<em>{PC} = \frac{\dot{Q}</em>{2 \text{ med orar}}}{P_{c \text{ med orar}} + P_{aux \text{ med orar}}})</td>
<td>• indispensable; • allows a better definition of HP qualities; • given by the manufacturer;</td>
</tr>
</tbody>
</table>
Table 1 – Cont.

| Global of whole installation       | COP₁ = \frac{\dot{Q}_2\text{ med orar}_{\text{util}}}{P_c\text{ med orar} + P_{\text{aux med orar}}} | • found after testing;                      |
|                                  |                                                                                   | • allow to observe the behavior of HP as a function of outside temperatures;  |
| Mean annual of compressor         | COP_{\text{a-c}} = \frac{\sum n_i \cdot \text{COP}_c}{\sum n_i} | • to avoid;                                      |
| Mean annual of HP                 | COP_{\text{a-PC}} = \frac{\sum f_i \cdot n_i \cdot \text{COP}_{\text{PC}}}{\sum f_i \cdot n_i} | • to avoid;                                      |
| Seasonal or global annual of whole installation | SPF = \frac{\text{annual heat produced}}{\text{total annual electric energy consumption}} | • allows to determine the economy of energy; |
|                                  |                                                                                   | • indispensable;                                                      |
|                                  |                                                                                   | • found after testing.                                                  |

\[ \text{SPF} = \frac{\text{annual heat produced}}{\text{total annual electric energy consumption}} \]

**Fig. 1 – Lay-out of the experimental installation:**

SST – underground subsystem; SPC – HP subsystem; SC – consumer subsystem; SCSO, SCSV – horizontal, respectively vertical ground heat exchanger; R₁ + R₁₂ – valves; PC₁, PC₂, PC₃ – circulation pumps; V – evaporator; Cp – compressor; Cd – condenser; VR – expansion valve; VEH – header; Co – heat consumer

where: SPF[-] – seasonal performance factor of GCHP; Q_{\text{cons}} [J] − heat required by the consumer; W_{\text{PC}} [J] – electric energy absorbed by the HP; W_{\text{aux}} [J] – electric energy for auxiliaries; is not included in COP_{\text{PC}} definition (represents the energy consumed by the circulation pump of the brine and of the water from heating system).

If GCHP works in bivalent mode, SPF of the system is:

\[ \text{SPF}_{\text{sist}} = \frac{Q_{\text{cons}}}{\delta \cdot Q_{\text{cons}} + \left(1 - \delta \right) \cdot Q_{\text{cons}}} \hspace{1cm} (2) \]

where: \( \delta \) [-] – fraction of heat required by the consumer covered by HP; \( \eta_{\text{rez}} \) [-] – efficiency of additional (back-up) heat source.
Electric energy consumption of the compressor ($W_{PC}$) is calculated from total heat production of the HP related to its coefficient of performance. Total heat delivered by the HP is calculated adding to consumer requirements both heat losses because of cyclic operation of the heat pump and storage heat losses [5]:

$$Q_{tot} = Q_{cons i} + Q_{cyclic i} + Q_{stoc i}$$

Therefore, daily performance factor ($PF_i$) is:

$$PF_i = \frac{Q_{cons i}}{Q_{cons i} + Q_{cyclic i} + Q_{stoc i} + W_{aux i}}$$

Performance factor of GCHP system working in monovalent mode, calculated for the entire heating period, is:

$$SPF = \frac{\sum_{i=1}^{n} PF_i}{n} = \frac{\sum_{i=1}^{n} \frac{Q_{cons i}}{COP_i}}{n} + W_{aux i}$$

where $i$, respectively $n$ represent the current day, respectively the total number of heating days.

3 Energy performance simulation for GCHP

Next steps have to be followed to accomplish SPF simulation:

a. simulate daily heating requirement of the consumer;

b. simulate ground heat transfer in order to determine mean brine temperature;

c. determine the available heat flow to be extracted from the ground, checking if it covers consumer requirements, setting therefore the operation mode of the HP (monovalent or bivalent);

d. calculate the parameters that characterize energy performances of GCHP, both as daily and annual values: heat delivered to consumer, electric energy consumption, COP, PF, SPF.

For the considered GCHP system, the consumer is the space itself where experimental HP was installed. This is the Thermodynamics Laboratory from Energy Engineering Faculty in Oradea. The first step is accomplished by running CALCER computer program for this specific consumer. Daily heat flow required by the Laboratory room is calculated for an inside temperature of 20 $^\circ$C, and the values are represented in Fig. 2. It must be said that even in summer time this space needs heating because it is located in the basement and external heat gains don’t cover heat losses to the ground. Maximum heat flow required is 2025 W and annual energy requirement is 8636 kWh. The experimental installation has got two types of heating equipment: a radiator and a fan-coil unit, both requiring a temperature of 50 $^\circ$C for inlet water.

![Fig. 2 – Heat flow requirement for a calendar year](image-url)
condenser side. For a brine-to-water GCHP, the analytical expressions of COP are:

\[
\text{COP} = \frac{0.0305 \cdot T_{SCS_e} + 1}{0.0005 \cdot T_{SCS_e} + 0.2225}
\]

\(T_{tur} = 35 \degree C\):

\[
\text{COP} = \frac{0.029 \cdot T_{SCS_e} + 0.985}{0.001 \cdot T_{SCS_e} + 0.255}
\]

\(T_{tur} = 40 \degree C\):

\[
\text{COP} = \frac{0.029 \cdot T_{SCS_e} + 0.965}{0.002 \cdot T_{SCS_e} + 0.28}
\]

\(T_{tur} = 45 \degree C\):

\[
\text{COP} = \frac{0.0275 \cdot T_{SCS_e} + 0.9475}{0.002 \cdot T_{SCS_e} + 0.31}
\]

\(T_{tur} = 50 \degree C\):

\[
\text{COP} = \frac{0.027 \cdot T_{SCS_e} + 0.925}{0.002 \cdot T_{SCS_e} + 0.34}
\]

where: \(T_{tur} [\degree C]\) – outlet water temperature at condenser side;

\(T_{SCS_e} [\degree C]\) – outlet brine temperature (when exiting borehole heat exchanger and entering the evaporator).

The second step is accomplished using EWS simulation program for specific conditions of experimental GCHP system, both for single-U and double-U borehole heat exchangers. Mean brine temperatures in the 5th year of simulation are shown in Fig. 3:

- for 1 circuit (single-U tube) marked 1V;
- for 2 circuits (double-U) marked 2V.

Fig. 3 – Simulated mean brine temperatures for single-U and double-U configurations, in the 5th year of operation

In order to calculate energy performance parameters, all types of heat and electricity must be known. Therefore, for the considered system, since HP and header are both located in the same environment as the consumer, storage heat losses are zero. Also, heat losses due cyclic operation are zero. Electricity consumption of auxiliaries is approx. 25% of heat pump electricity consumption (according to performed experimental measurements). Fig. 4 shows the results of simulated daily energies. Based on equations (1) ÷ (5) energy performance parameters were calculated for a calendar year. Simulation results are graphically represented in Fig. 5.

Mean annual values of energy performance parameters of vertical GCHP system from University of Oradea are obtained by integrating the above simulated daily values over the heating period. These values are shown in Table 2.
Fig. 4 – Mean daily values of heat delivered to consumer ($Q_{\text{cons}}$), active electric energy consumed by HP ($W_a$) and total electric energy ($W_{\text{tot}}$) consumed by experimental GCHP for both configurations (1V and 2V).

Tabel 2 – Mean annual values of energy performance parameters for vertical GCHP in Oradea

<table>
<thead>
<tr>
<th>Operational configuration of SCSV</th>
<th>$Q_{\text{cons}}$ [kWh/an]</th>
<th>$W_a$ [kWh/an]</th>
<th>$W_{\text{tot}}$ [kWh/an]</th>
<th>COP [-]</th>
<th>SPF [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 V</td>
<td>8636.39</td>
<td>2321.95</td>
<td>2902.44</td>
<td>3.72</td>
<td>2.98</td>
</tr>
<tr>
<td>2 V</td>
<td>2262.83</td>
<td>2828.54</td>
<td>3.82</td>
<td>3.05</td>
<td></td>
</tr>
</tbody>
</table>
4. CONCLUSION

Analyzing the results of the simulation shown in Fig. 4, Fig. 5 and Table 2, the following conclusion can be set:

- Values of HP coefficient of performance (COP$_{PC}$), respectively the performance factor of the system (PF) fit into normal range, COP values are between 3.6 ÷ 4, respectively 2.8 ÷ 3.2 for PF.
- Daily electricity consumption of the heat pump is 1.3 ÷ 13.5 kWh/day, and total electricity consumption of GCHP heating system is 1.6 ÷ 16.9 kWh/day.
- Results for daily electricity consumptions are relatively close for the two borehole heat exchanger configurations.
- Annual electricity consumption ranges between 2263 kWh and 2322 kWh for heat pump and 2828 kWh and 2902 kWh for the whole system.
- Mean annual value of COP$_{PC}$ and, respectively, of seasonal performance factor (SPF) is approximately 3.8 for COP$_{PC}$ and 3.0 for SPF.
- Very small differences (less than 3 %) can be seen between energy performance parameters belonging to 1V and 2V operational configuration.

- Results of all simulations range between values specified into literature or recommended by manufacturers, therefore they are considered as being realistic.

References:

[1] Research Project: Reaching the Kyoto targets by means of a wide introduction of ground coupled heat pumps (GCHP) in the built environment (GROUND-REACH), financed by European Commission (Contract No. EIE/05/105), 2006-2009


