

Efficiency and area demand of multi-layer ground heat exchanger using phase change of water

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Abstract. We conducted numerical simulations of a heat pump system connected to a horizontal ground heat exchanger (HGHX), using a coupling of the hygro-thermal simulation software DELPHIN with Modelica. The aim was to study the influence of different HGHX sizes and assemblies as well as the impact of passive cooling on the systems efficiency. We found that the required ground area could be reduced by up to 70 % compared to the recommendation of German standard when the pipes are placed in multiple layers. Passive cooling is possible but has a negligible effect on the systems efficiency.

1 Introduction

Modern industrial countries like Germany are undertaking a transformation of their mainly fossil-based energy systems. In the sector of heat supply for residential buildings, heat pumps are currently the most promising solution for the replacement of gas- or oil-fired heat generators. Over the last years, their sales increased significantly [1]. However, the majority of the sold devices are air-sourced with a relatively low efficiency compared to ground coupled heat pumps. Ground heat sources can be divided into two different types: Borehole Heat Exchangers (BHX), which are usually installed in a depth up to 100 m and Horizontal Ground Heat Exchangers (HGHX), which are buried within the first 3 m below the surface. While the installation of BHX is limited due to environmental restrictions (e.g. in water protection areas), high investment costs and area demand are considered the most important factors that prevent HGHX from installation. In order to lower both, area demand and investment costs, sizing of HGHX must be more precise, taking into account the phase change enthalpy of soil water. Moreover, the placement of HGHX pipes in multiple horizontal layers allows for further savings in area demand and installation costs.

A comprehensive study of these aspects and their impact on the systems efficiency requires a numerical model of the entire system, consisting of a realistic heat demand, the heat pump with buffer storage and the ground heat exchanger. Existing HGHX models are often created using FEM software and applying constant boundary conditions or calculating only short time periods as in [2], [3], [4]. In [5], a self-developed three-dimensional model is used, taking into account moisture transport and latent heat. The impact of soil moisture content and fluid flow rate on the heat extraction rate is presented. Due to simulation effort, the simulation period is limited to 90 days. However, for reasons of performance, these

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models are not suitable for the application in energy system simulations, since simulation periods of several years are necessary to reach quasi-steady state. This has been taken into account by [6], where a self-developed two-dimensional model is validated against experimental results and used to predict the impact of burial depth and pipe separation using a simulation period of up to 10 years. However, only a one-layer assembly is investigated and ice formation in the ground does not take place due to the local climatic conditions. A coupled simulation of heat supply system and one-layer HGHX is presented in [7] using a two-dimensional model for the ground, which is validated against experimental results. Ice formation is taken into account and the system is simulated over multiple years. The impact of different soil types and pipe separations on the systems seasonal performance factor is shown. It can be concluded, that smaller pipe separations than recommended in the German standard [8] allow for a significant reduction of area demand.

The present study contributes to these results, using a new method of co-simulation between system model and HGHX model, which is described in [9]. We use the hygro-thermal simulation software DELPHIN [10], [11] to model the HGHX, which takes into account moisture transport as well as ice formation. This allows us to study different HGHX assemblies with multiple horizontal layers and thus to predict further savings in area demand. Therefore, we carry out coupled simulations of the heat supply system and the HGHX under realistic climatic conditions over multiple years.

2 Ground heat exchanger model in DELPHIN

2.1 General assumptions and HGHX geometry

DELPHIN is a simulation program for coupled heat, moisture and matter transport, commonly used for simulation of porous building materials. In a recent research project, we applied it so soil materials and implemented a physical freezing model in DELPHIN. A numerical simulation of coupled heat and moisture transport requires the characteristics of the material specific moisture storage and transport properties. These are taken from various measurements that are conducted for each material as described in [12]. In the present study, we measured the material properties of silt, which is a typical type of soil in Germany.

The HGHX consists of polyethylene pipes filled with a water-glycol mixture and placed below the soil surface. As illustrated in Fig. 1, we investigated four different assemblies of HGHX: A 1-layer assembly with pipes separated 0.5 m from each other and buried in a depth of 1.5 m, which is a common assembly as recommended in German standard [8]. Moreover, we investigated a 3-layer, 4-layer and 8-layer assembly with pipes buried in depth between 1 m and 3 m using different pipe separations, respectively. The number of vertical pipe rows as well as the pipe length are varied in the study in order to obtain different total horizontal ground areas.

The HGHX model is reduced to the two-dimensional plane perpendicular to the pipes. Heat and moisture transport along the flow direction will be neglected. The HGHX is considered indefinitely wide, neglecting lateral boundaries. Hence, due to the symmetry of the temperature field, the effective computational domain can be reduced to the area showed in Fig. 1.

2.2 Boundary and initial conditions

At the soil surface, thermal convection, absorption of long wave and short wave radiation, vapour diffusion and precipitation are taken into account. The respective climate data is the

test reference year TRY 2010 (Zone 4) from German Weather Service (DWD). We assume constant temperature at the lower boundary, which is located at a depth of 15 m below the surface. The lower boundary is in direct contact with water. Both lateral boundaries are considered adiabatic, due to the temperature field symmetry.

Heat exchange between the porous material and fluid inside the pipe is approximated by a special boundary condition model. It assumes steady state flow and a constant soil temperature along the pipe. The analytical solution of the pipe outlet temperature reads

$$T_{out} = T_s + (T_{in} - T_s) \exp\left(-\frac{kA}{\dot{m}c_p}\right) \quad (1)$$

with T_{in} and T_s being the inlet and adjacent soil temperature, k refers to the heat transfer coefficient, A is the outer pipe area and \dot{m} and c_p are the fluid mass flow rate and its specific heat capacity.

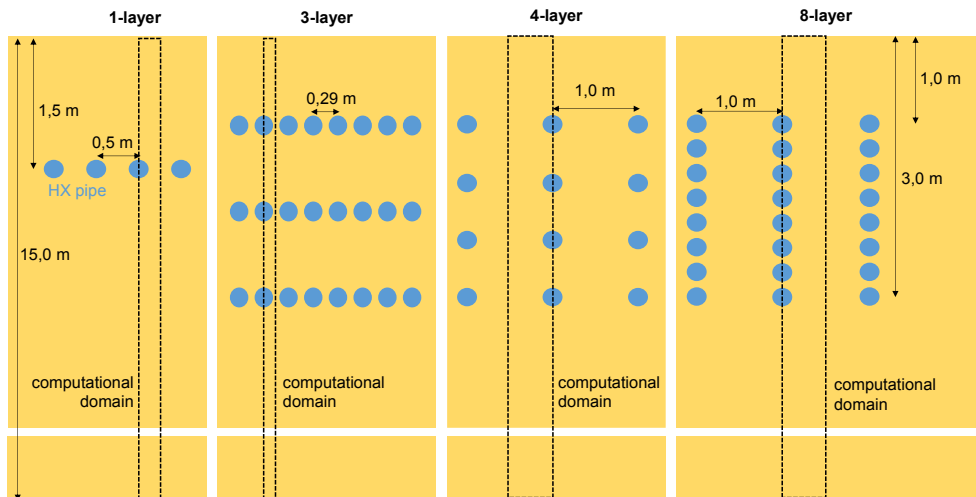


Fig. 1. Geometry and computational domain of the HGHX for the different HGHX assemblies.

3 Energy system simulation

3.1 Building and energy supply system

The aim of the present work is the determination of the systems efficiency and its dependence on the HGHX size. This requires sophisticated modelling of the heat supply system and the heating energy demand. Therefore, we created corresponding models using the modelling language Modelica. We coupled the obtained Modelica model with the HGHX model from DELPHIN using the so-called Waveform Relaxation Method, which exchanges time-series data between both models. An in-depth description of the building and heat supply system model as well as the coupling technique is given in [9]. The following paragraph shall just give a short overview.

The building model was created using the tool TEASER, which allows for generation of arche-type building models based on few parameters [13]. It is a small office building with an area of 400 m² and consists of different zones (Office, Corridor, Storage etc.). During the heating season, the temperature set point is 21°C in the daytime and 18°C at night (between 7 pm and 5 am) and during cooling season (between May and September) it is constant at 26°C. This leads to a total heating demand of 13900 kWh/a and a cooling demand of 2900 kWh/a.

The heat supply system model is based on components taken from the AixLib library [14] and Modelica Standard library. Basis is a brine/water heat pump, which charges a buffer storage for heat supply. Its electrical energy demand and heating power are calculated through interpolation using manufacturer data tables. While the heating demand is supplied by the buffer storage, the building can be cooled directly through passive cooling. The possible positive impact of regenerating the soil is investigated in the following section.

3.2 Simulation procedure

Before carrying out the coupled system simulation, some pre-processing steps were necessary: First, we simulated the building for a period of one year, assuming a limited heating and cooling power. Thus, we obtain heating and cooling demand profiles. Next, we simulated the undisturbed soil without any heat exchange with the HGHX for a period of five years, to make sure that soil temperature and moisture content are in quasi-steady state. Hence, they depend only on yearly cyclic boundary conditions. Finally, we conducted the coupled simulation of the heat supply system and HGHX according to [9], using the undisturbed temperature and moisture fields from the previous step as initial condition. We chose a simulation period of 3 years, to reach quasi-steady state of the system under heat exchange with the HGHX. Fig. 2 shows the resulting temperatures above the HGHX (0.5 m), at the first pipe, the third pipe and below the HGHX (3.5 m) for the 4-layer assembly.

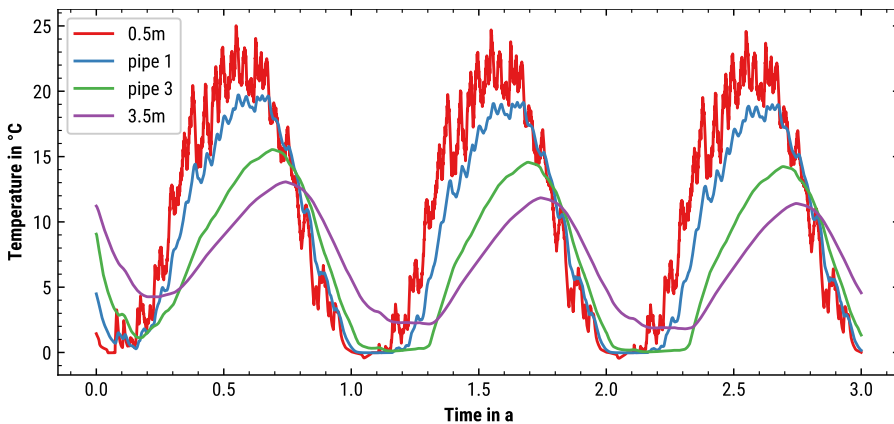


Fig. 2. Temperature above the HGHX (0.5 m), at the first pipe, the third pipe and below the HGHX (3.5 m) for the 4-layer assembly.

A noticeable trend can be observed in the ground temperatures. During the second and third heating season, temperatures close to the pipes maintain constant over a significant period of time. This is due to phase change of soil water content taking place around the HGHX pipes. Since the differences between the second and third year are small enough, the results of the third year are considered reliable. All results shown in the following sections are taken from the third year only.

3.3 Results for different HGHX sizes and assemblies

The most important indicator for the efficiency of heat pump systems is the seasonal performance factor (SPF). In general, it depicts the relation of supplied heat Q_{heat} to required electrical energy P . In the present work, we take into account cooling energy Q_{cold} as a benefit as well. The determination of the SPF thus is

$$SPF = \frac{\int_0^{1a} \dot{Q}_{heat} + \dot{Q}_{cold} dt}{\int_0^{1a} P_{HP} + P_{CP} dt} \quad (2)$$

where P_{HP} is the electrical energy for the heat pump and P_{CP} the electrical energy for the circulation pump.

In Fig. 3 the SPF is shown and Fig. 4 depicts the minimal evaporator inlet temperature and the ice mass hours (time integral of ice mass) for the described HGHX assemblies. Each point in the figures refers to a three-year simulation with a specific ground area. To obtain these different ground areas, we varied the pipe lengths and the number of vertical columns for each assembly. A significant parameter is the relation of total pipe length L to ground area A , which can be considered as pipe density in the ground. For the 4-layer assembly, this pipe density is doubled and for the 8-layer and 3-layer assemblies it is five times the value of the 1-layer assembly. In Fig. 3 and Fig. 4, another 4-layer assembly with a pipe separation of 0.45 m is shown which has the same pipe density like the 8-layer and 3-layer assemblies.

It can be seen that the multi-layer HGHX reaches the same efficiency (SPF) like a 1-layer HGHX, requiring significantly smaller ground areas. Providing constant SPF, the 4-layer ($dx=1$ m) assembly requires 45 % less ground area and the 8-layer, 3-layer and 4-layer ($dx=0.45$ m) assemblies require 65-70 % less ground area than the 1-layer assembly. Despite of their identical pipe densities, a difference can be observed between the 8-layer and 3-layer assembly: The efficiency of the 8-layer assembly is about 0.1 higher and hence, for the same efficiency, it requires about 10 % less ground area. We assume that this difference reveals a geometrical benefit of the 8-layer assembly: Heat gains in HGHXs originate mainly from solar radiation absorbed by the surface. This difference is expected to be even larger in real world, considering the fact that the model described in section 2.1 underestimates heat gains from lateral boundaries, which are significantly higher for the 8-layer assembly. Due to wider horizontal gaps between the pipes in the 8-layer assembly, the heat transport between the surface and the HGHX pipes is more efficient.

Considering the ice mass hours depicted in Fig. 4, it can be said that small ground areas are only accessible when ice formation takes place. A lower efficiency is therefore acceptable when the availability of ground area is the limiting factor for the HGHX installation. The dimensioning of HGHXs without ice formation would require a ground area of 200 % (1-layer) to 300 % (multi-layer) of the smallest possible size with ice formation.

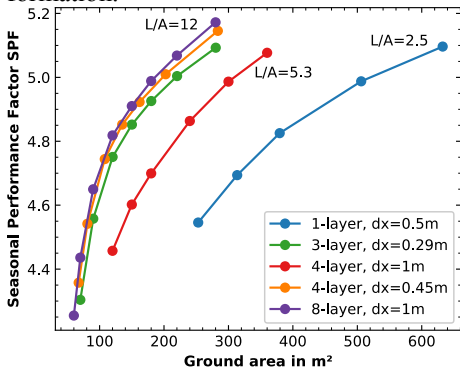


Fig. 3. Seasonal Performance Factor SPF for different HGHX assemblies and ground areas. L/A is the relation of total pipe length to ground area.

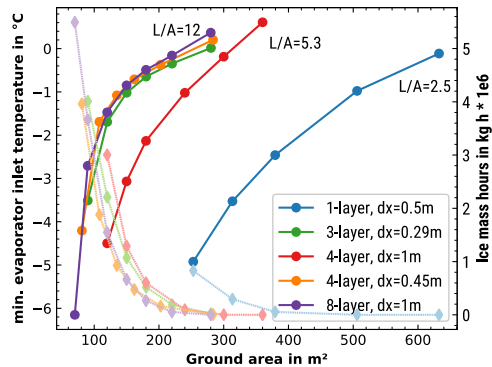


Fig. 4. Minimal evaporator inlet temperature (circles, dark) and ice mass hours (diamonds, bright) for different HGHX assemblies and ground areas. L/A is the relation of total pipe length to ground area.

3.4 Impact of passive cooling

As described in section 3.1, the building can be cooled directly using the HGHX. We studied three different cases: heating demand only (as presented above), heating demand with the presence of cooling demand during the summer and cooling demand only (as a reference case). Fig. 5 shows the daily averages of the evaporator inlet temperature for these cases over one year. In the presence of cooling demand, a recognizably higher temperature can be observed during summer and autumn. However, the difference drops relatively fast in the winter, so that the temperatures for both cases with present heating demand are almost equal in January and February. For the case of cooling demand only, the temperature is significantly higher during the whole year, leading to the problem that it exceeds the comfortable temperature range during some weeks in the summer.

In order to show the quantitative dependency of the evaporator inlet temperature from soil regeneration through passive cooling, we scaled the cooling demand from 50 % to 150 %. The result is shown in terms of the yearly averaged evaporator inlet temperature as a function of the relation of cooling demand to heating demand in Fig. 6. Even with a relatively high cooling demand (30 % of the heating demand), the yearly averaged evaporator inlet temperature increases by less than 1 K, which has a negligible effect on the systems efficiency. The results show that natural heat gains from solar irradiation are of significantly higher magnitude compared to heat gains from passive cooling.

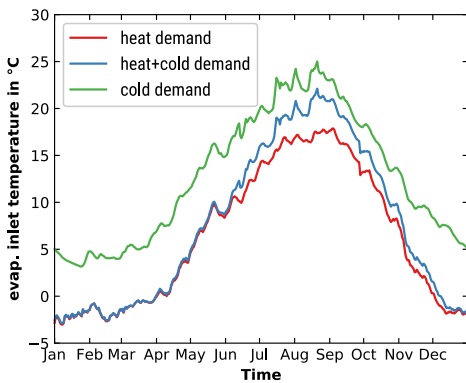


Fig. 5. Evaporator inlet temperature (daily averages) over one year

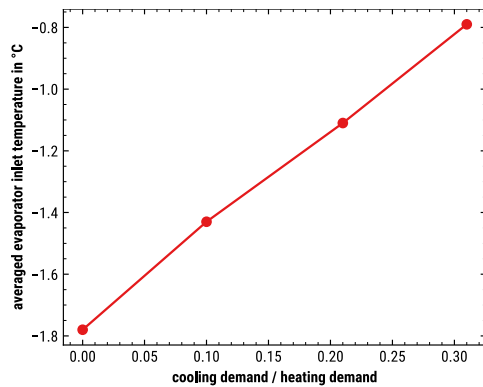


Fig. 6. Yearly averaged evaporator inlet temperature as a function of the relation of cooling demand to heating demand.

4 Conclusion

We conducted simulations of a heat pump system connected to a horizontal ground heat exchanger (HGHE). Therefore, we created a HGHE model in the hygro-thermal simulation software DELPHIN and coupled it to a heat supply system model for a building in Modelica. The aim was to study the dependency of different HGHE sizes and assemblies as well as the impact of passive cooling on the systems efficiency, which is determined by the seasonal performance factor (SPF). We found that the required ground area could be reduced by up to 70 % compared to the recommendation of German standard when the HGHE is buried in multiple layers, depending on the pipe density. However, economical aspects were not taken into account here. Moreover, we found ice formation to be of crucial importance for HGHE sizing. If ice formation should be avoided, the required area must be at least doubled. Finally, adding heat to the ground through passive cooling was found to have a negligible effect on the temperature of heat extraction. However, heat extraction

during the heating season leads to a lower source temperature for passive cooling during the summer.

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