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Thermal performance assessment of closed-loop geothermal heat exchangers with vertical, inclined, and curved boreholes

Análisis del rendimiento térmico de intercambiadores geotérmicos de circuito cerrado con pozos verticales, inclinados y curvados

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Abstract: Accurate sizing of closed-loop geothermal heat exchangers is crucial to ensuring the energy efficiency and cost-effectiveness of shallow geothermal HVAC systems. One common design limitation is the restricted surface area available for borehole drilling. To address this constraint, inclined and curved borehole configurations offer an alternative to conventional vertical ones, allowing a greater underground exchange volume without increasing the ground footprint. However, inclined —and especially curved— boreholes involve higher drilling costs, raising the question of whether thermal performance justifies the investment. This study assesses the thermal behavior of closed-loop geothermal heat exchangers with vertical, inclined, and curved borehole configurations. Results show that inclined configurations represent the best balance between thermal efficiency and economic feasibility among the three.

Palabras clave: geotermia somera, pozos inclinados, pozos curvos, rendimiento térmico

Resumen: *El correcto dimensionamiento de intercambiadores de calor geotérmicos es crucial para asegurar la eficiencia energética y la viabilidad económica de sistemas de climatización geotérmica. Una restricción típica a tener en cuenta es la disponibilidad limitada de terreno para la perforación de pozos. Para superar esta limitación, pueden utilizarse pozos inclinados y/o curvados en lugar de los convencionales verticales. Estos permiten aumentar el tamaño subterráneo del intercambiador de calor geotérmico sin requerir más espacio en superficie. Sin embargo, los pozos inclinados y, especialmente, los curvados son más costosos de construir, lo que plantea la cuestión de si realmente valen la pena. Este estudio analiza el rendimiento térmico de pozos verticales, inclinados y curvados para abordar esta cuestión, demostrando que los pozos inclinados emergen como la opción más efectiva entre los tres.*

Key words: *shallow geothermal energy, inclined boreholes, curved boreholes, thermal performance*

INTRODUCTION

Almost 23% of mankind's global energy consumption is due to the heating and cooling of buildings (International Energy Agency, 2021). This explains why decarbonization of heating, ventilation, and air conditioning (HVAC) systems is a top priority for many countries and regions like the European Union.

Closed-loop geothermal HVAC systems represent one of the best options to achieve the sought energy transition. These HVAC systems incorporate a water-to-water heat pump connected to a geothermal heat exchanger, typically composed of vertical boreholes. Each borehole contains pipes arranged in coaxial or U-shaped configurations, through which a heat-carrying fluid circulates to exchange heat with the surrounding ground. The space between pipes and borehole wall is usually filled with impermeable thermally conductive grout, which enhances heat transfer and prevents cross-contamination of aquifers.

Proper sizing of closed-loop geothermal heat exchangers plays a fundamental role in the energy efficiency and economic viability of geothermal HVAC systems. This sizing must consider, among other factors, the limited land available for the drilling of boreholes as well as the limited budget available for the construction of the geothermal heat exchanger.

One strategy to overcome the limited availability of land is to use inclined and/or curved boreholes instead of classical vertical ones. These borehole geometries make it possible to increase the underground size of the geothermal heat exchanger, thus improving its energy efficiency, without sacrificing more surface area.

However, the construction of inclined, and especially curved, boreholes is more expensive than vertical boreholes, naturally raising the question of whether their increased cost justifies the gain in energy efficiency. The aim of the present work is to address this question by assessing the thermal performance of three geothermal heat exchangers equipped with vertical, inclined, and curved boreholes.

HEAT EXCHANGER CONFIGURATIONS

The chosen configurations for the geothermal heat exchanger are represented graphically in Figure 1. The first geothermal heat exchanger is composed of eight vertical boreholes, of 150 m depth, placed uniformly along a circle of radius $R = 8$ m. The second configuration also consists of eight geothermal boreholes of 150 m length placed along the same circle and inclined outward at $\beta = 10º$. Finally, the third one is also formed by eight geothermal boreholes placed along the same circle, but with their geometry consisting of five segments of 30 m length each, with each segment inclined 10º outward relative to the previous one, leading to the polygonal approximation shown in Figure 1.

All three configurations share the same buried depth (as defined in the computer manual of the Superposition Borehole Model (Eskilson, 1986)) of 0.5 m, the same thermal properties for the grout filling the borehole, 1.73 W/(m·K) and 5.00 x 10^{-7} m^2/s, and the same characteristics for the ground, namely, 1.80 W/(m·K) and 7.83 x 10^{-7} m^2/s. As unperturbed ground state, a surface temperature of 15 ºC and a geothermal heat flux of 0.6 W/m^2 are used for all three cases.

The internal structure and operation of the boreholes are also identical across all three configurations, with two identical pipes of 40 mm outer diameter, 3.7 mm wall thickness, and 0.42 W/(m·K) thermal conductivity placed symmetrically inside the borehole, of diameter 150 mm, with a shank spacing of 70 mm. Pure water is used in all cases as heat carrying liquid, with a density of 999 kg/m^3, a specific heat of 4186 J/(kg·K), a thermal conductivity of 0.59 W/(m·K), and a dynamic viscosity of 1.1 x 10^{-3} Pa·s. The resulting inner and outer thermal resistances of the boreholes, computed using the enhanced multipole method (Rivero & Hermanns, 2021; Hermanns & Rivero, 2023) and considering a volumetric flow rate of 0.6 l/s per borehole, are $R_a = 0.390$ m·K/W and $R_b = 0.104$ m·K/W, respectively.

THERMAL PERFORMANCE

The thermal response of the heat exchangers is obtained using the g-function method (Eskilson, 1987). To that end, the g-functions are obtained using the Python library *pygfunction* (Cimmino, 2018; Cimmino & Cook, 2022), while the computation of the thermal responses,

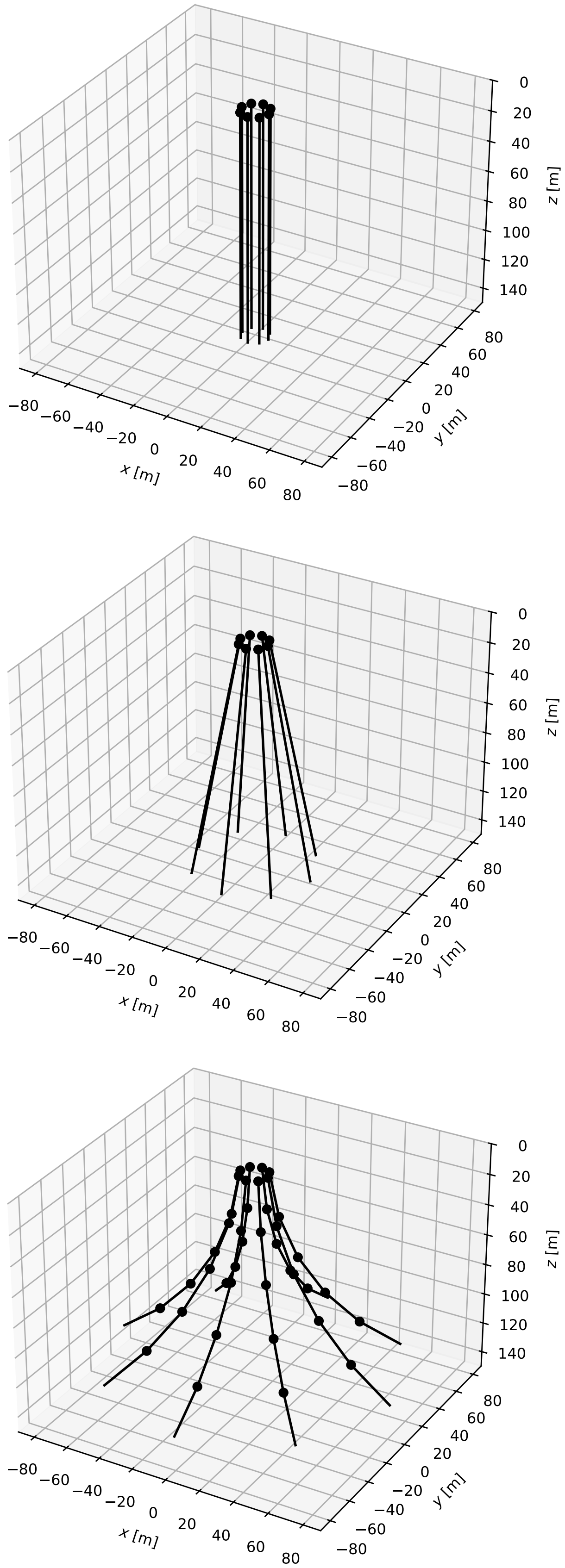

FIGURE 1. *Three-dimensional representations of the considered geothermal heat exchangers composed of eight (top) vertical boreholes, (middle) inclined boreholes, and (bottom) curved boreholes.*

which account for the inner structure and operation of the boreholes, is performed externally outside the library to ensure strict adherence to the original definition of the method (Eskilson, 1986; Hellström, 1991).

Although not shown here, additional models for the thermal response of geothermal heat exchangers have been used for cross-validation purposes, such as the finite element software package COMSOL (COMSOL, 2024) and the theoretical models under development at the leading author's research group (Hermanns, 2021).

The thermal performance of a given geothermal heat exchanger is assessed in the present work through the inlet temperature T_{in} required to sustain a certain constant heat injection rate over time, as inlet temperatures closer to the set temperature inside the building imply higher efficiencies of the heat pump, and consequently of the geothermal HVAC system.

Figure 2 shows, for the three considered geothermal heat exchangers, the time evolution of their inlet temperatures T_{in} for a sustained heat injection rate of 42 kW, equivalent to 35 W/m of average heat injection rate per unit borehole length. A time span of over 1000 years has been considered, well beyond the typical time horizon of 100 years, to include also the final steady state attained by all geothermal heat exchangers.

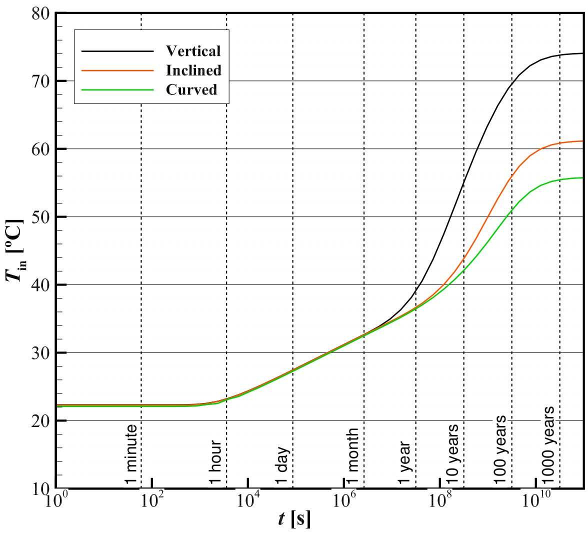

FIGURE 2. *Time evolution of the inlet temperature for the three considered geothermal heat exchangers composed of eight vertical, inclined, and curved boreholes, respectively.*

All three heat exchanger configurations present the same inlet temperature while the thermal interference between adjacent boreholes is negligible. That is, during the initial two months of operation. Thereafter, thermal interference appears first for the geothermal heat exchanger composed of vertical boreholes, leading to a rise in inlet temperature to keep injecting the same amount of heat into the ground. The geothermal heat exchanger composed of inclined boreholes follows next, with the onset of thermal interference starting after, approximately, one year of operation. Finally, the curved boreholes are also affected by thermal interference after approximately two years of operation.

The results shown in Figure 2 evidence that curved boreholes have a clear advantage in terms of energy efficiency of the resulting geothermal HVAC system as the required inlet temperatures are the lowest ones. Inclined boreholes also perform significantly better than vertical boreholes, but not as efficient as the curved borehole configuration.

EQUIVALENT HEAT EXCHANGERS

The main advantage of inclined and curved boreholes, compared to vertical ones, is the reduced need of space on the ground surface. A way of quantifying this advantage is to determine which radii R of the geothermal heat exchanger composed of vertical boreholes lead to the same thermal responses as the geothermal heat exchangers composed of inclined and curved boreholes.

Figure 3 shows the resulting inlet temperatures for five different geothermal heat exchangers. Three of them coincide with the configurations analyzed so far, while the additional two correspond to geothermal heat exchangers composed of vertical boreholes with circle radii equal to 19 m and 28 m. Interestingly, increasing the radius allows reproducing the improved thermal response of inclined and curved boreholes. However, an increase in surface area by factors of 5.6 and 12.3, respectively, is then required by the geothermal heat exchanger, which is not always available. Therefore, inclined and curved boreholes have a significant advantage over vertical boreholes in densely populated areas where plots of land tend to be tight.

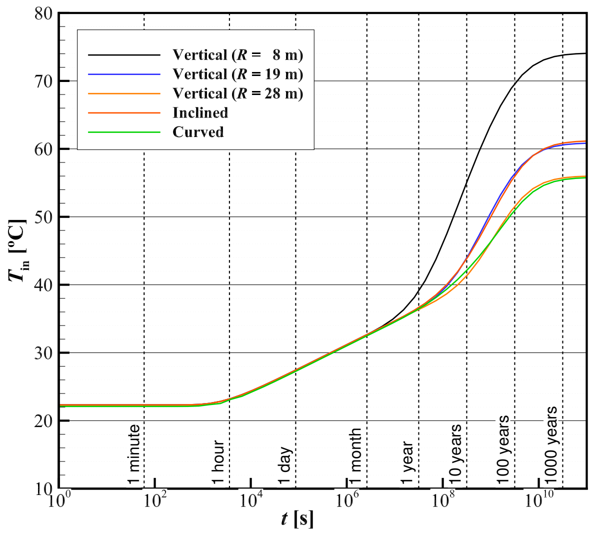

FIGURE 3. *Time evolution of the inlet temperature for five different geothermal heat exchangers composed of eight vertical boreholes with three different radii for the surface circle, eight inclined boreholes, and eight curved boreholes.*

Both inclined and curved boreholes share the advantage of reduced footprint on the ground surface. But the construction cost of curved boreholes exceeds that of inclined boreholes. Therefore, the question arises whether the favorable thermal response attained with curved boreholes can be matched by inclined boreholes with a greater inclination angle β.

Figure 4 shows the resulting inlet temperatures for four different geothermal heat exchangers. Three of them coincide again with the canonical configurations considered so far, while the fourth one corresponds to a geothermal heat exchanger composed of inclined boreholes with an inclination angle of 18º. Again, the favorable thermal response of curved boreholes can be achieved by using simpler engineering solutions, in this case, inclined boreholes with an increased inclination angle.

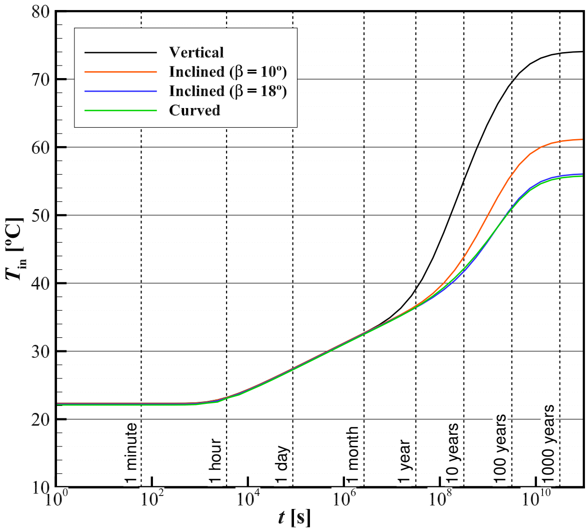

FIGURE 4. *Time evolution of the inlet temperature for four different geothermal heat exchangers composed of eight vertical boreholes, eight inclined boreholes with two different inclination angles, and eight curved boreholes.*

CONCLUSIONS

In the present work, the thermal performance of three different closed-loop geothermal borehole heat exchanger configurations—vertical, inclined, and curved—was assessed by examining the time evolution of the inlet temperature of geothermal heat exchangers equipped with them. The results indicate that inclined boreholes emerge as the most effective option among the three, as they are less expensive to construct than curved boreholes while achieving comparable thermal performance.

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