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Shallow Geothermal Energy Systems – Where Does the Energy Come From?

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ABSTRACT

Shallow Geothermal Energy Systems provide local, free and renewable energy from the underground. The energy reaches the ground via solar radiation, air, groundwater and geothermal heat flow from the Earth's interior, and is stored as sensible heat in the ground material and groundwater.

This paper sorts out the energy balance and contribution from the different heat sources over time for the undisturbed ground as well as for extraction-only ground source heat pump (GSHP) systems and underground thermal energy storage (UTES) systems.

1. INTRODUCTION

Heat extraction by vertical boreholes exploits shallow geothermal resources. How much of the extracted originates from the ground surface and how large is the contribution from the geothermal heat flow? These questions have been addressed by different authors in the past and are still debated (Claeson and Eskilson, 1988; Huber and Pahud, 1999; Eugster, Hopkirk and Rybach, 1999).

2. BASIC EQUATIONS

The annually fluctuating temperature at (or near) the ground surface can by Fourier analysis be divided into a number of harmonic components with different frequencies. The maximum penetration depth of the resulting thermal impact is given by the basic harmonic with a period length of one year. This periodic thermal impact reaches a depth of 10-15 m below ground surface in typical geological materials. The periodic temperature variations near the ground surface is not included in the analysis presented here, but can be superimposed on the given solutions.

The initial ground temperature is assumed to be a function of the depth z below the ground surface. The average ground surface temperature T_m is assumed to be constant.

The heat transport in the ground takes place by conduction only and is governed by the partial differential equation:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{a}\frac{\partial T}{\partial t}$$

Where the temperature $T(r,z,t)$ depends on a radial coordinate r and a depth coordinate z. The thermal diffusivity of the ground is denoted a. It is the ratio between the thermal conductivity λ and the volumetric heat capacity C.

The boundary condition at the ground surface is:

$$T(r,0,t) = T_m$$

The borehole has a thermally active depth H starting at a depth D. See Figure 1.

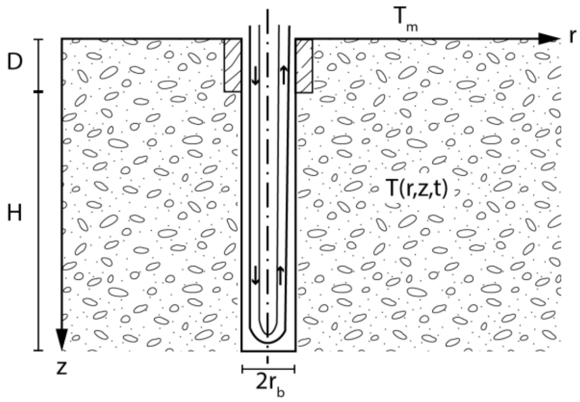

Figure 1: The borehole has a thermally active depth *H* starting at a depth *D*.

The temperature at the borehole wall T^b varies with time t:

$$T(r_b,z,t) = T^b(t) \qquad D \le z \le (D+H)$$

The specific heat transfer rate q (W/m) at the borehole radius r_b satisfies:

$$-2\pi r_b \lambda \left[\frac{\partial T(r,z,t)}{\partial r}\right]_{r=r_b} = q(z,t) \qquad D \le z \le (D+H)$$

The total heat transfer rate Q *(W)* is equal to:

$$\int_{D}^{D+H} q(z,t)\ dz = Q(t)$$

The initial ground temperature varies with depth and is given by:

$$T(r,z,0) = T_m + T_z(z)$$

The average initial ground temperature along the borehole becomes:

$$\frac{1}{H}\int_{D}^{D+H} T(r,z,0)\ dz = T_m + \frac{1}{H}\int_{D}^{D+H} T_z(z)\ dz = T_m + \tilde{T}_z$$

3. SUPERPOSITION

The ground temperature $T(r,z,t)$ may with use of the superposition technique be expressed as a sum of two components $T_1(r,z,t)$ and $T_2(r,z,t)$, namely

$$T(r,z,t) = T_1(r,z,t) + T_2(r,z,t)$$

where both components fulfil the heat equation. Together they satisfy the boundary and the initial conditions given above.

There is now a choice with regard to what the two components represent. Claesson and Eskilson (1988) choose to let one part represent the active heat transfer from/to the borehole with the initial ground temperature and the ground surface temperature taken as constant equal to the initial average temperature $T_m + \tilde{T}_z$ along the borehole. The other part represented the superimposed disturbance due to the difference between the actual undisturbed temperature and the initial average temperature along the borehole.

Here, we instead choose to let one part represent the complete thermal process due to circulation of the fluid without any net heat extraction from the borehole (Q=0). The circulation is assumed to result in a uniform borehole temperature. The borehole will exchange heat with surrounding ground depending on the temperature difference between the borehole and the surrounding ground. In the presence of a varying ground temperature, this will lead to a redistribution of heat along the borehole. The second part takes care of the temperature disturbance caused by the active heat transfer to and from the borehole ($Q \neq 0$).

3.1 Temperature component T_1

The temperature at the ground surface ($z=0$) is constant:

$$T_1(r,0,t) = T_m$$

The borehole wall temperature is uniform:

$$T_1(r_b,z,t) = T_1^b(t) \qquad D \le z \le (D+H)$$

The specific heat extraction rate q_1 is satisfies:

$$-2\pi r_b \lambda \left[\frac{\partial T_1(r,z,t)}{\partial r}\right]_{r=r_b} = q_1(z,t) \qquad D \le z \le (D+H)$$

The temperature $T_1^b(t)$ is chosen so that there is no net heat transfer:

$$Q_1(t) = \int_{D}^{D+H} q_1(z,t)\ dz = 0$$

The initial condition ($t=0$) allows for temperature variation with depth:

$$T_1(r,z,0) = T_m + T_z(z)$$

The average initial temperature along the borehole becomes:

$$\frac{1}{H}\int_{D}^{D+H} T_1(r,z,0)\ dz = \frac{1}{H}\int_{D}^{D+H} [T_m + T_z(z)]\ dz = T_m + \tilde{T}_z$$

The average value of the deviation $\tilde{T}_z$ from the ground surface temperature becomes 0 if the initial ground temperature is uniform.

3.2 Temperature component T_2

Superimposed on the thermal process handled by temperature component 1 there is the process caused by the active heat transfer $Q(t)$. This part is represented by temperature component 2.

The temperature at the ground surface ($z=0$) is constant:

$$T_2(r,0,t) = 0$$

The borehole wall temperature is uniform:

$$T_2(r_b,z,t) = T_2^b(t) \qquad D \le z \le (D+H)$$

The specific heat transfer rate satisfies:

$$-2\pi r_b \lambda \left[\frac{\partial T_2(r,z,t)}{\partial r}\right]_{r=r_b} = q_2(z,t) \quad D \le z \le (D+H)$$

The temperature $T_2^b(t)$ is chosen so that the total heat transfer rate $Q_2(t)$ for component 2 equals $Q(t)$:

$$Q_2(t) = \int_{D}^{D+H} q_2(z,t)\ dz = Q(t)$$

The initial ground temperature is given by:

$$T_2(r,z,0) = 0$$

The average initial temperature along the borehole becomes:

$$\frac{1}{H}\int_{D}^{D+H} T_2(r,z,0)\ dz = 0$$

Note that the solution for the active heat exchange is independent of the initial ground temperature profile $T_z(z)$ and the associated vertical heat flow.

3.3 Example

Consider a 150 m deep borehole with an active depth *H* of 146 m and an inactive part *D* of 4 m. The ground thermal conductivity is 3.5 W/m,K and the volumetric heat capacity is 2.2 MJ/m^3,K. These values are typical of Swedish crystalline rock (granite/gneiss). The ground surface temperature is kept constant at an annual average value of 7 ˚C. The net heat extraction is 15 MWh/year corresponding to an annual average of 11,7 W/m. The initial vertical temperature profile is assumed to increase with 0.0162 ˚C/m. Figures 2-3 show the computed isotherms after 25 years of operation. Figure 2(left)

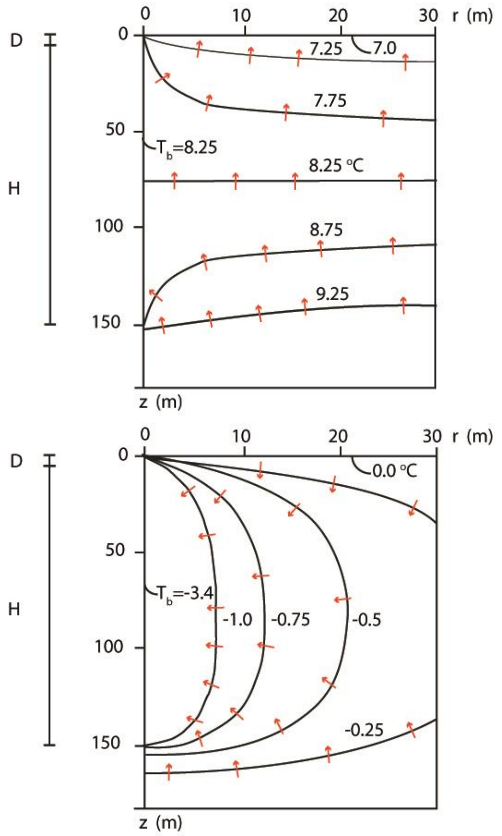

Figure 2: Computed isotherms after 25 years for temperature component 1 (upper) and temperature component 2 (lower). Temperature component 1 shows the effect of circulating the heat carrier fluid without any net heat extraction. Temperature component 2 shows the superimposed effect of heat extraction.

The circulation of the fluid without any heat extraction results in a redistribution of heat from warm surroundings to cold surroundings of the borehole. See Figure 2:upper. In this case the heat redistributed from the lower part to the upper part of the borehole. The superimposed temperature field due to heat extraction (Figure 2:lower) is independent of the thermal process associated with initial temperature distribution and circulation of the fluid without heat extraction (Figure 2:upper).

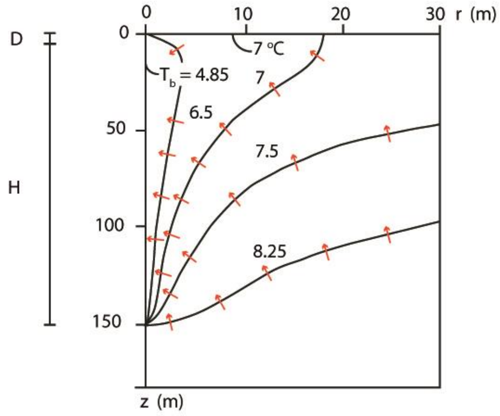

Figure 3: Computed isotherms after 25 years. The ground temperature is a sum of temperature component 1 and 2.

4. COMMENTS

4.1 Initial ground temperature

Claesson and Eskilson [1988] observed that, based on numerical simulations, the influence on the borehole temperature of the superimposed disturbance due to the difference between the actual undisturbed temperature and the initial average temperature along the borehole was negligible in comparison to the variation of the borehole temperature due to the active heat transfer *Q(t)*. The recommended procedure for ground loop design purposes was then to set the initial ground temperature and the ground surface temperature equal to the initial average temperature $T_m + \tilde{T}_z$ along the borehole.

The analysis performed here shows that any magnitude or variation of active heat transfer is a superimposed thermal process independent of the initial temperature profile $T_z(z)$ in the ground. For a case with heat extraction, the energy is initially obtained by cooling the surrounding ground. The ensuing temperature decrease leads to a gradually increasing heat flow from the ground surface. Finally, when a steady-state condition has been attained, all heat flows from the ground surface (if the heat extraction remains unchanged). See Figure 4. The existence of a vertical geothermal temperature gradient, or alternatively, a geothermal heat flow, does not contribute to recharge the thermal disturbance caused by the heat extraction.

If the initial ground temperature is uniform, then $T_z(z) = 0$ and consequently its average value $\tilde{T}_z = 0$. Nothing will then happen for the thermal process associated with temperature component 1. If there is an initial variation with depth, $T_z(z) \neq 0$, the thermal process of the component T_1 will redistribute the heat along the borehole. As an example, assume a linear increase of ground temperature with depth. During circulation only there will be a heat flow to the upper half of the borehole and a corresponding heat flow from the borehole in the lower half. The proximity of the ground surface and its constant temperature makes the situation asymmetric. The influence of this asymmetry will depend on how the resulting temperature disturbance spreads out in relation to the distance *D* to the ground surface and the active length *H* of the borehole.

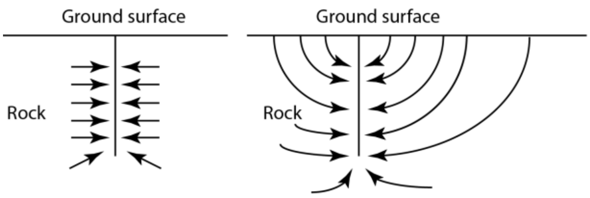

Figure 4: Heat flows at an initial stage (left) and at final steady-state conditions (right).

4.2 Ground surface temperature

The assumption that the ground surface temperature is constant, or actually that is has a constant annual average temperature, deserves a comment.

The ground surface temperature depends on the energy flows at the ground surface:

- Incoming short-wave solar radiation (absorption, reflection)
- Incoming long-wave radiation (absorption, reflection)
- Outgoing long-wave radiation
- Convective-conductive heat exchange between air and ground
- Precipitation (rain and snow)
- Evaporation
- Heat flow from the ground

The geothermal heat flow from the earth crust is relatively small in comparison with the incident solar energy. In Sweden, the incident solar energy is about 1000 kWh/m^2,year whereas the geothermal heat flow contributes with about 0,5 kWh/m2,year. The ground temperature levels utilized in shallow geothermal applications are largely a result of the solar driven heat flows at the ground surface (including the greenhouse effect) and the resulting accumulated and stored heat in the ground.

Design work and simulation of shallow geothermal systems often require an estimate of the initial ground temperature. A simple way to describe the undisturbed vertical ground temperature profile is to assume a constant ground surface temperature with a steady geothermal temperature gradient determined by the geothermal heat flow and the thermal conductivity of the geological material. However, the picture has become somewhat more complicated due to impacts of global warming and changes in local climate and boundary conditions caused by urbanization. Nowadays there is often a net heat flow into the ground due to warmer climate and/or heat losses from building foundations in urban areas.

5. HEAT FLOWS

5.1 Heat flow from the ground surface

The superimposed heat extraction from the borehole gives a cooling of the surrounding ground with a subsequent heat flow from the ground surface. The contribution from the ground surface increases with time. Figure 5 shows the heat flow for two different borehole depths, 125 m and 250 m, for two cases with different thermal properties of the ground. The ground thermal conductivity and volumetric heat capacity are either 2.5 W/m,K and 2.4 MJ/m^3,K or 3.5 W/m,K and 2.2 MJ/m^3,K respectively. The distance from the ground surface to the active part of borehole, *D*, is assumed to be 5 m.

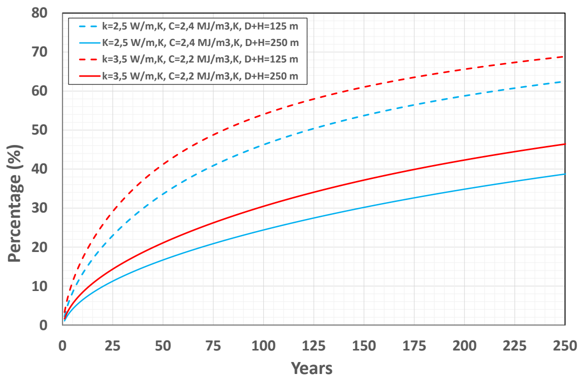

Figure 5: Percentage of heat flow at ground surface in relation to average net heat extraction rate from the borehole as a function of time from start of operation. Borehole depth is either 125 m (dashed) or 250 m (solid). Ground thermal conductivity and volumetric heat capacity are either 2.5 W/m,K and 2.4 MJ/m^3,K (blue) or 3.5 W/m,K and 2.2 MJ/m^3,K (red) respectively

After 25 years of operation, it is apparent that a fairly small fraction of the heat comes from the ground surface. For a 125 m deep borehole in ground with a ground thermal conductivity of 2.5 W/m,K and a volumetric heat capacity of 2.4 MJ/m^3,K about 23 % of the extracted heat flows from the ground surface while the remaining part, 77 %, is due to heat being removed from the surrounding ground. When the borehole reaches a depth of 250 m, only 11 % of the heat comes from the ground surface after 25 years of operation. In ground with a higher thermal conductivity, 3.5 W/m,K, the fraction of heat flow from the ground surface is slightly higher.

5.2 Total amount of heat from the ground surface

The accumulated contribution of heat from the ground surface is shown in Figure 6.

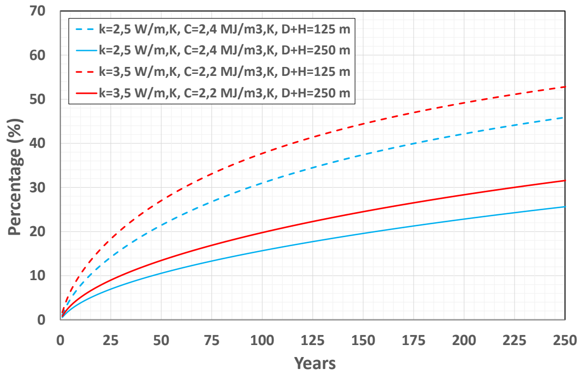

Figure 6: Percentage accumulated amount of heat from ground surface in relation to accumulated heat from the borehole as a function of time. Borehole depth is either 125 m (dashed) or 250 m (solid). Ground thermal conductivity and volumetric heat capacity are either 2.5 W/m,K and 2.4 MJ/m^3,K (blue) or 3.5 W/m,K and 2.2 MJ/m^3,K (red) respectively.

The accumulated contribution from the ground surface after 25 years is about 14 % for a 125 m deep borehole and 7 % for a 250 m deep borehole in the low thermal conductivity case (2.5 W/m,K) . Higher conductivity (3.5 W/m,K) gives a slightly higher contribution.

It should be noted that the above figures relates to the net heat extraction. If, as an example, 50 % of the extracted heat is recharged during an annual cycle, then 50 % of the extracted heat comes from the recharge and the remaining 50 % are distributed according to the fraction in the figures above.

The analyses and figures above relate to a single borehole. However, the general conclusions are by superposition also valid for multiple borehole systems. Closely spaced multiple borehole systems require a large degree of recharge in order to avoid long-term detrimental cooling or heating of the active ground volume.

Underground thermal energy storage (UTES) systems often operate at a higher temperature than the surrounding ground. The operation involves a cyclical injection and extraction of heat over the year combined with a superimposed net heat injection to sustain heat losses from the storage volume. A large part of the net heat loss results in increased ground temperatures around the store and another, often smaller, part is lost to (through) the ground surface.

6. CONCLUSIONS

The thermal process in the ground due to heat extraction from a single borehole is analysed in order to clarify the influence of geothermal heat flow and interaction with the ground surface. The superposition technique is used to divide the process into two parts.

One part deals with the process where the heat carrier fluid is circulated without any net heat extraction in a ground at an initially undisturbed temperature. The initial ground temperature is to a large extent a result of the incident solar energy and its interaction at the ground surface. The boundary conditions at the ground surface in combination with the geothermal heat flow determines the vertical temperature profile. The circulating heat transfer fluid and the associated interaction between the fluid temperature and the surrounding ground leads to a redistribution of heat along the borehole.

The second part contains the influence of the superimposed net heat extraction, which is independent of the conditions governing the first part, i.e., it is *independent* of temperature profile and geothermal heat flow. The net heat extracted from the borehole is obtained by lowering the ground temperature and by heat flowing from the ground surface. The contribution from the ground surface grows from 0 % at the start to 100 % at steady-state conditions. However, the time to reach steady-state conditions is extremely long. Examples given above for typical borehole depths used in ground-source heat pump application show that the largest contribution comes from lowering the temperature of the ground, i.e. extracting previously passively stored solar heat, originally transferred from the ground surface (“heat mining”). This effect becomes more pronounced with deeper boreholes.

REFERENCES

Claesson, J. and Eskilson, P.: Conductive heat extraction by a deep borehole. Thermal analyses a dimensioning rules. Energy, Vol. 13, No. 6, (1988), pp. 509-527.

Eugster, W., Hopkirk, J. and Rybach, L.: Ist untiefe Geothermie erneubar? Bundesamtes für Energie, Program Geothermie, (1999), Bern.

Huber, A. and Pahud, D.: Untiefe Geothermie: Woher kommt der Energie? Bundesamtes für Energie, Program Geothermie, Schlussbericht, (1999), Proj-Nr 33’206, Vertrags-Nr 73’162.