An approach for including heat pump performance in the design of thermo-active piles

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Summary

The focus on sustainable built environment has grown with the drive for net-zero. The use of pile foundations and other geotechnical structures as ground heat exchangers (GHEs) is key to unlocking the economic viability of ground-source energy systems (GSESs) in dense urban areas. However, current design procedures characterise the performance of GHEs under a given temperature or heat flux, which consider the heat exchanger in isolation from the rest of the GSES. This study proposes a new method to assess the thermal performance of GHEs based on the electricity consumption of the heat pump by introducing explicitly a model describing its performance based on operating temperatures. This general method is applied to a thermo-active pile, providing insights into the impact of pile diameter and length.

1 Introduction

Ground-source energy is currently being adopted as an alternative source of cooling and heating in urban and rural environments. It provides a low-carbon alternative to conventional sources of heating such as burning fossil fuels or using electricity from non-renewable sources [1]. One way to harvest subsurface energy is using thermo-active piles, where heat exchanger pipes are embedded inside concrete piles and connected to heat pumps to obtain or release heat. However, current approaches do not usually consider the effect of the performance of these heat pumps, quantified using the coefficient of performance (COP), on the thermal performance of the heat exchangers [2]. The COP relates the electrical input (E) required for a given thermal output (H):

$$\mathrm{COP} = \frac{H}{E} \tag{1}$$

This study proposes a new approach to quantify the thermal performance of heat exchangers, including thermo-active piles, thermo-active retaining walls and borehole heat exchangers. This is illustrated using an analytical model for the COP of a heat pump that removes heat from a building and stores it in the ground using a thermo-active pile as a ground heat exchanger.

2 Proposed Methodology

The heat being exchanged with the ground, P [$\mathrm{W \cdot m^{-1}}$] can be determined from the inlet and outlet temperatures (T_{inlet} [K] and T_{outlet} [K], respectively), the volumetric heat capacity of the fluid, here assumed to be water ($(\rho c)_{\text{w}}$ [$\mathrm{W \cdot m^{-3} \cdot K^{-1}}$]), its flow velocity ($v_{\text{fluid}}$ [$\mathrm{m \cdot s^{-1}}$]), and the cross-sectional area of the heat exchanger pipe (A_{pipe} [$\mathrm{m^2}$]):

$$P = \frac{(\rho c)_{\text{w}} \cdot v_{\text{fluid}} \cdot A_{\text{pipe}} \cdot (T_{\text{inlet}} - T_{\text{outlet}})}{L} \tag{2}$$

where L [m] is the length of the heat exchanger. The sign convention is such that positive heat transfer to the ground is associated with a positive value of P as $T_{\text{inlet}} > T_{\text{outlet}}$. Systematic studies to determine the thermal performance of a given heat exchanger by applying a known inlet temperature and monitoring the outlet temperature were presented, together with a simplified implementation using only two-dimensional analyses, in [2]. An alternative to this approach, also detailed in [2], consists of closing the ground circuit, promoting the recirculation of the fluid, and providing heat H [W] to an external section of the heat exchanger pipe. This is illustrated in Fig. 1. Clearly, rearranging Eq. (1), the temperature difference between inlet and outlet can be predicted. As it is a closed system, the supplied heat H must match that transferred to the ground (P in Eq. (1)):

$$\Delta T = T_{\text{inlet}} - T_{\text{outlet}} = \frac{H}{\rho_{\text{w}} c_{\text{w}} \cdot v_{\text{fluid}} \cdot A_{\text{pipe}}} \tag{3}$$

As before, a positive value of H indicates heat transferred to the ground. In this approach, both inlet and outlet temperatures vary with time and need to be monitored in order to assess the suitability of the design: excessive variations leading to very high or very low temperatures are naturally undesirable as the performance of the heat pump, the characteristics of which are not considered in either of the above assessment methodologies, is significantly affected by operating temperatures.

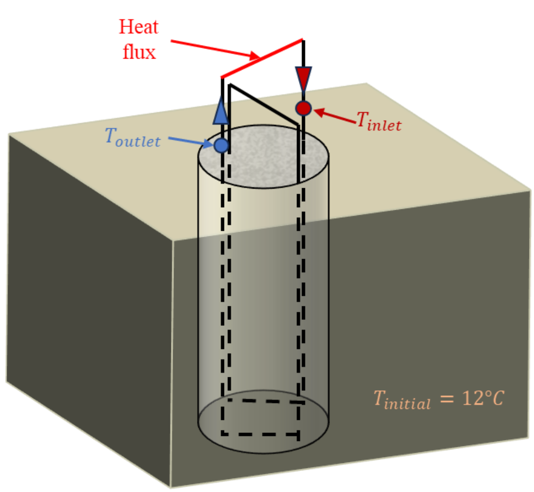

Figure 1: Illustration of the pipe arrangement adopted in the analysis.

In this paper, a new approach is proposed where, rather than considering heat transferred under a given temperature (Eq. (2)) or temperature changes due to a given supplied heat (Eq. (3)), thermal performance is assessed using electricity consumption by the heat pump. Such an approach explicitly introduces the characteristics of the heat pump in the assessment of the thermal performance of the ground heat exchanger and enables optimisation of systems by exploring different combinations of heat pump and ground heat exchanger. The application of the proposed approach is demonstrated herein by adopting an analytical model [3,4] for estimating the coefficient of performance (COP) of a heat pump when used to cool a building (i.e. the heat pump is used as a chiller and heat is injected into the ground):

$$\mathrm{COP_{chiller}} = \sqrt{\frac{T_{\mathrm{hot}}}{T_{\mathrm{hot}} - T_{cold}}} - 1 \tag{4}$$

where T_{hot} [K] and T_{cold} [K] are the temperatures of the hot sink and cold source, respectively. In the analyses performed, it is assumed that the building is being cooled by a circuit at a constant temperature T_{cold} = 10 °C = 283.15 K, whereas the heat exchanger pipes transferring heat into the ground are initially at a temperature of T_{hot} = 12 °C = 285.15 K. However, the latter is clearly not a static temperature and evolves as energy is transferred to the ground, as $T_{\mathrm{hot}} = T_{\mathrm{outlet}}$ given the adopted pipe arrangement illustrated in Fig. 1. Therefore, rearranging Eq. (4) and combining it with Eq. (1), it is possible to establish the instantaneous electric consumption of the heat pump, E $[W]$, using:

$$E = \frac{H}{\mathrm{COP_{chiller}}} = \frac{H}{\sqrt{\frac{T_{\mathrm{outlet}}}{T_{\mathrm{outlet}} - 283.15}} - 1} \tag{5}$$

The total electricity can then be calculated by integrating the time-varying value of E over the period of interest, and used to compare the performance of different heat exchangers.

3 Numerical Modelling and Results

To demonstrate the application of the proposed approach, a thermo-active pile with a diameter of 900 mm and a length of 30 m was simulated in COMSOL. The pile was embedded in a 80 m × 80 m × 40 m domain, which was observed to be sufficiently large to avoid boundary effects. The ground was modelled as a material with a thermal conductivity $\lambda_{\mathrm{soil}} = 1.8\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$, a volumetric heat capacity $(\rho c)_{\mathrm{soil}}$ = $1800\ \mathrm{kJ \cdot m^{-3} \cdot K^{-1}}$, and an initial temperature of T_{initial} = 12 °C. All the boundaries of the domain were set to remain at the initial temperature. The thermal properties of the concrete were assumed to be $\lambda_{\mathrm{pile}} = 2.3\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ and $(\rho c)_{\mathrm{pile}} = 1900\ \mathrm{kJ \cdot m^{-3} \cdot K^{-1}}$, with a double U-loop configuration being adopted. This was modelled as a single circuit (see Fig. 1) using one-dimensional elements capable of simulating heat transfer through diffusion and advection, as well as thermal interaction with the surrounding material. The HDPE pipes ($\lambda_{\mathrm{pipe}} = 0.4\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$) were assumed to have an inner diameter of 26.2 mm, with water being used as the heat carrier fluid ($\lambda_{\mathrm{w}} = 0.6\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$, $(\rho c)_{\mathrm{w}} = 4180\ \mathrm{kJ \cdot m^{-3} \cdot K^{-1}}$), circulating with a flow rate of $0.1\ \mathrm{kg \cdot s^{-1}}$. A constant 1500 W heat flux was applied to one of the pipe elements, corresponding to an assumed normalised heat transfer of $50\ \mathrm{W \cdot m^{-1}}$.

Steady state analyses were performed in order to characterise the thermal performance of the heat exchanger in the long term. This is done employing the total electricity consumed in one year of continuous operation using $\bar{E} = E \cdot 24 \cdot 365/1000$ [kWh], where E is determined using Eq. (4). Two parametric studies were performed to assess the importance of the diameter and length of the thermo-active pile on the calculated thermal performance. The details of the studies and associated results are shown in Table 1, where values in brackets denote the relative change from the reference analysis.

Table 1: Details of the parametric studies performed.

Property	Reference	D1	D2	L1	L2
Diameter [mm]	900	600	1200	900	900
Length [m]	30	30	30	20	40
T_{outlet} [°C]	27.5	29.3	26.3	33.9	23.3
$\bar{E}$ [kWh]	4170	4437 (+6%)	3990 (−10%)	5073 (+27%)	3640 (−28%)

Clearly, the results show that the diameter has a relatively minor impact on the estimated performance, though the obtained trend is reasonable: larger diameters introduce a higher volume of concrete which is modelled here as having larger thermal conductivity than that of soil and, crucially, allow the pipes to be placed at higher distances from each other, leading to a reduction in electricity consumption (i.e. higher thermal performance) as the diameter increases. The variations for the pile length are substantially larger, with the shorter pile ($L = 20$ m $\Rightarrow P = 75$ W $\cdot$ m^{-1}) requiring 27% more electricity than the reference case. Conversely, the electric consumption for the longer pile ($L = 40$ m $\Rightarrow P = 37.5$ W $\cdot$ m^{-1}) is 28% lower than that of the reference case.

4 Conclusion

The two established methods of characterising the thermal performance of ground heat exchangers involve either circulating a fluid with a known inlet temperature or a heat flux, which enable the determination of power or fluid temperatures, respectively. However, neither of these methods allow the variation of the heat pump performance with operating temperatures to be explicitly considered in the design of the ground source energy system. This paper addresses this limitation, proposing a new approach to establish the thermal performance of ground heat exchangers, which is based on the required electricity input by a heat pump to run the designed system. The new methodology, using a simple analytical model for the COP of the heat pump, is applied to the problem of a thermo-active pile foundation, demonstrating the impact on electricity consumption of varying pile diameter and pile length. As expected, the increase in contact area resulting from the increase of either of these two quantities leads to a reduction in electricity consumption, indicating the more favourable thermal performance of larger heat exchangers.

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