Dynamic thermal simulation of ground heat exchangers for renewable heating of buildings

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Abstract: The temperature of deep soil is relatively stable throughout a year and the thermal energy stored in soil can be used to provide renewable heat or coolth for a building. A ground heat exchanger is required to transfer heat between the fluid in the heat exchanger and surrounding soil. The control volume method is used to solve the equations for coupled heat and moisture transfer in soil and the dynamic interactions between the heat exchanger, soil and atmosphere. The method is used for numerical simulation of the dynamic thermal performance of horizontally coupled heat exchangers, taking account of dynamic variations of climatic, load and soil conditions. The thrmal performance is compared for two types of ground heat exchangers - earth-liquid heat exchanger for a ground source heat pump and earth-air heat exchanger for ventilation. The amount and rate of heat transfer through an earth-liquid heat exchanger are larger than those for an earth-air heat exchanger and their differences increase with the length of heat exchanger and operating time.

Keywords: ground heat exchanger, heat and moisture transfer, dynamic thermal simulation

1 Introduction

A ground-coupled heat exchanger is employed to transfer heat between the fluid within the heat exchanger and surrounding soil with a relatively stable temperature for a number of renewable energy systems including earth-air tunnel ventilation, ground source and wastewater source heat pumps. The heat exchanger consists of a series of pipes or ducts buried in shallow ground. Deployment of earth-air tunnel ventilation can reduce energy use for heating or cooling of supply air to a building whereas a ground (wastewater) source heat pump can provide a building with either hot water or heating/cooling of supply air or both. The heat exchanger pipes for a ground source heat pump (GSHP) are relatively small, typically 25 mm to 50 mm in diameter, and can be installed vertically or horizontally. The pipes for earth-air tunnel ventilation (EATV) are comparatively large, 100 mm or larger, and are generally installed horizontally with a slight inclination to allow condensation to drain away. For comparison of the thermal performance, the two types of heat exchanger considered in

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this work are horizontally installed.

The performance of a ground heat exchanger can be assessed using analytical and numerical methods as well as experimental testing. An analytical technique makes use of an assumption of one dimensional (axi-symmetric) heat transfer in a circular pipe or the surrounding soil of homogeneous properties. However, heat and moisture transfer occurs simultaneously in moist soil and the transport phenomena as well as moisture-dependent soil properties vary in time and space due to the influence of daily and seasonal climatic variations and interactions between soil and the heat exchanger. Therefore, to obtain an accurate solution for multi-dimensional heat and moisture transfer requires the use of a numerical method. The author has developed a general three-dimensional numerical model for the simulation of transient heat and moisture transfer in soil with a horizontally coupled earth-air heat exchanger[1]. The purpose of the work presented in the paper is to apply the model for not only earth-air but also earth-liquid heat exchangers.

2 Method

To simulate transient thermal performance of a ground-coupled heat exchanger, a control volume method is used to solve equations for three dimensional heat and moisture transfer in soil together with initial and boundary conditions.

2.1 Model equations

The following coupled energy and mass conservation equations describe the three-dimensional transient heat and moisture transfer in soil with phase change:

$$\frac{\partial(\rho C T)}{\partial t} = \nabla\left(\left(k + L\rho_l D_{T,v}\right)\nabla T\right) + \nabla\left(L\rho_l D_{\Theta,v}\nabla\Theta\right) + q_v \tag{1}$$

$$\frac{\partial\Theta}{\partial t} = \nabla\left(\left(D_{T,l} + D_{T,v}\right)\nabla T\right) + \nabla\left(\left(D_{\Theta,l} + D_{\Theta,v}\right)\nabla\Theta\right) + \frac{\partial K}{\partial z} + \Theta_v \tag{2}$$

where $D_{T,l}$ and $D_{T,v}$ are the thermal liquid and vapour moisture diffusivities, respectively, (m^2/sK); $D_{\Theta,l}$ and $D_{\Theta,v}$ are the isothermal liquid and vapour moisture diffusivities, respectively, (m^2/s); ρ, C, k and K are the density (kg/m^3), specific heat (J/kgK), thermal conductivity (W/mK) and hydraulic conductivity (m/s) of soil, respectively; L is the latent heat of vaporisation (for evaporation/condensation) or fusion of water (for freezing/thawing) (J/kg); ρ_l is the density of liquid water (kg/m^3); q_v is the volumetric heat production/dissipation rate (W/m^3); T is the temperature of soil (K); t is the time (s); z is the vertical coordinate (m); Θ is the volumetric moisture content (m^3/m^3); Θ_v is the source/sink of moisture (m^3/m^3s).

The four moisture diffusivities and hydraulic conductivity are all dependent on the moisture content of soil whereas the density, specific heat and thermal conductivity are functions of the volumetric composition of moisture, dry solid matter and gases[1].

Equations (1) and (2) are solved for a three-dimensional model using the control volume method with the initial and boundary conditions described below.

2.2 Initial and boundary conditions

A heat exchanger is represented by a series of parallel pipes inside a large computational domain. The initial soil moisture content is assumed to be uniform whereas the initial soil temperature profile is taken to be the following expression for the annual variation of the soil temperature at the start of system operation

$$T = T_m - T_{amp} e^{-Z/D} \sin\left((t - t_o) \frac{2\pi}{365} - \frac{Z}{D} - \frac{\pi}{2} \right) \tag{3}$$

where T_m is the annual mean temperature of deep soil (^{o}C), T_{amp} is the annual amplitude of surface temperature (^{o}C), t_o is the time lag from a starting date to the occurrence of the minimum temperature in a year and D is the damping depth (m) of annual fluctuation.

Table 1 shows the boundary conditions for heat and moisture transfer at the top soil surface, the interior and exterior surfaces of a heat exchanger pipe, the inlet and outlet openings for the pipe, the far-field bottom face and four vertical faces and Fig. 1 illustrates the boundary conditions on a vertical plane normal to the heat exchanger.

Table 1 Boundary conditions for heat and moisture transfer

Type of boundary	Heat transfer		Moisture transfer	
Top soil surface	$(k + L\rho_l D_{T,v})\frac{\partial T}{\partial \xi} + L\rho_l D_{\Theta,v}\frac{\partial \Theta}{\partial \xi} = q_f$		$(D_{T,l} + D_{T,v})\frac{\partial T}{\partial \xi} + (D_{\Theta,l} + D_{\Theta,v})\frac{\partial \Theta}{\partial \xi} = \Theta_f$	
Outer pipe surface	$(k + L\rho_l D_{T,v})\frac{\partial T}{\partial \xi} + L\rho_l D_{\Theta,v}\frac{\partial \Theta}{\partial \xi} = 0$		$(D_{T,l} + D_{T,v})\frac{\partial T}{\partial \xi} + (D_{\Theta,l} + D_{\Theta,v})\frac{\partial \Theta}{\partial \xi} = 0$	
Far-field	Equation (3)		Zero mass flux	
Pipe outlet	Zero heat flux		Zero mass flux	
Pipe fluid	*Air*	*Refrigerant*	*Air*	*Refrigerant*
Pipe inlet	Ambient air temperature and flow rate (or velocity)	Temperature and flow rate (or velocity)	Vapour pressure	100% liquid
Inner pipe surface	Convection + Condensation (evaporation	Convection	Condensation (evaporation)	Zero mass flux

where ξ is the direction normal to the surface; q_f is the net heat flow resulting from short and long wave radiation, natural convection due to combined wind and buoyancy effects, evaporation of moisture from or condensation to the ground surface and sensible heat from precipitation; Θ_f is the net mass flow due to precipitation and evaporation or condensation of moisture.

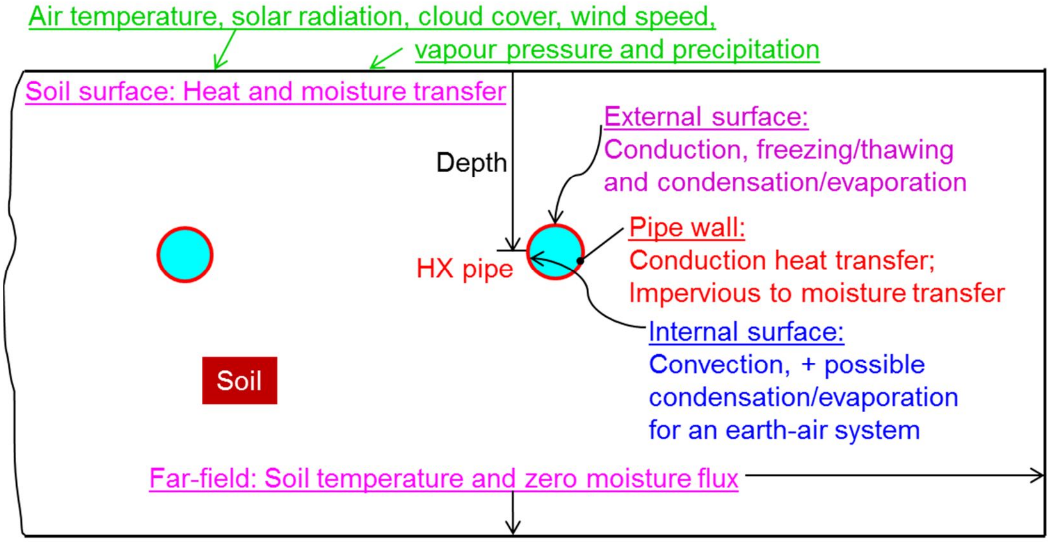


Fig. 1 Boundary conditions for simulation of heat and moisture transfer on a vertical plane normal to the heat exchanger

When incoming fluid temperature is higher than the pipe temperature such that heat extraction from soil is not feasible, the inlet opening is prescribed with zero heat and mass flux for continuous simulation of heat and moisture transfer in soil and heat transfer in the pipe wall. Further details of the boundary conditions are given in references[1 & 2].

The model has been validated for simulation of transient heat transfer through a similar heat exchanger[1 & 3].

3 Results and discussion

The model is applied to performance assessment of an earth-air heat exchanger for preheating of supply air and an earth-liquid heat exchanger for a ground source heat pump in a climate in the Southern England in January. Both earth-air and earth-liquid heat exchangers are made of high density polyethylene and installed horizontally at 1.5 m below the ground surface. Table 2 shows the dimensions of the heat exchangers and fluid properties and Table 3 shows the properties of soil in consideration. The inlet fluid velocities are different but are typical values for operating the two types of system. Even though the air velocity in a larger pipe is much higher, the mass flow rate through the liquid pipe is about five times higher than that in the air pipe. The incoming temperature of both fluids is set the same as varying ambient air temperature. This is merely for the purpose of comparing their performance as in practice the liquid temperature is unlikely to follow the variation of ambient air temperature. The fluid properties such as the density, thermal conductivity and viscosity are temperature dependent. The climatic data for simulation is obtained from two sources - hourly data for ambient air temperature, partial water vapour pressure, solar radiation, cloud cover and wind speed for each month from the CIBSE Guide[4] and the monthly rainfall from a weather station[5].

Table 2 Properties of heat exchangers and fluids

Type of heat exchanger	Earth-air	Earth-liquid
External diameter (mm)	200	40
Internal diameter (mm)	184.6	32.6
Fluid	Air	65% water and 35% antifreeze
Inlet velocity (m/s)	2	0.4

Table 3 Properties of soil

Texture		Loamy
Composition		43% sand, 18% clay and 39% silt
Moisture content (%)	Saturation	44
	Residual	5
	Initial	22
Temperature of deep soil (^{o}C)		10

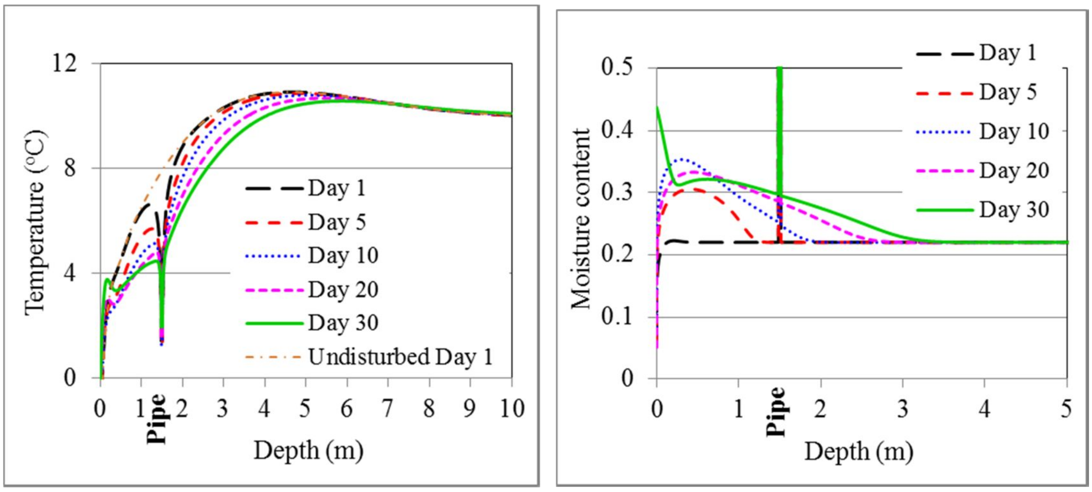
Results are presented first for the earth-liquid heat exchanger and then compared with the earth-air heat exchanger.

3.1 Earth-liquid heat exchanger

The daily air temperature at the site varies from the minimum of 0.5^{o}C in the early morning (3am) to the maximum of 5.5^{o}C in the afternoon (3pm) at the beginning of January, rising gradually to 1^{o}C and 7.6^{o}C, respectively, at the end of the month. The temperature of the undisturbed soil at 1.5 m deep is about 8^{o}C at the beginning of the month, decreasing to 6.2^{o}C at the end of the month, according to Equation (3).

Figure 2 shows predicted variations of soil temperature and moisture along a vertical line through the earth-liquid heat exchanger at the end of five selected days in January. The soil temperature above the heat exchanger is much lower than the deep soil temperature. During the night time the soil temperature decreases from heat transfer to the cold ambient at the ground surface while at any time of a day it would also decrease with operating time due to heat extraction through the heat exchanger when in operation. Thus, the soil temperature generally decreases with time for the month up to a depth of about 7 m. However, the temperature near the surface increases slightly on a rainy day (eg Day 30) due to the sensible heat gain from rainfall.

Moisture transfer at the soil surface also varies. In general, during day times, surface moisture decreases due to evaporation, unless it rains, the effect of which is shown for Day 30. During night times, the surface moisture would increase as the rate of evaporation decreases which could turn into surface condensation, or frost, if the temperature drops below the dew point, or freezing point, respectively. In the depth direction, the overall trend of moisture variation is increasing with time because precipitation exceeds net surface evaporation in the month. The moisture content at the pipe depth is 1 m^{3}/m^{3} for the earth-liquid heat exchanger.



(a) Temperature (b) Moisture content

Fig. 2 Predicted vertical variations in soil temperature and moisture

Figure 3 shows the predicted variation with time in the heat transfer per unit length of the heat exchanger 10 m long in January. The heat transfer rate per unit length of a heat exchanger is also called the specific heat extraction. Because the soil temperature is more stable than air temperature, the specific heat extraction is higher during the night time when the air temperature (= inlet fluid temperature) is much lower than that in the daytime. The rate of heat transfer generally peaks at about 2am and decreases for a period of 12 hours to a minimum at about 2pm and then increases for 12 hours. Results for the first day are unusual high with a maximum heat transfer rate of about 68 W/m at the beginning because the heat exchanger is assumed to be at equilibrium with surrounding soil and the temperature difference between the surrounding soil (heat exchanger) and incoming fluid is at maximum. The heat transfer rate decreases rapidly with decreasing temperature difference to a minimum of 4.3 W/m at 2pm on the day. The rate of heat transfer would decrease each day due to the decreasing soil temperature and increasing ambient air temperature. The decrease in soil temperature results not only from the effect of heat transfer taking place naturally in soil but also from forced heat extraction through the heat exchanger. One consequence of decreasing soil temperature is that at a certain time the temperature of the heat exchanger pipe could drop below the ambient air (incoming fluid) temperature and then heat in surrounding soil would not be available for extraction. This would occur for two hours between 1pm and 3pm on Day 4, increasing with operating time to 12 hours on the last day of the month from 8am to 8pm.

The amount of daily heat transfer or energy is the sum of the product of the heat transfer rate and time for heat extraction over the 24-hour period. As heat could not be extracted all day long from Day 4, the daily heat transfer decreases faster than does the heat transfer rate. Taking values for Day 5 and Day 30 as an example, the peak heat transfer rate (at 2am) decreases by 19% from 19.4 to 15.7 W/m, respectively, while the daily heat transfer decreases by 46% from 222 to 120 Wh/m.

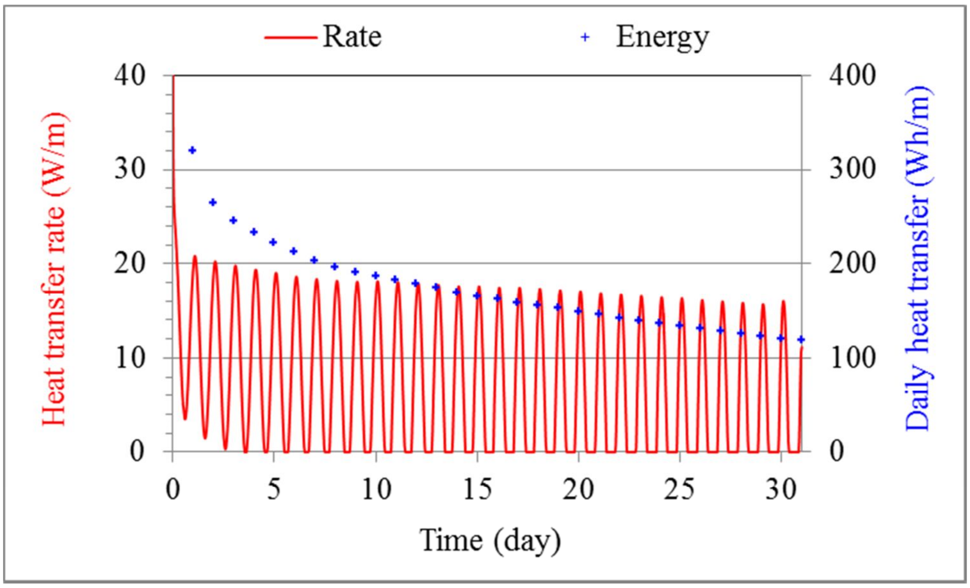


Fig. 3 Predicted heat transfer through a 10 m long earth-liquid heat exchanger

3.2 Comparison between two types of heat exchanger

Figure 4 shows a comparison of the amount of daily heat transfer per unit length of earth-air heat exchanger for EATV and earth-liquid one for GSHP. The fluid temperature increases and heat transfer rate decreases along a heat exchanger during heat extraction but such variations are much less in a liquid pipe than in an air pipe because of the larger mass flow rate of the liquid. For example, the air temperature increase through a 40 m long heat exchanger could be as much as 6°C but the liquid temperature increase would be no more than 1°C after flow is fully established. Therefore, heat transfer through the earth-liquid heat exchanger is larger than that for the earth-air heat exchanger and their difference varies with operating time.

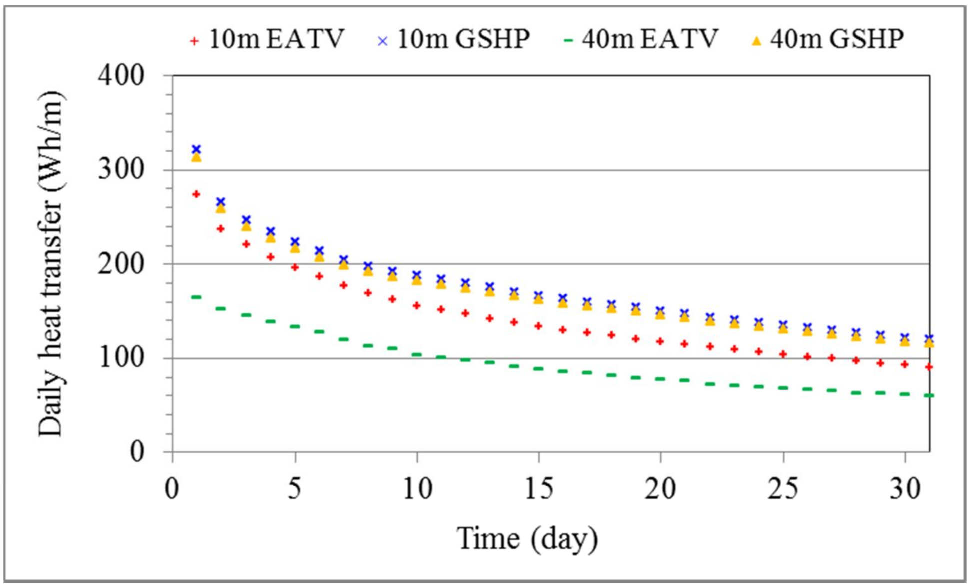


Fig. 4 Predicted daily heat transfer for two types of heat exchanger

Because the heat transfer rate decreases along the heat exchanger, the length-averaged mean heat transfer decreases with increasing length of heat exchanger and the rate of decrease through an air pipe is higher than that in a liquid pipe. Consequently, the difference in mean heat transfer between the liquid and air pipes also increases with the length of heat exchanger. The difference increases from about 12% for a 10 m long pipe to 63% for a 40 m long pipe in the early days (from the 2nd to 5th day) and from 32% for a 10 m long pipe to 96% for a 40 m long pipe at the end of the month.

In practice, the temperature of the fluid in a heat exchanger for a ground source heat pump does not vary as much as that of ambient air and would be at a lower magnitude say 1°C (than the monthly mean air temperature of 3.3°C in January) for heating applications in order to maximise the potential of the system. Hence, the difference between the two types of heat exchanger would be larger than predicted with the same incoming temperature profile.

4 Conclusion

A three-dimensional numerical model has been developed for simulation of the dynamic thermal performance of ground heat exchangers to transfer heat stored in soil for tunnel ventilation and ground source heat pumps. Fluid temperature and heat transfer through a ground heat exchanger vary with time and space (along the flow passage) due to varying atmospheric conditions and heating demand. The fluid temperature increase and heat transfer decrease are smaller along an earth-liquid heat exchanger than those for an earth-air heat exchanger. Besides, specific heat extraction is higher for a ground source heat pump than for an earth-air ventilation system. The longer the heat exchanger, the larger the difference between the two types.

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