Simulation of Dynamic Interactions of the Earth-Air Heat Exchanger with Soil and Atmosphere for Preheating of Ventilation Air

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ABSTRACT

Earth-air tunnel ventilation is an energy efficient means of preheating and cooling of supply air to a building. Due to changing soil and atmospheric conditions and the consequent changes in heating and cooling loads of a building during operation, an earth-air heat exchanger interacts with the environments and the performance varies with the conditions. A computer program has been developed for modelling of coupled heat and moisture transfer in soil and for simulation of the thermal performance of an earth-air heat exchanger for building ventilation, taking account of dynamic variations of climatic, load and soil conditions. The importance of dynamic interactions between the three media - heat exchanger, soil and atmosphere - is illustrated from the comparison of the heat transfer rates and supply air temperature through the heat exchanger under continuous and intermittent operation in heating seasons. It is shown that neglecting the interactions between any two or all three media would significantly over or under predict the heat transfer rate and air temperature. Neglecting the interactions between the heat exchanger, soil and ventilating air would over predict the thermal performance of an earth-air heat exchanger whereas neglecting the interactions between the soil surface and atmosphere would fail to produce reliable data for long term operational performance of the earth-air heat exchanger installed in shallow ground. The level of over-prediction could be larger for intermittent operation than for continuous operation.

KEYWORDS: Earth-air heat exchanger, building ventilation, energy efficient heating, heat and moisture transfer, soil property, thermal interaction.

NOMENCLATURE

b	constant dependent on the type of soil
C	specific heat of soil (J/kgK)
D	damping depth of annual temperature fluctuation (m)
$D_{T,l}$	thermal liquid diffusivities (m^2/sK)
$D_{T,v}$	vapour moisture diffusivities (m^2/sK)
D_v	diffusion coefficient of water vapour in air (m^2/s)
$D_{\Theta,l}$	isothermal liquid diffusivities (m^2/s)
$D_{\Theta,v}$	isothermal vapour moisture diffusivities (m^2/s)
f	ratio of the average temperature gradient of the soil constituent to that of water
$f(\Theta)$	fractional volume of gas-filled pores ($f(\Theta) = \Theta_s - \Theta$)
g	gravitational acceleration (m/s^2)
K	hydraulic conductivity of soil (m/s)
K_s	saturated hydraulic conductivity (m/s)
k	thermal conductivity of soil (W/mK)
k_a	thermal conductivity of dry air (W/mK)
L	latent heat of vaporisation or fusion of water (J/kg)
p_{atm}	atmospheric pressure (Pa)

p_v partial pressure of water vapour (Pa)
q specific heat extraction (W/m)
q_f source or sink of heat at a boundary (W/m^2)
q_v volumetric heat production/dissipation rate in soil (W/m^3)
T temperature of a medium (soil) (^oC)
T_a air temperature in the heat exchanger (^oC)
T_{amp} annual amplitude of surface temperature (^oC)
T_m annual mean temperature of deep soil (^oC)
T_s temperature of the inner surface of the pipe (^oC)
T_v temperature of water vapour (^oC)
t time (s)
t_o time lag from a starting date to the occurrence of the minimum temperature in a year (day)
x horizontal distance from pipe inlet (m)
z vertical coordinate (m)
Z depth from soil surface (m)

α tortuosity factor for diffusion of gases in soil
Θ volumetric moisture content (m^3/m^3)
Θ_f source or sink of moisture at a boundary (m^3/m^2s)
Θ_s saturated volumetric moisture content (m^3/m^3)
Θ_v source or sink of moisture in soil (m^3/m^3s)
θ volumetric fraction of a constituent in soil
ξ direction normal to a boundary
ρ density of soil (kg/m^3)
ρ_l density of liquid (kg/m^3)
ρ_v density of water vapour (kg/m^3)
ρ_{vs} density of saturated water vapour (kg/m^3)
ϕ relative humidity of soil air (fraction)
Ψ matric potential (m)
Ψ_s saturated matric potential (m)

1 INTRODUCTION

Earth-air tunnel ventilation has been studied and applied to buildings for decades. Properly designed and operated, the system is able to reduce the energy use for heating or cooling of a building through a ground or earth-air heat exchanger. The heat exchanger consists of a series of pipe or duct buried in the shallow ground for transferring heat between the supply air in the pipe and the surrounding soil with a relatively stable temperature. The most commonly used pipe material for a heat exchanger is plastic such as high density polyethylene.

The performance of earth-air heat exchangers can be assessed using analytical or numerical techniques or experimental measurements. Bisoniya, et al. [1] have recently reviewed experimental and analytical studies of earth-air heat exchangers worldwide but mainly in India where there has been a lot of research in this area. Analytical techniques are generally based on the simplified solution of one dimensional (axi-symmetric) heat transfer in a circular pipe or the surrounding soil of homogeneous properties. Such models range from a simple thermo-hydraulic equation for constant soil and air properties [2] to a set of analytical equations for daily and seasonally varying soil and air temperatures [3-5]. However, in earth-air tunnel ventilation, heat and moisture transfer occurs simultaneously and these transport phenomena are neither axi-symmetric normal to the pipe nor varying uniformly along the pipe for long term operation due to the influence of daily and seasonal climatic variations and interactions between soil and the heat exchanger. To account for the non-uniform variations requires numerical solution of three-dimensional model equations. The numerical methods can again vary from models for heat transfer only [6-11] to those for simultaneous heat and moisture transfer [12-15] in soil. However, all these investigations have made use of some form of simplifications. For example, in the models for simultaneous heat and moisture transfer, a cylindrical coordinate system, i.e, an axi-symmetric model in horizontal direction, was used for numerical solution of the equations. Such a model would in theory not be able to differentiate boundary conditions at different positions from atmosphere to deep soil and as such the model was often applied only to part of soil surrounding the heat exchanger rather than the whole area within its influence. Besides, the heat and moisture transfer in reality is not symmetrical as will be shown from the results presented in this article. The main difference between this type of axi-symmetrical model and another even more simplistic axi-symmetric model [16] is that the former could involve the top soil boundary that links with atmospheric conditions through approximations whereas the latter was based on pure axi-symmetrical heat transfer and thus the influence of atmosphere was completely ignored. Three dimensional models had of course been developed previously, e.g. by Gauthier, et al. [11], but when used for simulation of earth-air heat exchangers, the main consideration was given to heat transfer in soil while the direct influence of moisture variation on heat transfer was neglected. This may be acceptable under the assumption of constant soil properties. However, the thermosphysical properties of real soil are highly dependent on the moisture content and soil moisture could vary considerably in shallow ground. Despite its obvious shortcomings, this approach has been pursued by a number of researchers in recent years for analysis of earth-air heat exchangers using commercial software that is basically designed for modelling of general fluid flow and heat transfer rather than coupled heat and mass transfer in soil [16-20].

Three-dimensional numerical models for coupled heat and moisture transfer have nevertheless been developed for a wide range of applications from prediction of the development of caking in granular materials [21], analysis of heat, moisture, air flow and deformation in unsaturated soil [22], prediction of the moisture evolution in porous building materials [23] to assessment of the indoor thermal environment [24]. These models are generic in their own areas but modelling of an earth-air heat exchanger requires unique considerations such as interactions between the heat exchanger, soil and atmosphere which this has not been thoroughly investigated. Therefore, there is a need for a three-dimensional model that takes account of not only the coupled heat and moisture transfer in soil but also interactions between soil and atmosphere and between the heat exchanger and ventilating air in order to predict more accurately the thermal performance of an earth-air tunnel ventilation system.

The author has recently developed a more general three-dimensional numerical model for the simulation of transient heat and moisture transfer in soil with a horizontally coupled earth-air heat exchanger for preheating and cooling of buildings [25]. The mathematical model is based on the general conservation equations for heat and moisture transfer in soil. The soil is subjected to extraction/injection of heat and moisture at two types of interface. One is the ground surface where heat transfer takes place by convection, short and long wave radiation and those associated with moisture transfer due to condensation/evaporation, possible freezing/thawing and precipitation. Another is the heat exchanger buried below the ground where convection heat transfer between the inner surface and ventilating air dominates but condensation/evaporation could also occur on both the inner and outer surfaces. The model thus takes account of interactions of heat and moisture transfer in soil and between the atmosphere, soil, heat exchanger and supply air passing through the heat exchanger. It incorporates key components for earth-air heat exchange modelling from model equations and boundary conditions to spatial and temporal variations in soil properties and transport processes. The model equations are solved using the control volume method and a computer program has been developed using FORTRAN for the solution. In this article the numerical model is outlined for simulation and then the simulated performance of an earth-air heat exchanger is discussed for preheating of supply air in building ventilation. The consequences of simplifying simulation or using inadequate methods for simulation on the predicted performance are also examined and the importance of taking full account of the interactions is demonstrated.

2 METHOD

To simulate transient heat and moisture transfer simultaneously through an earth-air heat exchanger, a numerical method is used to solve three-dimensional energy and mass conservation equations for soil coupled with the heat and mass balances at the two interfaces: a) between earth and atmosphere and b) between the heat exchanger and supply air.

2.1 Model Equations

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

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

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

The four moisture diffusivities in the above equations are defined as follows:

$$D_{T,l} = K\frac{\partial\Psi}{\partial T} \tag{3}$$

$$D_{T,v} = D_v \alpha f(\Theta)\frac{1}{\rho_l}\frac{\partial\rho_v}{\partial T} \tag{4}$$

$$D_{\Theta,l} = K\frac{\partial\Psi}{\partial\Theta} \tag{5}$$

$$D_{\Theta,v} = D_v \alpha f(\Theta)\frac{1}{\rho_l}\frac{\partial\rho_v}{\partial\Theta} \tag{6}$$

The matric potential and hydraulic conductivity of soil are given by the following pedo-transfer functions of moisture content [26]

$$\Psi = \Psi_s\left(\frac{\Theta}{\Theta_s}\right)^b \tag{7}$$

$$K = K_s\left(\frac{\Theta}{\Theta_s}\right)^{2b+3} \tag{8}$$

Soil is a mixture of solid matter, gases and liquids as well as living organisms. The thermal properties of a soil mixture including the density, specific heat and thermal conductivity vary with the composition of its constituents. They are represented by the following functions of the volumetric composition of dry solid matter, gases and three phases of moisture – liquid water, water vapour and solid ice:

$$\rho = \rho_d \theta_d + \rho_l \theta_l + \rho_i \theta_i + \rho_p \theta_p \tag{9}$$

$$\rho C = \rho_d C_d \theta_d + \rho_l C_l \theta_l + \rho_i C_i \theta_i + \rho_p C_p \theta_p \tag{10}$$

$$k = \frac{k_l \theta_l + f_i k_i \theta_i + f_p k_p \theta_p + \sum_{m=1}^{n} f_m k_m \theta_m}{\theta_l + f_i \theta_i + k_p \theta_p + \sum_{m=1}^{n} f_m \theta_m} \tag{11}$$

In the above equations, subscripts d, l, i and p represent dry soil, liquid moisture, ice and gas-filled pores, respectively, and m is the mth component of n types of dry soil grains.

The thermal conductivity of pores is influenced by dry air and the phase change of moisture:

$$k_p = k_a + LD_v \phi \frac{p_{atm}}{p_{atm} - p_v} \frac{d\rho_{vs}}{dT_v} \tag{12}$$

The moisture in soil varies in space and time as described with Equation (2). The most obvious change in the moisture content is often observed near the soil surface. It increases with precipitation and condensation and decreases due to evaporation. There are however limits for soil to hold moisture. The upper limit of moisture in soil is defined as the saturation moisture content and the lower limit is the residual moisture content. In simulation, the moisture content in soil at any time is set within these lower and upper limits.

The partial differential equations (1) and (2) are solved for a three-dimensional model using the control volume method with the initial and boundary conditions described below. A heat exchanger is represented by a series of parallel pipes inside a computational domain. In practical installation, parallel pipes are connected to the external air intake and supply air outlet through two headers of larger pipe. The size and configuration of the headers and associated piping to the above-ground environments depend on the design of both a building and the ventilation system including the ground heat exchanger and thus vary from one design to another. Therefore, these components are not modelled in this work. Fig. 1 shows a schematic diagram of the heat exchanger and the boundary conditions for simulation.

2.2 Initial Conditions

Empirical expressions are available that represent the annual variation of the soil temperature. The following expression is used to set the initial soil temperature and the far-field temperature at any time t (day) and depth,

$$T = T_m - T_{amp} e^{-Z/D} \sin\left((t - t_o) \frac{2\pi}{365} - \frac{Z}{D} - \frac{\pi}{2} \right) \tag{13}$$

Such an expression is however not available for moisture variation in soil. It is assumed therefore that at the beginning of simulation the soil moisture content is uniform.

2.3 Boundary Conditions

Boundary conditions for the solution of the three-dimensional heat and moisture transfer equations include heat and moisture transfer for the ground or top soil surface, the bottom face, four vertical faces, the inlet and outlet openings, and the interior and exterior surfaces of the heat exchanger pipe.

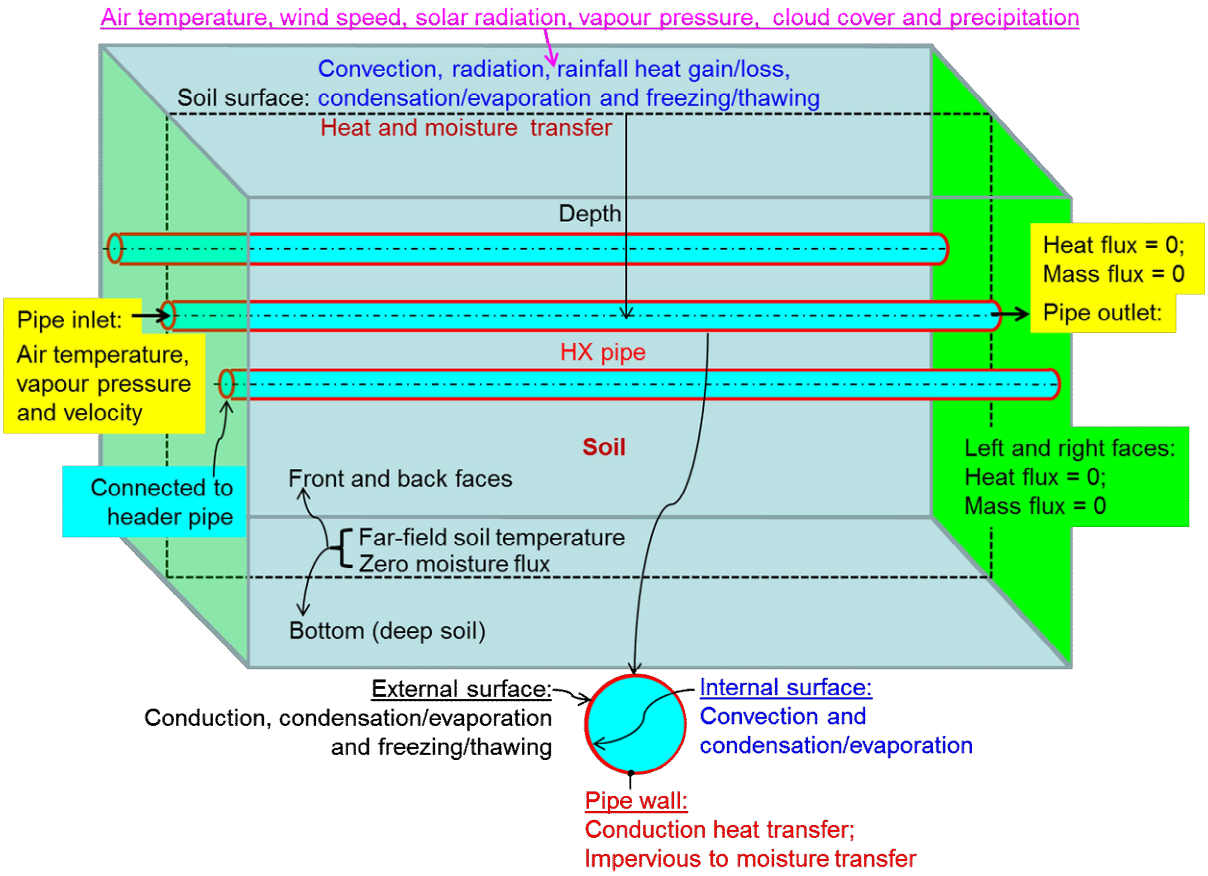


Fig. 1 Boundary conditions for simulation of heat and moisture transfer through an earth-air heat exchanger

For areas where soil is directly exposed to the environment or in direct contact with other types of material/medium, i.e., the top soil surface or outer surface of the heat exchanger pipe, the boundary conditions are given by the heat and mass balances for a control volume with a thickness of $\delta\xi$

$$\left(k + L\rho_l D_{T,v}\right)\frac{\partial T}{\partial \xi} + L\rho_l D_{\Theta,v}\frac{\partial \Theta}{\partial \xi} = q_f \tag{14}$$

$$\left(D_{T,l} + D_{T,v}\right)\frac{\partial T}{\partial \xi} + \left(D_{\Theta,l} + D_{\Theta,v}\right)\frac{\partial \Theta}{\partial \xi} = \Theta_f \tag{15}$$

The term on the right hand side represents the net heat (mass) flow into the control volume resulting from the sources given in Table 1.

Table 1 Sources of heat and moisture flow at the soil surface and outer pipe surface

Type of boundary	**Heat flow (q_f)**	**Moisture flow (Θ_f)**
Top soil surface	• Short and long wave radiation • Wind and buoyancy induced convection • Moisture evaporation or condensation • Sensible heat from precipitation	• Evaporation or condensation • Precipitation
Outer pipe surface	Zero	Zero

For other surfaces, the boundary conditions are summarized in Table 2. A complete description of the boundary conditions is given in references [25 and 27].

At times when incoming air temperature is higher than the pipe temperature such that preheating of supply air is not possible or during the times when the system is switched off for intermittent operation, the inlet opening is prescribed with zero heat and mass flux for continuous simulation of heat and moisture transfer in soil.

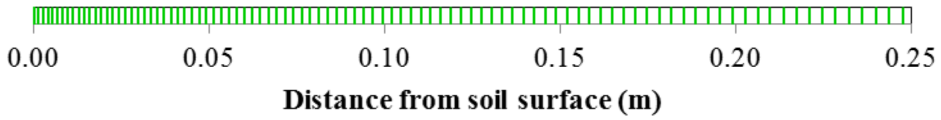
Table 2 Boundary conditions for heat and moisture transfer

Type of boundary	Heat transfer	Moisture transfer
Far-field – vertical faces and bottom face	Equation (13)	Zero mass flux
Pipe inlet	Ambient air temperature and Ventilation rate (or velocity)	Vapour pressure (or relative humidity
Pipe outlet	Zero heat flux	Zero mass flux
Inner pipe surface – ventilating air	Advective and conductive heat transfer → Convection + Condensation (evaporation)	Convective and diffusive moisture transfer → Condensation (evaporation)

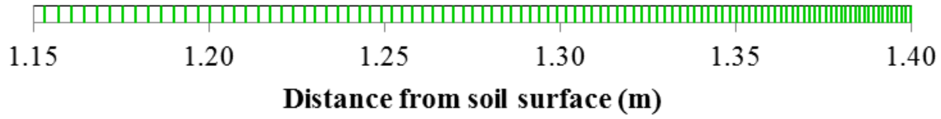
2.4 Solution method

The partial differential equations for the coupled heat and moisture transfer are solved using the control volume method. This involves firstly decomposing a three-dimensional computational domain into numerous hexahedral control volumes or cells. Each partial differential equation is then integrated over each of the control volumes to obtain an integral equation. Next, the integral equation is discretised into an algebraic equation, one equation for one control volume, and the total number of algebraic equations is equal to the product of the number of variables (soil temperature and moisture) and the number of control volumes. Finally, all the algebraic equations are solved iteratively for given initial and boundary conditions some of which, e.g., Equations (14) and (15), are dependent on the outcomes of the iteration. The solution is considered to have converged when the sum of the normalised residual for each variable for the whole domain is less than 10^{-3} and more importantly changes in both the residual and variables between iterations become negligible. Because the equations are highly non-linear, under relaxation is used to achieve a converged solution; the required under-relaxation factors could be as small as 0.1 at the beginning, whenever the system is switched on or off for intermittent operation, or when the heat transfer rate through the heat exchanger is high.

The size of the computational domain is such that at the end of the operating period under simulation the influence of the variations of the key variables would not reach the far-field, i.e., bottom, front and back faces denoted in Fig. 1. For simulation of one month's operation, a distance of 5 m from the heat exchanger would be sufficient. A larger domain is however used in this work to ensure that the above requirement is met, e.g., a total depth of 10 m in the vertical direction. A non-uniform mesh is used for such a large computational domain. Previous work by the author has shown the importance of using fine meshes and time steps for accurate simulation of heat and moisture transfer particularly with varying environmental conditions [25, 27 and 28]. The edge size is about 1 mm for cells close to the heat exchanger and the soil surface where potential variations in the heat and/or moisture transfer are large and the size increases gradually away from these areas to avoid the need for an excessive number of cells. Fig. 2 shows the distribution of cells in the depth direction through the centreline of the heat exchanger for three small sections – a) starting from the soil surface downwards, b) from the crown of the pipe upwards and c) from the bottom of the pipe downwards – and for the whole depth where only one in 14 cells are included.

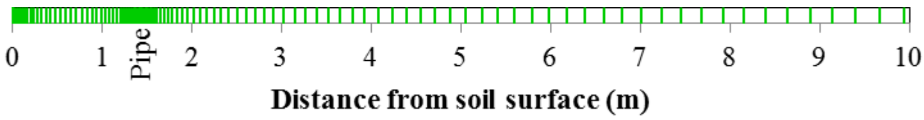


a) Near the soil surface



b) Near the crown of the pipe

c) Near the bottom of the pipe



(d) For the full depth of the domain with one in 14 cells shown

Fig. 2 Cell distribution in vertical direction

The model has been validated for simulation of transient heat transfer for preheating of supply air through a straight pipe of 200 mm external diameter buried 1.5 m below the ground for an ambient air temperature of 5°C and an initial deep soil temperature of 10°C [25] and for refrigerant flow in a 40 mm diameter slinky heat exchanger [29].

In order to confirm the accuracy of the in-house program, further validation has been carried out through comparison of predicted heat transfer with that using commercial software FLUENT [30] which had been validated with experimental measurements [29]. The conditions for validation presented here are the same as for the previous work [25] except that the ambient air temperature is reduced from 5°C to 1°C for winter application. Detailed conditions are as follows:

- Heat exchanger pipe = 200 mm external diameter; depth of installation = 1.5 m.
- Soil density =1588 kg/m^3; specific heat = 1465 J/kgK; thermal conductivity = 1.24 W/mK, all based on measurements [29].
- Deep soil temperature = 10°C.
- Ambient air temperature = 1°C; wind speed = 4 m/s; mean air velocity in the pipe = 2 m/s.

The predicted heat transfer rate per unit length of the heat exchanger is compared in Fig. 3. Good agreement between the two sets of results can be observed with a maximum difference of about 0.8% and average difference of less than 0.2% during a period of 30 days.

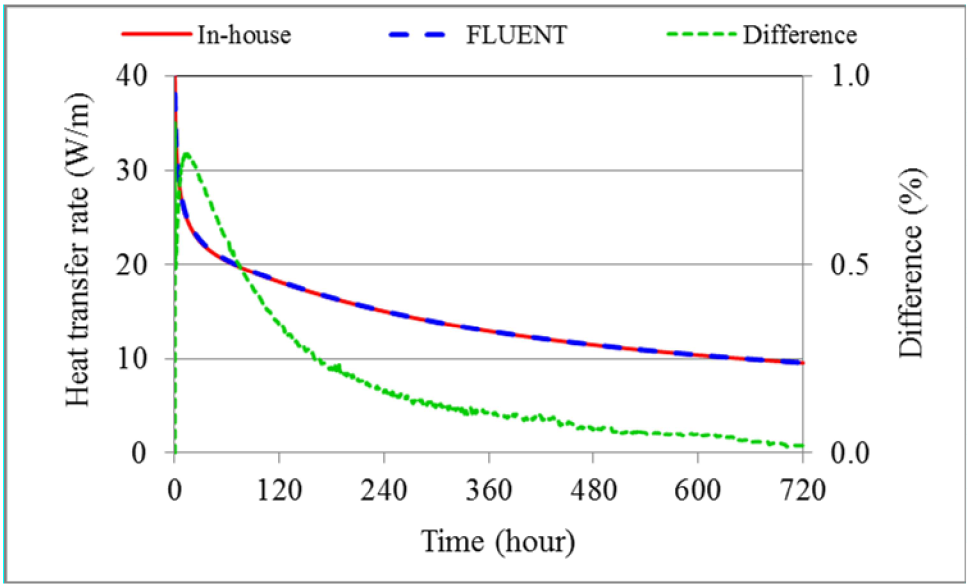


Fig. 3 Predicted heat transfer rate using in-house and FLUENT programs

2.5 Simulation conditions

The numerical method is used to assess the performance of an earth-air heat exchanger for preheating of supply air for continuous and intermittent operation in a climate in the Southern England. The heat exchanger is made of high density polyethylene with an external diameter of 200 mm and a wall thickness of 7.7 mm. It is installed horizontally at 1.5 m below the ground surface. Environmental properties are required to account for the interactions not only for supply air inside the heat exchanger but also at the top soil surface. These include the hourly data for air temperature, partial vapour pressure (or wet bulb temperature), solar radiation, cloud cover and wind speed for each month [31] and the monthly rainfall [32]. Values at any time of a day are then calculated from these hourly/monthly data through linear interpolation. The frequency of rainfall is such that it would rain for three hours in evening on every third day. The mean velocity of supply air is 2 m/s at the inlet of the heat exchanger. The soil is of loam texture with 43% sand, 18% clay and 39% silt [33]. Its saturation moisture content is 44% and residual moisture content 5%. The initial moisture content is taken to be one half of the saturation value. The temperature of deep soil is 10°C which can be taken approximately as the annual mean air temperature for the location.

3 RESULTS AND DISCUSSION

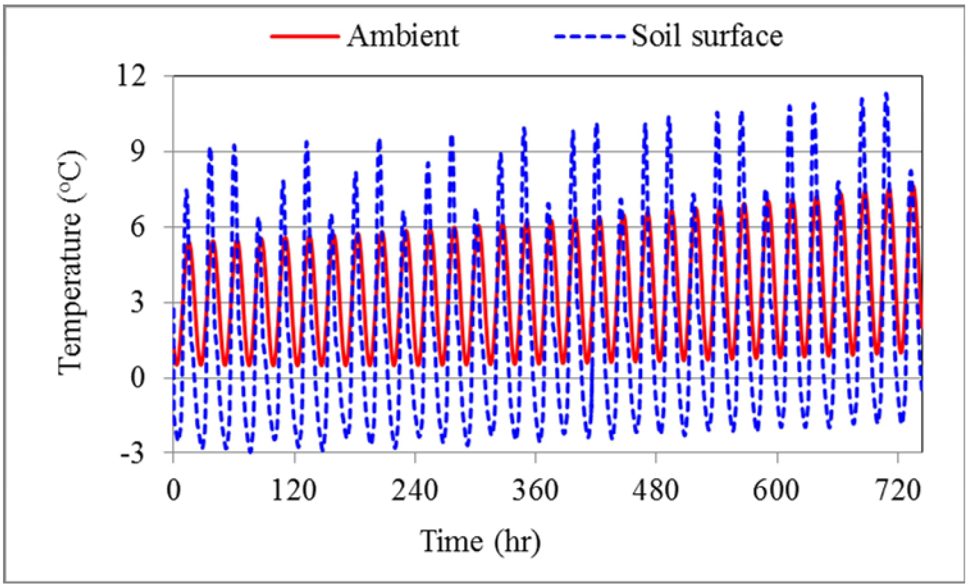
Simulation has been carried out for two modes of operation - continuous and intermittent. For continuous operation, heat is transferred from soil to air through the heat exchanger at any time of a day when the air temperature is lower than the temperature of the heat exchanger at the inlet opening. For intermittent operation, the heat transfer to air takes place only in a prescribed period of the daytime, again when preheating of supply air is feasible. In other times, heat and moisture transfer still takes place in simulation. However, heat would transfer from soil to the heat exchanger to increase the temperatures of the heat exchanger and surrounding soil as well as static air inside the heat exchanger but not for ventilation. The performance of the heat exchanger is investigated for operation in four months - October, November, December and January - but the discussion is focused on the results for January.

3.1 Continuous operation

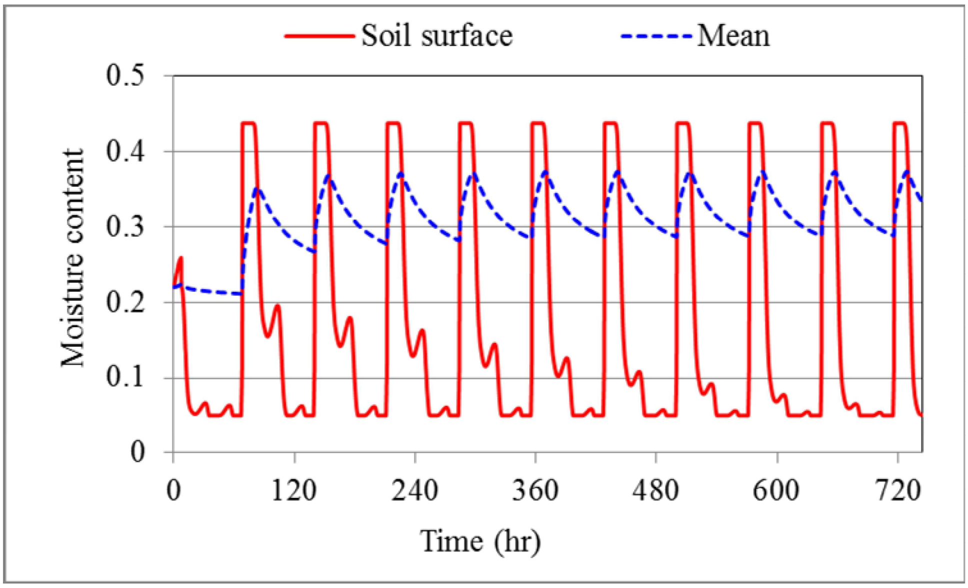
Figure 4 shows the predicted daily variations in ambient air temperature, soil surface temperature and moisture, and mean moisture for the soil layer between the soil surface and the crown of the pipe (i.e., heat exchanger) in January. Fig. 5 shows the variations of soil temperature and moisture along a vertical line through the mid-length and centreline of the heat exchanger for heating at the end of five typical days. In Fig. 5a, the difference refers to the temperature difference between the undisturbed (reference) soil and the soil in question. The soil temperature variation for the first day of October and December is also presented for comparison of monthly performance later on. The daily air temperature varies by about 5^{o}C 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 the month. The air temperature rises gradually with the minimum and maximum to 1^{o}C and 7.6^{o}C, respectively, at the end of the month. The daily variation of soil surface temperature is much larger mainly because of absorption of solar radiation during the day and long wave radiation heat loss during the night. The soil surface temperature drops below the freezing point during much of the night times. The minimum surface temperature is about -3^{o}C (at 4am) at the beginning (the 2nd day) of the month and it increases to -1.8^{o}C near the end (last but one day) of the month. The corresponding maximum surface temperature is 9.2^{o}C (at noon) at the beginning and 11.3^{o}C near the end of the month. The rain in the proceeding night would decrease the soil surface temperature in the following day due to the lower rainwater temperature (= wet bulb air temperature) and increased moisture evaporation; e.g., the maximum surface temperature for the 3rd and last day of the month drops to 6.4^{o}C and 8.2^{o}C, respectively.

The temperature of the undisturbed soil at 1.5 m deep is about 8^{o}C at the beginning of the month and decreases to 6.2^{o}C at the end of the month. It is higher than the night time air temperature. The soil temperature above the heat exchanger is much lower than the deep soil temperature. At the midnight of the first day, soil temperature 1 m below the heat exchanger is however still higher than the deep soil. The vertical soil temperature variation is influenced by the heat exchanger in an area of only 0.6 m from the pipe at the end of the first day, as seen from the difference in comparison with the temperature of undisturbed soil. 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.

Moisture evaporates from the soil during day times. As a result, the surface moisture would drop rapidly after the sun rises and reach the minimum (residual) value at about 11am and would remain so till 3 hours after sunset because the evaporation rate would be larger than the moisture transfer rate from soil below. If it rains in the night before, the soil surface would not become dry in the following day but the surface moisture would drop to the minimum in the day after and at a later time from 5pm. During the evening and onwards, the surface moisture would increase as a result of upward moisture transfer in soil and potential surface condensation, or frost, if the temperature drops below the dew point, or freezing point, respectively. Condensation of moisture (or frost formation) on the soil surface occurs as observed from a slight rise in the moisture content in the first night. The mean moisture for the soil layer would increase during the rainfall on every third evening and then decrease afterwards. Overall, the amount of rainfall and moisture condensation exceeds that of surface evaporation during the first half of the month. This is indicated by the higher mean moisture from Day 4 than the initial value; the lowest mean is 26.7% on Day 6 before the next round of rain and 28.4% on Day 15. The soil moisture peaks on Day 15 and remains almost at the same levels for the rest of the month varying from 28.6% to 37.3% within each rain cycle.



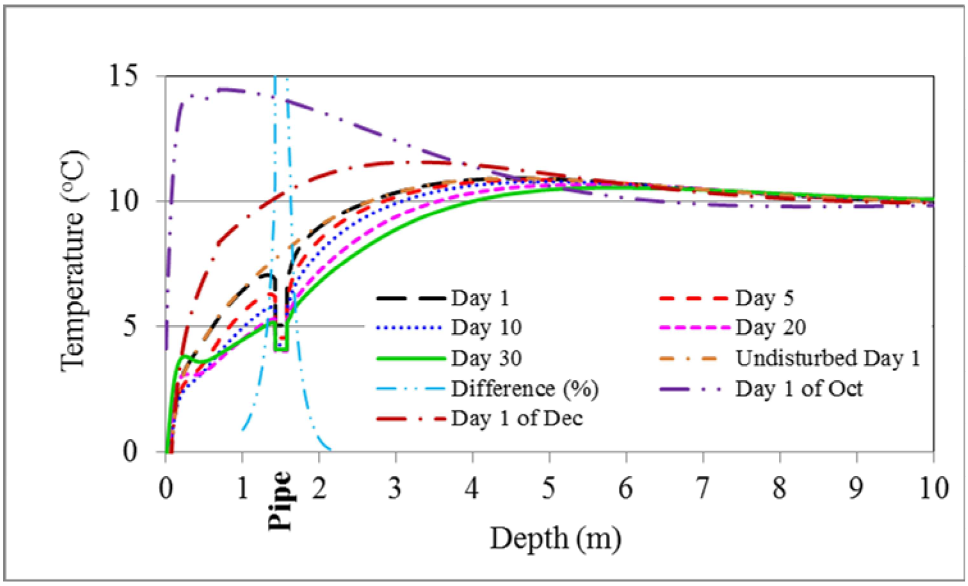
a) Temperature



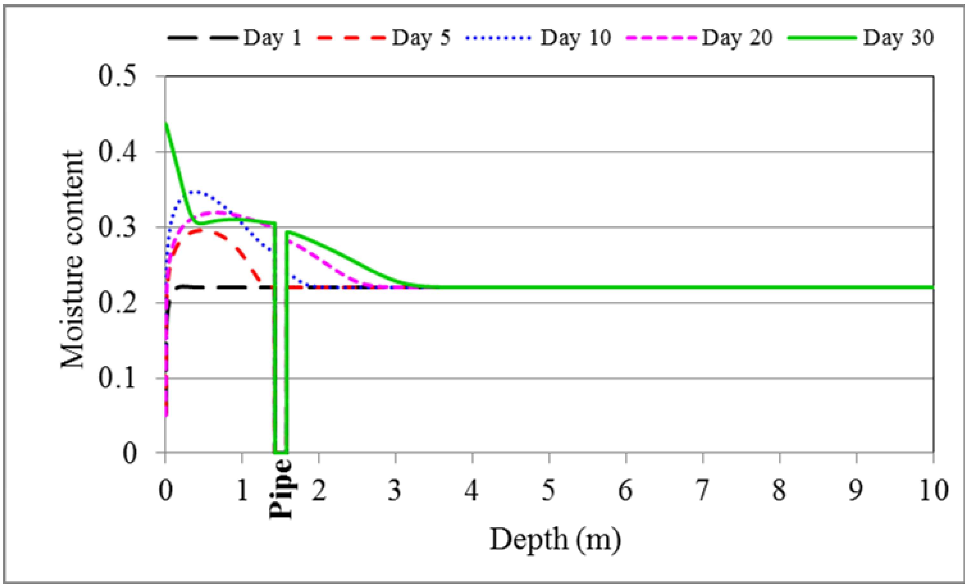
b) Moisture content

Fig. 4 Predicted daily variations in ambient air temperature, soil surface temperature and moisture, and mean soil moisture in January

In the depth direction, the overall trend of moisture variation is also increasing with time. At the end of the first day, the moisture variation is limited to the close vicinity of soil surface but the influence of moisture variation reaches 3.5 m below the soil surface at the end of the month.



a) Temperature



b) Moisture content

Fig. 5 Predicted vertical variations in soil temperature and moisture in January

3.1.1 Variations along the heat exchanger

The temperature rise of supply air and the rate and amount of heat transfer through a heat exchanger vary with the length. Simulations have been performed for the heat exchanger with different lengths from 10 m to 40 m in addition to a unit length (1 m).

Figure 6 shows the predicted variations with time in the temperature of the inner pipe surface and heat transfer rate through one pipe of a 10 m long heat exchanger, as well as the ambient air temperature and the temperature of undisturbed soil at a depth of 1.5 m (denoted by soil temp) for reference, for heating in January. The variation in the mean temperature of the 10 m long heat exchanger (defined as the average temperature of the inner surface of the pipe) is much less than that of the ambient air. The daily variation is about 1.4°C compared with 5°C to 6.6°C for the ambient air.

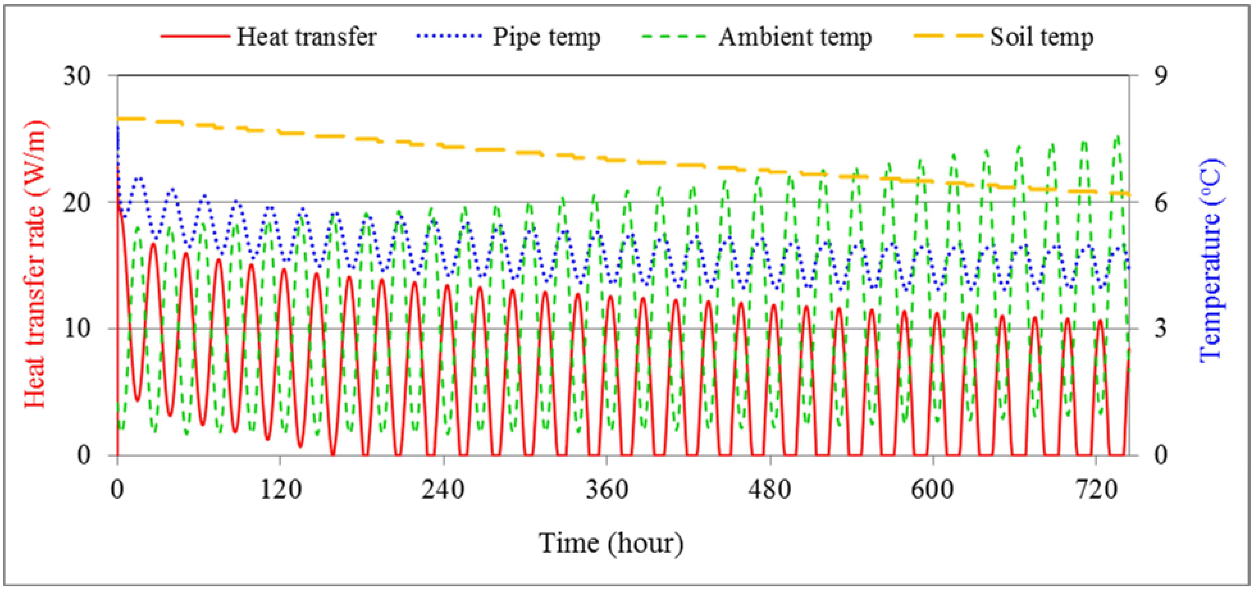


Fig. 6 Predicted variations with time of pipe temperature and heat transfer rate for a 10 m long heat exchanger in January

The specific heat extraction, or the heat transfer rate per unit length of the heat exchanger, varies with time and with soil and ambient temperatures. Because the soil temperature is more stable than air temperature, the specific heat extraction is higher during the night when the air temperature is much lower than that in the daytime. The general variation pattern is that starting from the midnight the rate of heat transfer increases until at about 3am and then decreases to a minimum at about 3pm and finally increases again through the rest of the day. For the first day, however, the maximum heat transfer rate of 23 W/m occurs at the beginning when the heat exchanger is assumed to be at equilibrium with surrounding soil and the temperature difference between the surrounding soil (heat exchanger) and incoming air is thus at maximum. The heat transfer rate decreases with decreasing temperature difference to a minimum of 4.3 W/m at 3pm on the first day. The rate of heat transfer would decrease day by day due to the decreasing soil temperature and from Day 7 the minimum value drops to zero at about 2pm when the air temperature becomes higher than the temperature of the pipe inlet. This is defined to be the moment when heat in surrounding soil is not available for extraction and preheating through the heat exchanger is supposed to stop by means of e.g. by-passing ventilating air through the heat exchanger. The duration when heat extraction is not feasible increases with operating time from two hours (1pm to 3pm) on Day 7 to 11 hours on the last day of the month from 9am to 8pm, i.e., practically no preheating during the daytime.

It should be pointed out that supply air could still be preheated in theory through the heat exchanger even if the temperature of ambient air is slightly higher than that of the pipe inlet but lower than the average pipe temperature. However, the passing air would be cooled down through part of the heat exchanger near the entrance and then heated up in the rest of the heat exchanger. Besides, the temperature variation through the length of pipe would be small by then. For example, at the time when the air temperature approaches the temperature of pipe at the entrance, the temperature increase from the inlet to outlet of a 10 m and a 40 m long heat exchangers is only 0.4 K and 1.2 K, respectively, around 2 pm of the 7th day (the 1st day of the month with a period of time when ambient air temperature is lower than pipe temperature), decreasing to 0.3 K and 1.0 K, respectively, around 10 am of the last day of the month.

The three-dimensional simulations have revealed that temperatures of soil, air and heat exchanger and the heat transfer rate also vary with the distance from the inlet along the air flow direction (inside the heat exchanger) and that the variations are non-linear. Fig. 7 shows the variations in the pipe and air temperatures and heat transfer rate for a 40 m long heat exchanger at the end (midnight) of Day 5. The air temperature increases along the heat exchanger from 1.3°C at the inlet to 6°C at the outlet because of heat transfer from soil to air. The pipe temperature also increases along the heat exchanger from 4.6°C to 6.7°C. The increase in the pipe temperature is smaller than that in the air temperature along the air passage and thus the temperature difference between the pipe and air (heating potential) is much larger near the entrance. The heat transfer rate decreases along the pipe by nearly five times from 16.3 W/m at the inlet to 3.5 W/m at the outlet. The magnitude of variations in the temperatures and heat transfer with the distance is dependent on the time and duration of operation as well as ambient air and soil properties but the variations along the flow passage are approximately quadratic. The air and pipe temperatures and heat transfer rate along the heat exchanger at the end of Day 5 for example can be represented by the following correlations,

$$T_a = -0.0022\,x^2 + 0.202\,x + 1.36 \qquad (R^2 = 0.9993) \qquad (16)$$

$$T_s = -0.00092\,x^2 + 0.091\,x + 4.53 \qquad (R^2 = 0.9996) \qquad (17)$$

$$q = 0.0063\,x^2 - 0.56\,x + 15.94 \qquad (R^2 = 0.9986) \qquad (18)$$

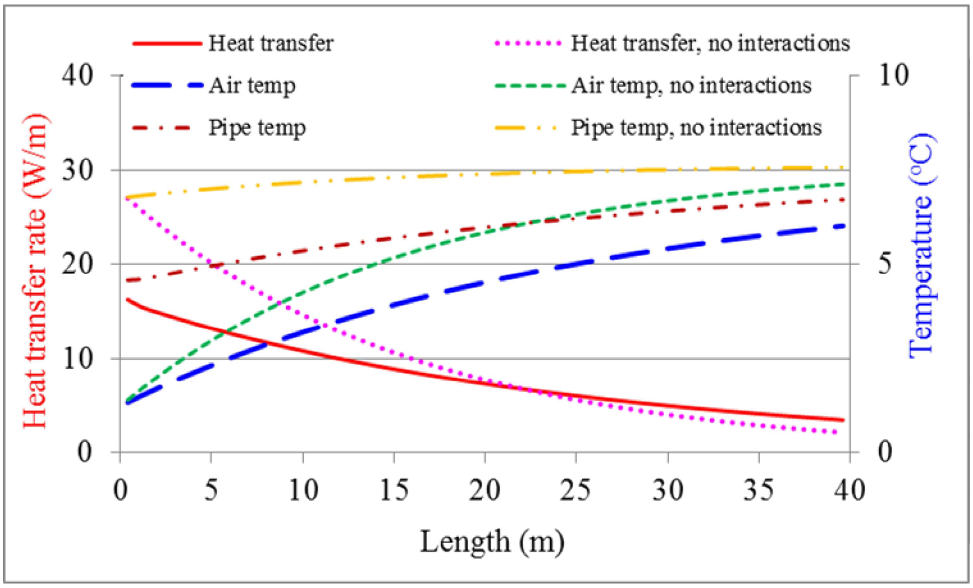


Fig. 7 Predicted variations of supply air and pipe temperatures and heat transfer rate along the pipe length at the end of Day 5

The variations decrease with increasing operating time as illustrated in Fig. 8 for heat transfer. It is also seen that the magnitude of the heat transfer rate decreases with increasing time.

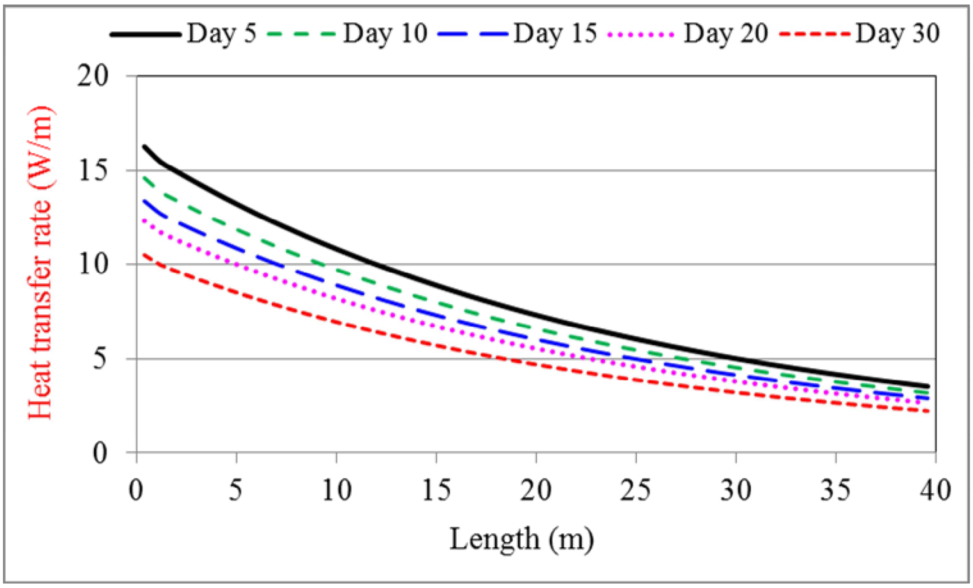
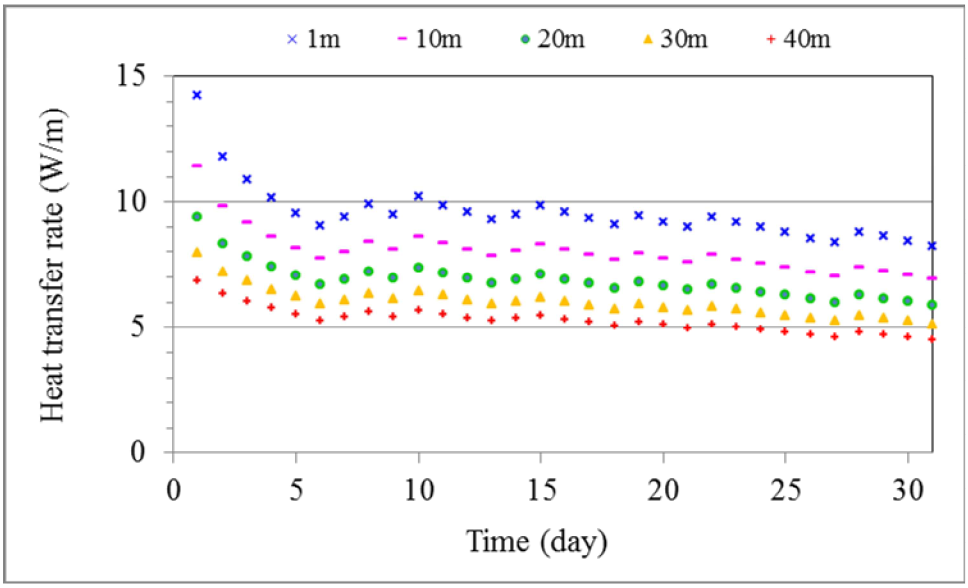
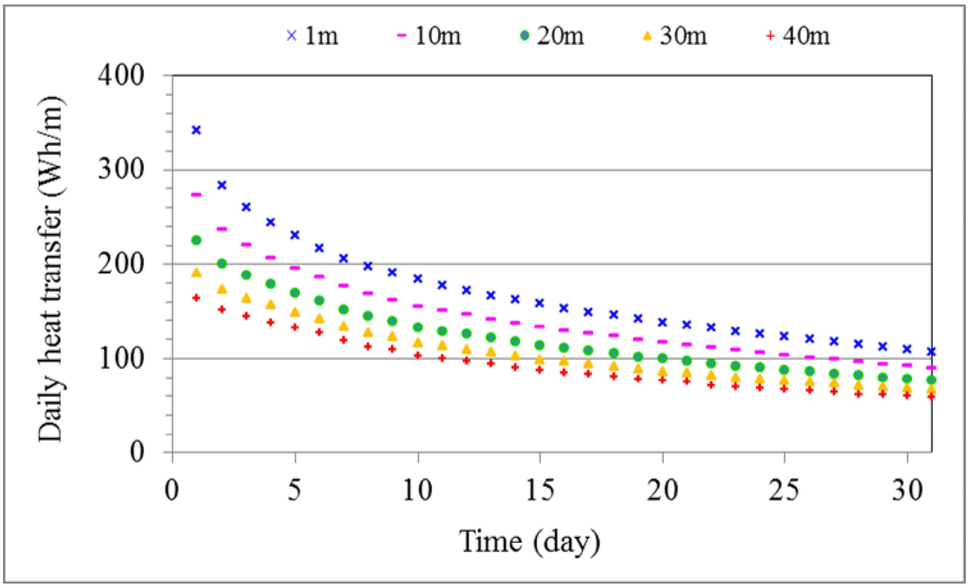


Fig. 8 Predicted variation of heat transfer rate along the pipe length

The results for heat transfer are used to calculate the daily mean values - amount of daily heat transfer and mean rate of daily heat transfer. The amount of daily heat transfer (extraction) is the cumulative product of the heat transfer rate and time for the duration of heating period and the mean rate of daily heat transfer or daily mean heat transfer rate is the average of the heat transfer rate for the duration when heat is available for extraction. The daily mean heat transfer rate (W/m) and the amount of daily heat transfer (Wh/m) decrease with increasing length as shown in Fig. 9. The total heat transfer rate (W) is the product of the mean heat transfer rate and the pipe length and this would however increase with length. As a result, the temperature of air flowing out of the heat exchanger would depend on the pipe length as well as the ambient air temperature. It is seen from Fig. 10a that a 10 m long pipe would be able to reduce the daily temperature swing of supply air at the outlet by 1/3 and a 20 m long pipe by 2/3. A 40 m long pipe would maintain the daily supply air temperature swing within 0.7^{o}C (compared with a diurnal ambient air temperature swing of 5 to 6.6^{o}C). The ambient air temperature is lower than the undisturbed soil temperature for the first three weeks of the month but higher afterwards in some of the day time when preheating of supply air would not be feasible.

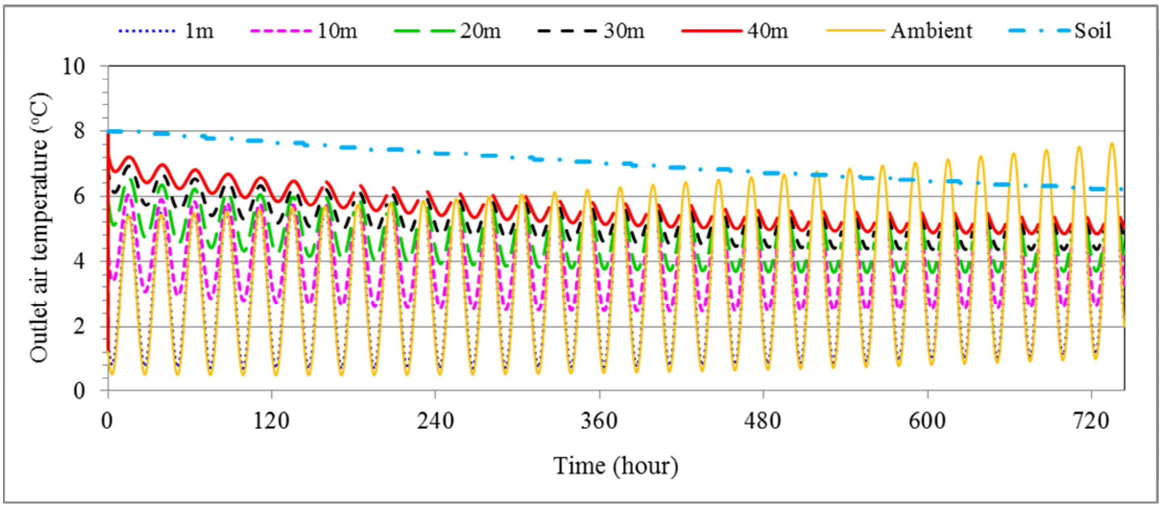


(a) Daily mean heat transfer rate

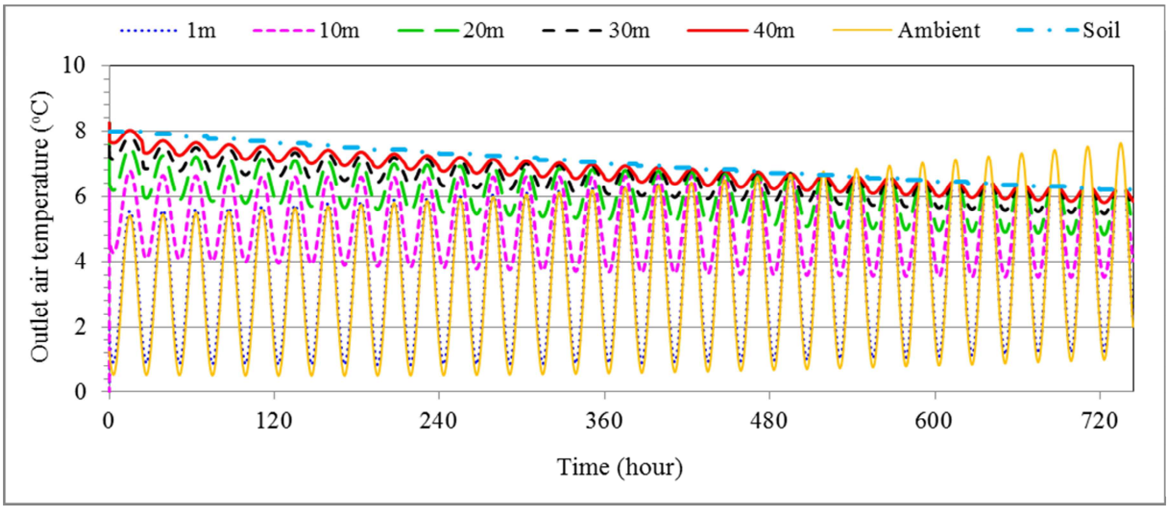


(b) Daily heat transfer

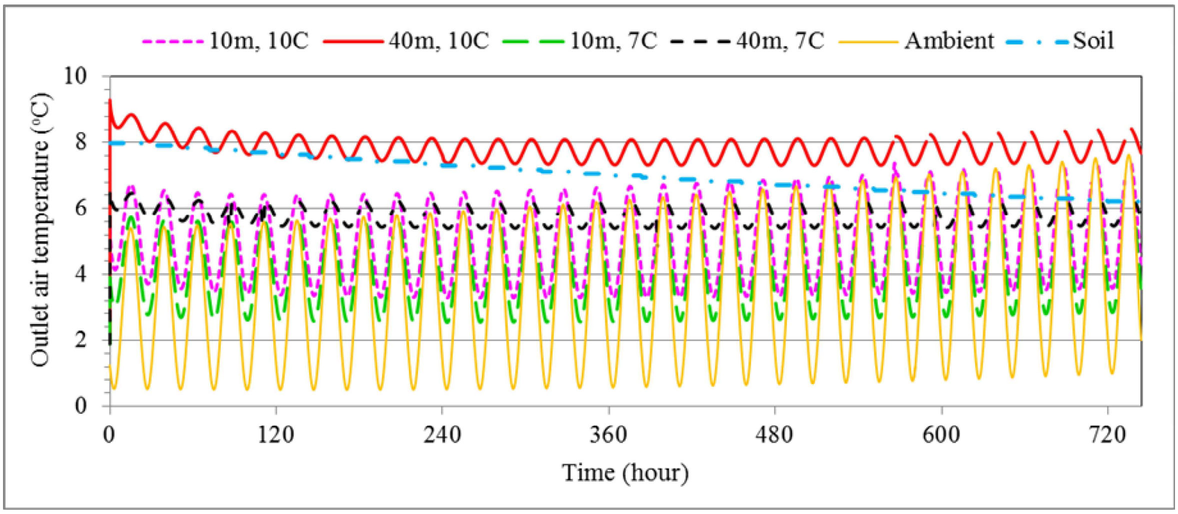
Fig. 9 Predicted variations of heat transfer with time for different heat exchanger lengths



(a) With interactions between the heat exchanger and environments



(b) With Equation (13) for soil temperature



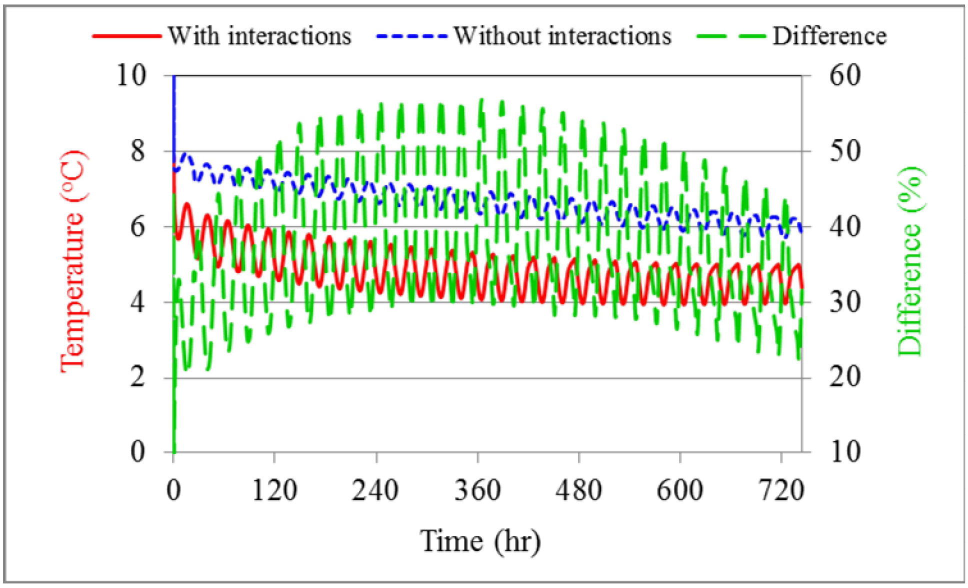
(c) With axi-symmetric model for initial soil temperature of 10°C or 7°C

Fig. 10 Predicted outlet air temperature for different heat exchanger lengths

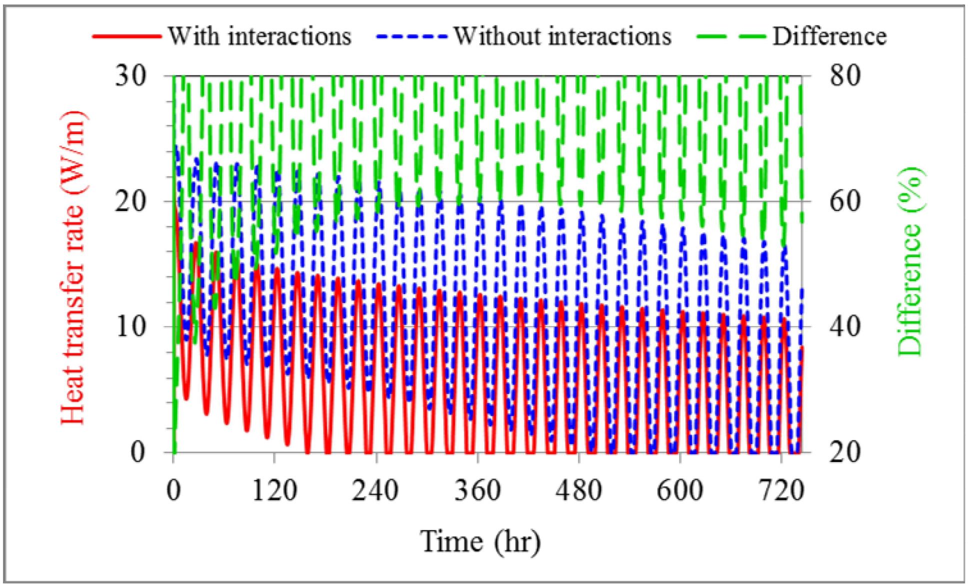
3.1.2 Effect of interactions between the heat exchanger, soil and atmosphere

The heat transfer through the heat exchanger is highly influenced by the interactions between the pipe and surrounding soil, between the pipe and supply air inside the pipe, and between soil and atmosphere at the soil surface. Without consideration of these interactions, e.g., the soil temperature at pipe location is given by Equation 13 as used in some of the previous investigations [4 and 5], the predicted heat transfer rate would be much higher because the equation does not take account of the history of heat transfer to air that decreases the soil and pipe temperatures during heat extraction. Fig. 11 shows that, without the cooling effect of supply air, the interior pipe surface temperature is higher but its daily variation is much smaller than those with thermal and moisture interactions between the pipe and soil. The daily pipe temperature swing without considering the interactions is only 0.5°C compared with 1.3°C with interactions. The difference between the two temperature values with and without consideration of the interactions varies all the time each day but overall increases with operating time for the first half of the month and then decreases slightly; the maximum difference occurs on Day 16 with the maximum of 57.2% in the early morning (at around 5am) and the minimum of 29.2% in the early evening (at 7pm) at resumption of heat extraction after the soil temperature recovery period in the daytime when air temperature is higher than the pipe temperature. Fig. 11 also indicates that the difference in the heat transfer rate is larger than that in the temperature and that the peaks and troughs of its daily variation do not follow those of temperature variation. The minimum difference in the heat transfer rate generally occurs at night between 1am and 2am. The difference would be much larger at other times particularly when the air temperature approaches the pipe temperature, leading to negligible heat transfer, during much of the daytime and hence there would be no preheating in the daytime for simulation with consideration of the interactions whereas simulation without considering the interactions would indicate as if heat could be extracted nearly all day long up to Day 21. The highest minimum difference in the heat transfer rate is 60%, found again on Day 16.

The daily amount and mean rate of heat transfer decrease with operating time as shown in Fig. 12. The amount of daily heat extraction decreases because of both decreasing heat transfer rate and operating hours in a day. The difference in the amount or rate of daily heat transfer between the predictions with and without considering the interactions also increases with time up to the middle of the month. The difference in the daily heat extraction predicted with and without consideration of the interactions is larger than that in the heat transfer rate; for example, for the 15th day of the month, the predicted daily heat extraction through a 10 m long heat exchanger without considering the interactions is 112% higher than that with full interactions compared with 86% in the heat transfer rate for the same operating period based on the simulation with consideration of the interactions. The larger amount of daily heat transfer without considering the interactions results not only from the predicted higher heat transfer rate but also from the longer time period for heating of supply air – continuous heating for 21 days compared with 6 days only with consideration of the interactions. Note that the presented daily variation in the heat transfer rate is not smooth because the simulated results were recorded hourly for post-processing but the exact period when heat is available for extraction would vary from day to day by minute or second. When the same period for heat extraction, i.e., from 8pm to 9am, is used for processing, the variation becomes smooth as is also shown in Fig. 12a. Note also that the maximum (or minimum) differences for the instantaneous (Fig. 11b) and daily mean (Fig. 12) values could occur in different days (e.g. the 15th and 16th days).



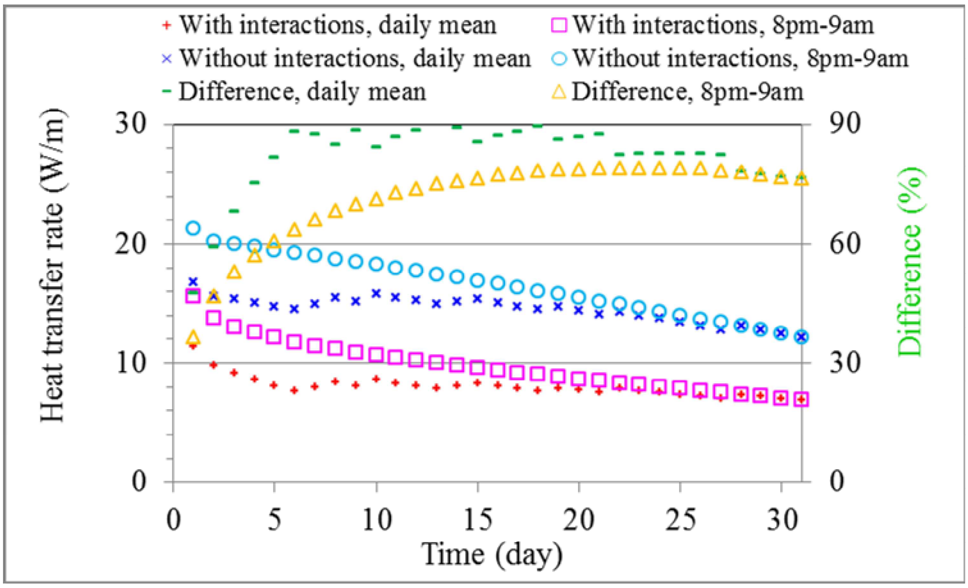
(a) Pipe temperature



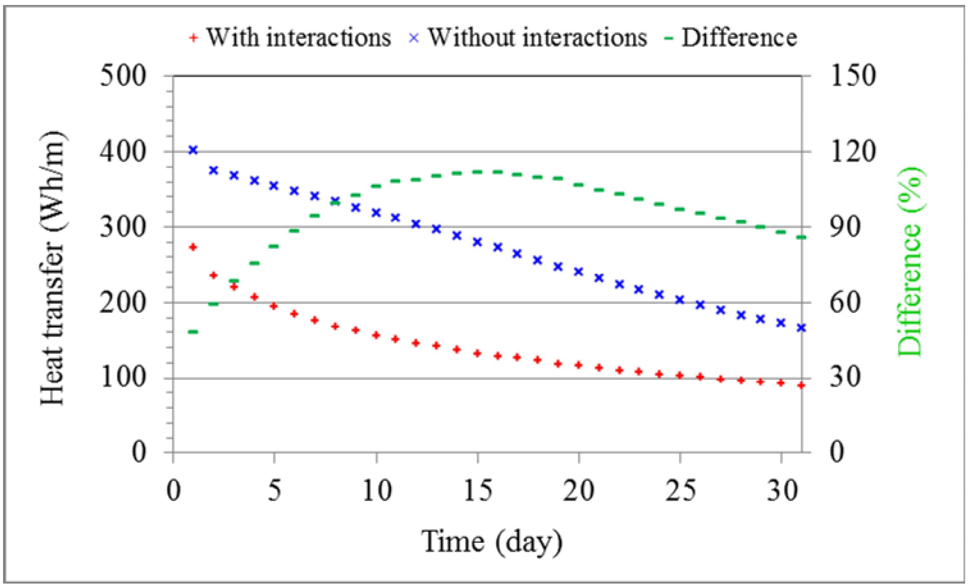
(b) Heat transfer rate

Fig. 11 Effect of interactions on the predicted variation in pipe temperature and heat transfer rate for a 10 m long heat exchanger

The degree of the interactions between the heat exchanger and the surrounding soil and atmosphere also varies along the air flow direction in the heat exchanger. These interactions lead to the increases in air and pipe temperatures but decrease in the heat transfer rate along the heat exchanger. Neglecting the interactions between the heat exchanger and the soil and ambient environments, however, the soil temperature given by Equation (13) does not vary horizontally. The predicted variation in the pipe temperature along the heat exchanger is therefore smaller but the variation in the air temperature is larger as the potential for heat transfer is larger near the air entrance. This is indicated in Fig. 7 by the higher heat transfer rate without considering the interactions compared with the prediction with the interactions for the first half of the pipe length. Also, the decrease in the heat transfer rate along the heat exchanger is larger without considering the interactions. As a result, at the end of Day 5, after air travels horizontally for about 22 m through the 40 m long heat exchanger, the heating potential and heat transfer rate without considering the interactions become smaller than those with the interactions. However, the mean heat transfer rate for the whole pipe is still larger without considering the interactions than that with the interactions, e.g. 10 W/m compared with 8.2 W/m at the end of Day 5 and 6.7 W/m compared with 5.3 W/m at the end of Day 30.



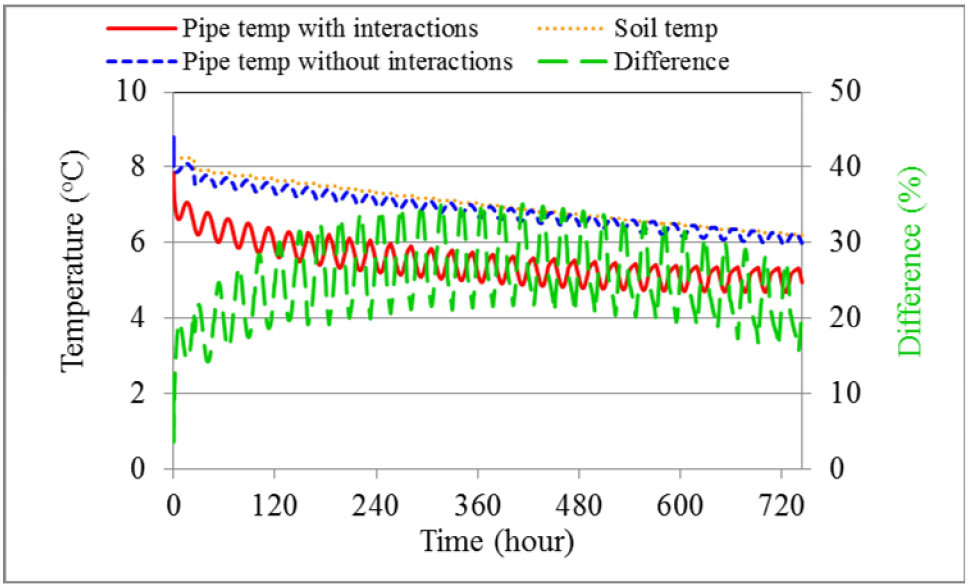
(a) Mean heat transfer rate



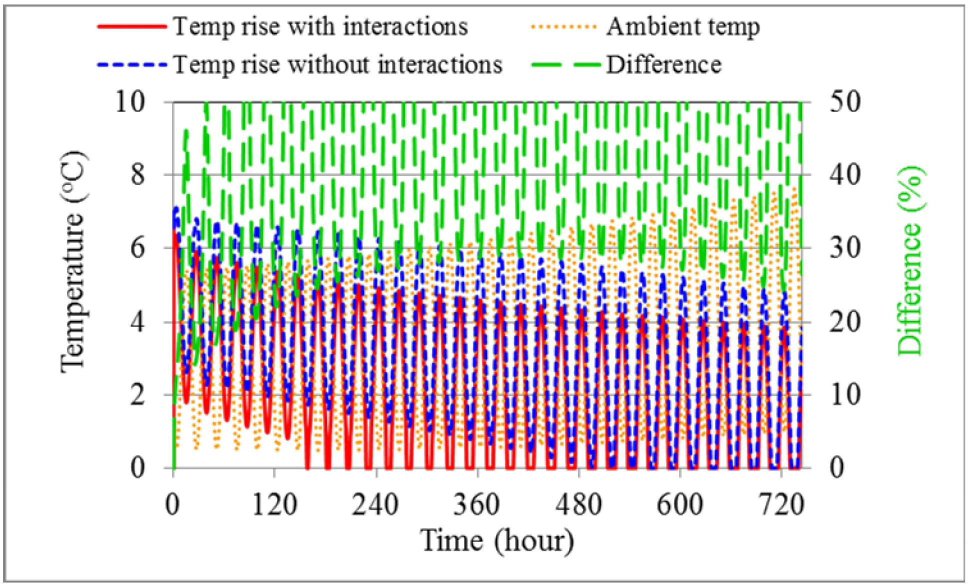
(b) Daily heat transfer

Fig. 12 Effect of interactions on the predicted variation in daily heat transfer through a 10 m long heat exchanger

As discussed above, the undisturbed soil temperature is higher than air temperature for most of days in the month when preheating of supply air would be possible if the interactions between the heat exchanger, soil and ambient environments were not taken into consideration. By comparing Fig. 10b with Fig. 10a, it is seen that, without considering the interactions, a 10 m long pipe could have reduced the temperature difference between soil and ambient air or daily air temperature swing by ½ compared with only 1/3 with consideration of the interactions and a 40 m long could have maintained a nearly constant temperature of supply air at the outlet with a deviation from the soil temperature of less than one half degree (cf 0.7^{o}C with interactions). However, due to the interactions, the real soil temperature near the heat exchanger would decrease and the achievable supply air temperature would be lower. Hence, the error or the difference between the predictions with and without considering the interactions would increase with operating time for the first half of the month as shown in Fig. 13 for a 40 m long heat exchanger. The difference decreases afterwards because the ambient air is warming up from then on and the decrease in the pipe surface temperature is slower when considering the interactions than that without. At the middle of the month (Day 16), the difference in the predicted pipe temperature for a 40 m long heat exchanger would be between 22.6% for the daytime and 35.4% for the night time. The daily average temperature difference in supply air between the inlet and outlet, i.e., air temperature rise, through a 40 m long pipe predicted with and without considering the interactions would be 3^{o}C and 4.2^{o}C, respectively, a difference of 42%. At the peak of the heat transfer process on the day (3am), the temperature rise is 4.4^{o}C and 5.3^{o}C, respectively, with and without considering the interactions and the (minimum) difference is 29%. In other words, neglecting the interactions would over predict the supply air temperature rise through a 40 m long pipe by as much as 2/5. This is similar to the difference in the predicted heat transfer rate. The difference in the amount of predicted heat transfer with and without considering the interactions would be even larger for the reasons mentioned before. Fig. 14 shows that the difference in the daily mean heat transfer rate and daily heat transfer would reach 40% and 59%, respectively, at the middle of the month.

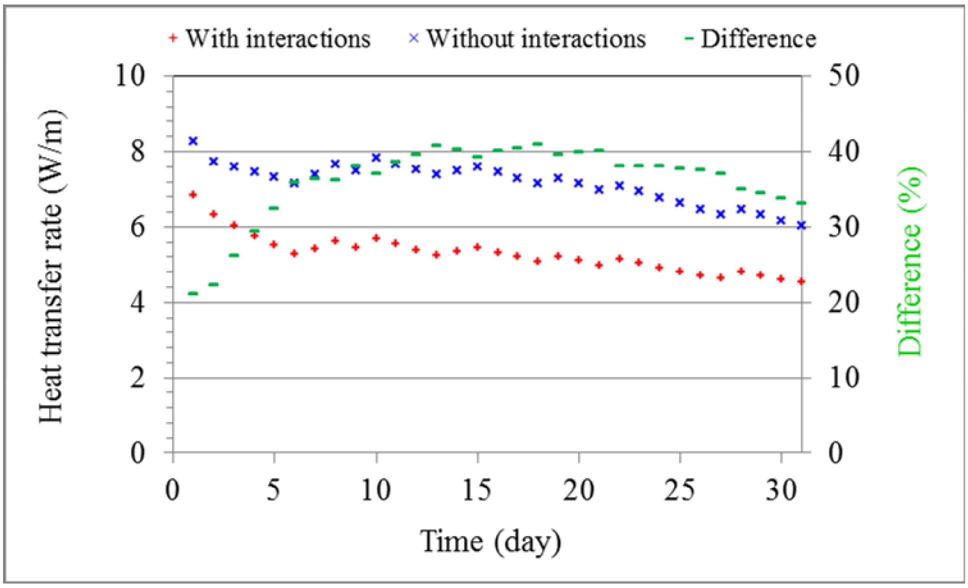


(a) Pipe temperature

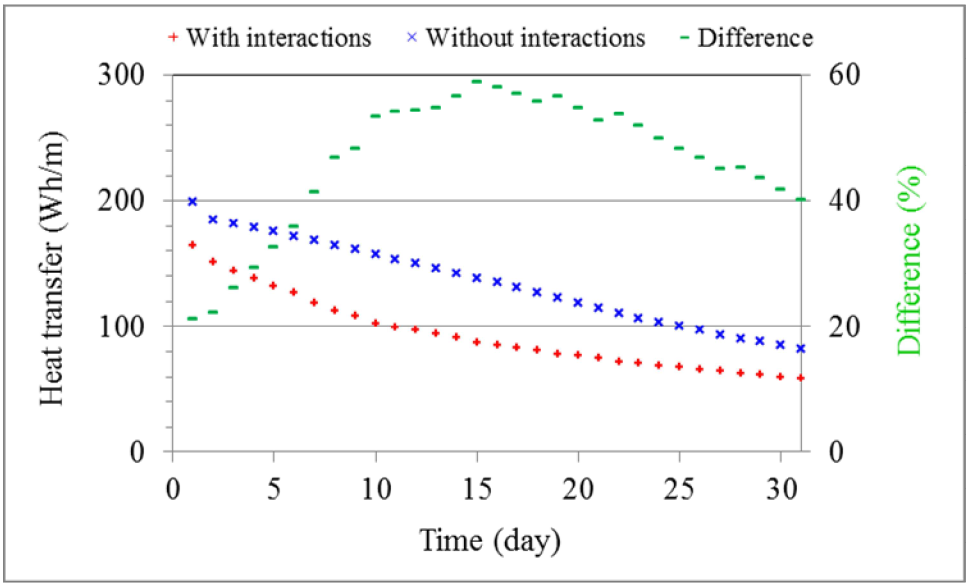


(b) Temperature increase of supply air

Fig. 13 Predicted variations with time of pipe and supply air temperatures for a 40 m long heat exchanger



(a) Daily mean heat transfer rate



(b) Daily heat transfer

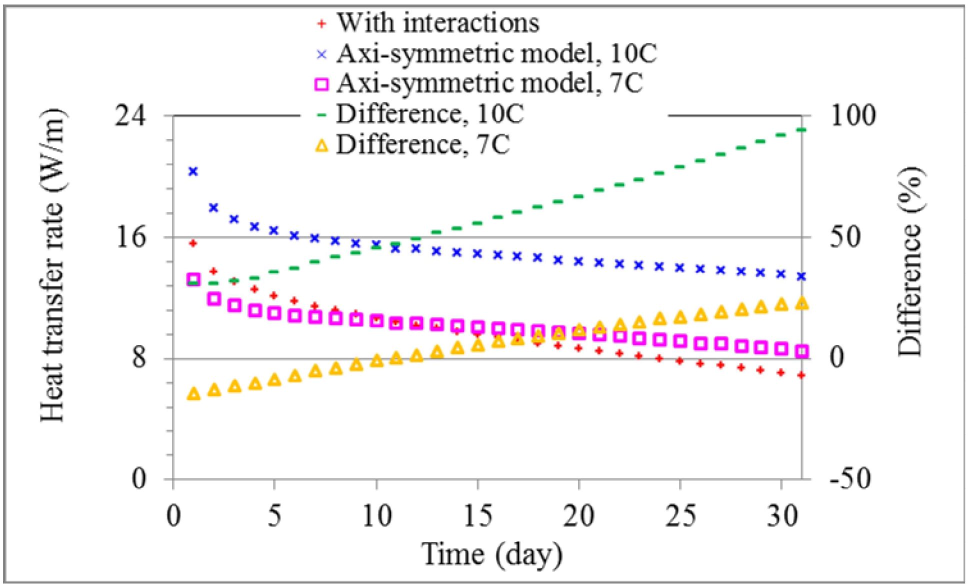
Fig. 14 Predicted heat transfer for a 40 m long heat exchanger

3.1.3 Effect of interactions between soil and atmosphere

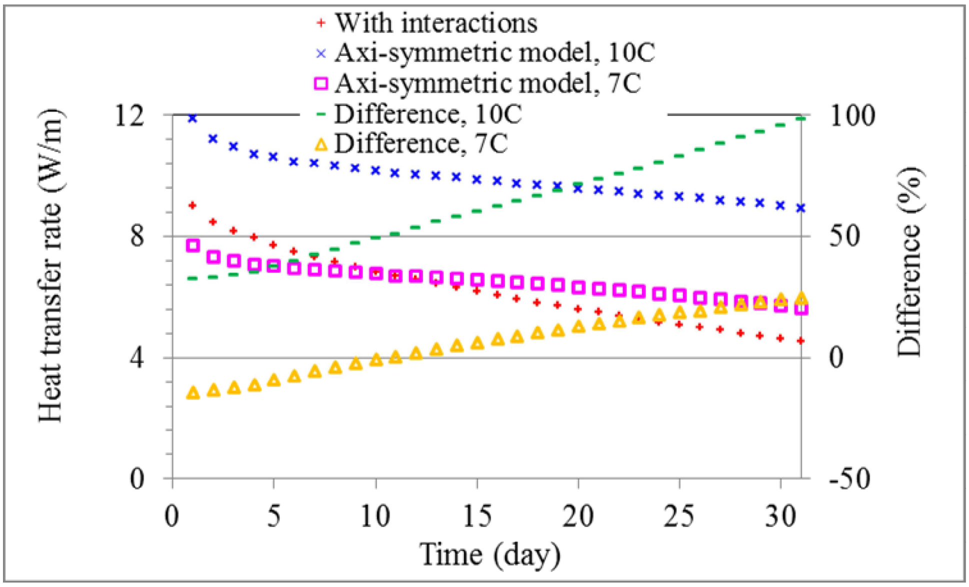
Some of the recent studies on the earth-air heat exchanger made use of commercial fluid flow software mainly to analyse air flow inside the heat exchanger and heat transfer between the heat exchanger and air using an axi-symmetric model [16]. This type of model neglected the interactions between soil and atmosphere and spatial variations in thermal and physical properties of soil, thus essentially assuming that the heat exchanger would be installed in deep soil with uniform properties rather than the shallow ground in practice.

To investigate the effect of neglecting the interactions and variations, additional simulations have been conducted where the initial soil temperature is set to be uniform as the deep soil temperature (10^{o}C) and the heat and moisture transfer at the soil surface as well as far-field soil boundary is taken to be zero. Meanwhile the heat exchanger is positioned at a great depth such that there would be no heat transfer across the boundary for the period of operation investigated. Fig. 15 shows that the heat transfer rate predicted with the axi-symmetric model is much higher than that predicted with full interactions. This results not only from increasing daily mean heat transfer rate but also from the excessive heating potential for non-stop operation for over three weeks. Besides, the percentage difference between the predictions is almost independent of the length of the heat exchanger, increasing from 31% and 32% for the 10 m and 40 m long heat exchangers, respectively, at the beginning to 94% and 98%, respectively, at the end of the month. Compared with the predictions using Equation (13) for the soil temperature, which includes indirectly the influence of varying atmospheric conditions but takes no account of the interactions between soil and the heat exchanger (Fig. 12 and Fig. 14), the axi-symmetric model would produce much worse results for the (40 m) long heat exchanger. For the (10 m) short heat exchanger the model could be better for predicting the performance in early days but eventually it would produce worse results near the end of the month as well. Moreover, Fig. 10c indicates that the outlet air temperature either increases with time for a short heat exchanger (to above the likely soil temperature which is unrealistic) or is almost independent of the time for a long heat exchanger after operation for a week or so when the soil temperature would in fact decrease with increasing time for this month. This is because the model could not take account of daily and seasonal soil temperature variations while employing a varying (increasing on the daily basis) ambient air temperature. Such results are obviously wrong.

Of course, the difference could be reduced using a soil temperature closer to operating conditions such as the temperature at the installation depth. However, as the soil temperature in the shallow ground varies significantly with time and depth, it is always a hit-and-miss process. For example, when a soil temperature of 7^{o}C (the mean temperature of undisturbed soil at the installation depth in January) is used as the far-field value as well as the initial value, compared with the model including the dynamic interactions, the axi-symmetric model would under predict the heat transfer rate for the first 10 to 11 days and then over predict the rate as shown also in Fig. 15. The maximum under-prediction is 15% for the first day and maximum over-prediction is 23% and 25% at the end of the month for the 10 m and 40 m long heat exchangers, respectively. The difference between the maximum under- and over-predictions of heat transfer in one month is between 38% and 40% and the difference would increase further as operation continues throughout the heating season. In addition, after a few days' operation, the outlet air temperature would change much on the daily basis and near the end of the month the air temperature would reach the temperature of undisturbed soil. Consequently, the model would not be able to predict the day-to-day variation in the temperature of supply air in trend or magnitude and thus would fail to provide reliable data for indoor thermal control. Therefore, the model cannot be used for system design or evaluation of the long term operational performance of an earth-air heat exchanger.



(a) 10 m long heat exchanger



(b) 40 m long heat exchanger

Fig. 15 Comparison of the daily mean heat transfer rate from 8pm to 9am predicted with full interactions and with the axi-symmetric model with a deep soil temperature of 10^{o}C or 7^{o}C

An axi-symmetric model for earth-air tunnel ventilation without association with the installation depth and the atmospheric conditions at the ground surface is inappropriate, if not fundamentally wrong, from the viewpoint of physics and mathematical modelling. The validity and reliability of the output is dependent on the inputs such as boundary conditions. The soil temperature and moisture in shallow ground are neither uniform nor axi-symmetric in most of the times in a year when an earth-air heat exchanger is in operation for preheating or cooling of supply air. For example, the soil temperature is generally lower near the ground surface in winter but higher in summer than deep soil. The temperature variation along the depth is more anti-symmetric than symmetric through the heat exchanger, as shown in Fig. 5. Besides, the main source of heat stored in shallow ground is solar radiation and the main processes of heat dissipation from the soil are convection, long wave radiation and evaporation through the top surface in winter. The heat capacity of shallow ground soil is therefore influenced much more by the atmospheric conditions than by geothermal energy. In the axi-symmetric model, however, soil is considered as if it were a giant limitless thermal reservoir like a geothermal energy source. The model will inevitably fail to predict the long term thermal performance of a horizontal ground heat exchanger.

3.1.4 Monthly performance

The performance of a heat exchanger and the impact of the interactions change not only daily but also monthly. Fig. 16 shows the predicted daily amount of heat transfer for three months - October, December and January - for a 40 m long heat exchanger. The heat transfer predicted with consideration of the interactions increases daily in October for the whole month because the air temperature decreases faster than does the relatively stable soil temperature and hence the heating potential – the temperature difference between the heat exchanger and air - increases. The predicted heat transfer decreases in December as well as January because the air temperature slowly approaches the minimum in the early December and increases afterwards. However, in terms of monthly mean performance, a combination of warm soil and ambient air results in a smaller preheating potential in October than other months investigated. As air temperature drops faster and further in winter, the preheating potential reaches the maximum monthly potential in December. The air temperature in January is actually lower than in December but the soil in the shallow ground is also cold by then. Consequently, the preheating potential in January is lower than December. The preheating potential would continue to decrease till the end of heating seasons as air gradually warms up while the increase in soil temperature lags behind.

Neglecting the interactions between the heat exchanger, soil and ventilating air through the use of Equation (13) would give rise to higher heat transfer for each of the months investigated. The predicted increase in heat transfer with operating time for October is even larger without considering the interactions than with consideration of the interactions and the difference between them also increases with time. By comparison, the predicted heat transfer for December decreases at a smaller rate without consideration of the interactions than with the interactions because of the lower rate of the decrease in soil temperature in the first half of the month and the time lag of the increase in soil temperature in the second half. Accordingly, the difference between the predictions increases in the first half of the month and the overall effect of neglecting the interactions using Equation (13) is the largest in December. The reason for the largest difference for December is because the afore-mentioned largest heating potential would cool the surrounding soil by the heat exchanger fastest which could not be taken into account in Equation (13). In terms of the daily heat transfer, the maximum over-prediction is 72% in the mid-December.

The level of the difference using the axi-symmetric model compared with the model taking account of all the interactions is dependent on the deviation of the initial temperature (often of deep soil) used in simulation from the soil temperature which varies with time and depth. The model would under predict the thermal performance for periods of time such as October when the temperature of shallow ground (at the installation depth) is higher than the annual mean value used for simulation but would otherwise over predict the performance as for January and all but first few days of December. When the soil temperature differs significantly from the annual mean value, the under- or over-prediction using the axi-symmetric model would be much larger than that using Equation (13). For heating in October, e.g., the difference in the daily heat transfer from the prediction with consideration of all the interactions increases with operating time using both the axi-symmetric model and Equation (13). However, using the annual mean temperature for initialisation would lead to higher air temperature than soil temperature in the daytime for the whole month and so preheating of supply air would only be feasible during night time. The axi-symmetric model would thus significantly under predict the performance whereas using Equation (13) would over predict the performance. As mentioned above, using Equation (13) would produce larger over-prediction for December than that for other months. In contrast, the axi-symmetric model would yield similar results to those with consideration of the interactions in the early days of this month when the soil temperature at the depth of the heat exchanger happens to be close to the annual mean value (see Fig. 5). However, if simulation were continued from previous months as likely in practice for heating, the shallow ground would have been cooled down by the heat exchanger and the results for these days using the axi-symmetric model would also differ significantly from those considering the interactions. Besides, the difference for December increases daily and the total difference for the whole month is over 120%, i.e. the predicted heat transfer rate at the end of the month using the axi-symmetric model is more than double the value predicted with consideration of all the interactions. For January, the difference in the daily heat transfer using the axi-symmetric model increases with operating time while the difference using Equation (13) peaks in the middle of the month. Thus, the level of over-prediction using the axi-symmetric model is much more than that using Equation (13).

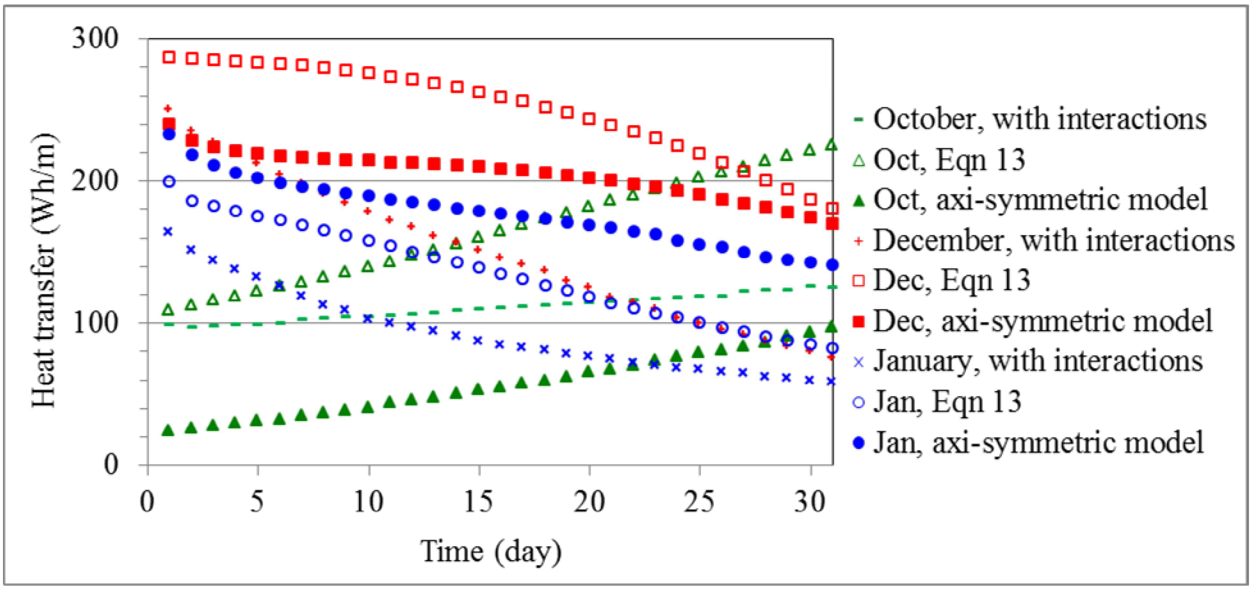


Fig. 16 Predicted daily heat transfer for a 40 m long heat exchanger for three months

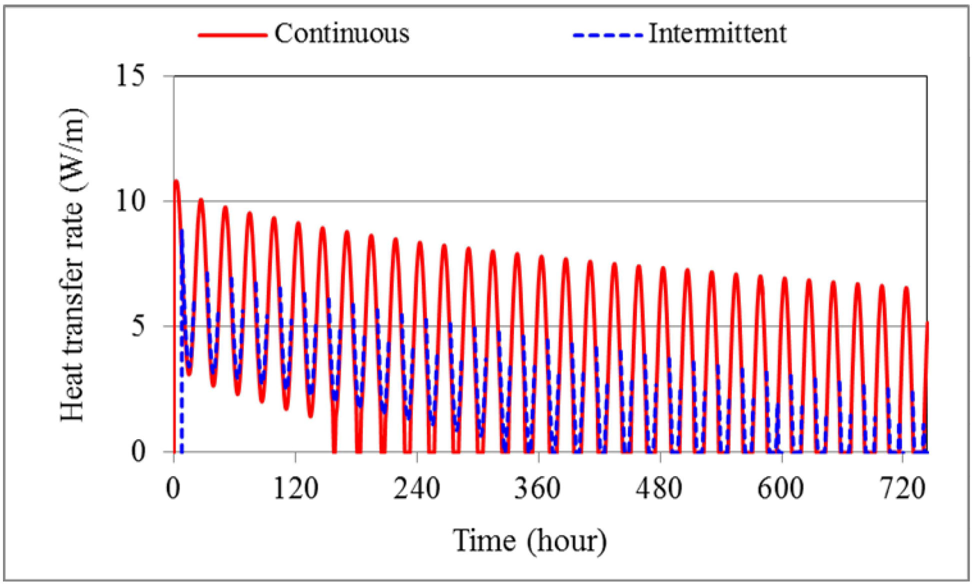
3.2 Intermittent operation

As seem from the results for continuous operation, heat extraction from soil may not be possible continuously even in the coldest months of the year. Simulations have therefore also been performed for two settings of intermittent operation – one for 12 hours for potential tunnel ventilation from 8am to 8pm and another for six hours from 8am to 2pm. Accurate simulation involving full interactions for intermittent operation is an extremely slow process as small time steps have to be used each time the mode of operation is switched in order to capture the rapid variations of temperature and moisture with time. Simulation with the soil temperature calculated from Equation (13) is however independent of the mode of operation if the effect of heat storage by the heat exchanger is ignored. The axi-symmetric model is not used for simulation of intermittent operation as it is not suitable for analysis of heat transfer in shallow ground unless consideration is given to the thermal and moisture interactions with atmosphere at the soil surface.

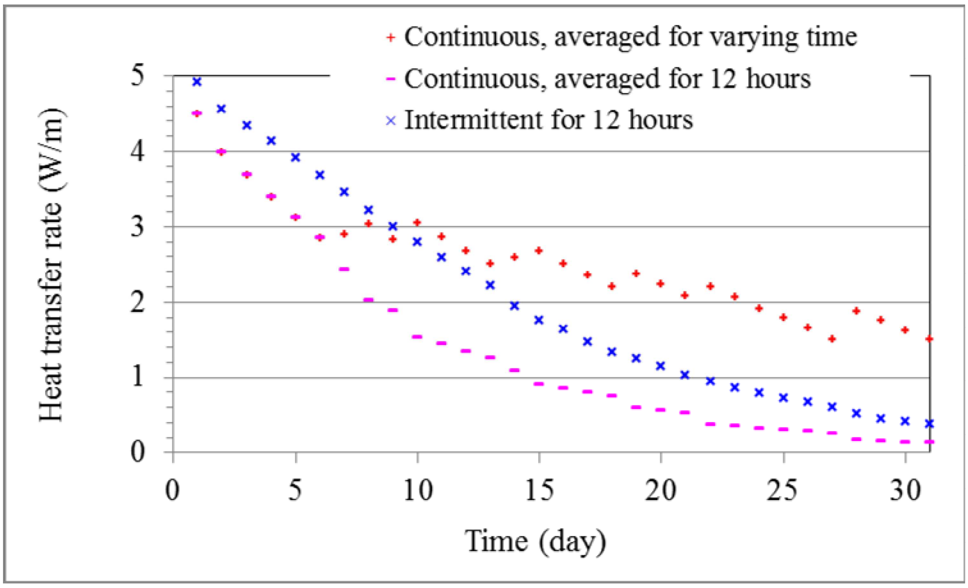
3.2.1 Ventilation between 8am and 8pm

The predicted heat transfer for intermittent operation is compared with that for continuous operation in Fig. 17. Note that the heat transfer rate at the beginning is very low for intermittent operation from the equilibrium conditions at 8am (Fig. 17a) whereas the heat transfer rate at 8am for continuous operation starting from the midnight has already passed its peak for the day. It is seen from Fig. 17b that the heat transfer rate for intermittent operation in the daytime is higher than that for continuous operation in the same period of operation for nine days. However, the heat transfer rate averaged for the operating time for intermittent operation afterwards decreases to less than the corresponding value for continuous operation. This is because for continuous operation air temperature would be higher than the pipe temperature at the inlet during the hours around the noon and heat is not available for extraction. As a result, the average heat transfer rate during the reduced operating period (e.g. four hours on Day 15) is higher than that averaged for the 12-hour intermittent operation. Of course, the rate averaged for the 12 hour period would never be lower for intermittent operation than that for continuous operation as is seen from the same figure.

Even so, the daily mean heat transfer rate predicted without considering the interactions using Equation (13) is still higher than that with consideration of interactions for intermittent operation in the same daytime period, increasing from 12% on Day 1 to 40% on Day 10 for a 40 m long pipe (Fig. 18). The difference would be larger for shorter heat exchangers; it is 32% for Day 1 and 84% for Day 10 for a 10 m long heat exchanger. The maximum difference occurs on Day 18 with 127% and 79% for the 10 m and 40 m long heat exchangers, respectively. The percentage difference between the predictions with and without consideration of the interactions is less for intermittent operation than that for continuous operation in the early days of operation. However, the percentage difference from Day 10 is larger for intermittent operation than that for continuous operation because the magnitude of heat transfer during the daytime is lower than that for the night time (comparing Fig. 18 with Fig. 12 and Fig. 14). For example, on the 10^{th} day, the mean heat transfer rate through a 40 m long heat exchanger for the 12-hour intermittent (daytime) operation (in which mode, however, heat would not be available for extraction during six hours of the daytime) is 2.8 W/m compared with the mean value of 7.0 W/m for the 12-hour night time for continuous operation.



(a) Instantaneous heat transfer rate



(b) Mean heat transfer rate

Fig. 17 Comparison of the predicted heat transfer rate through a 40 m long heat exchanger between intermittent and continuous operation in January

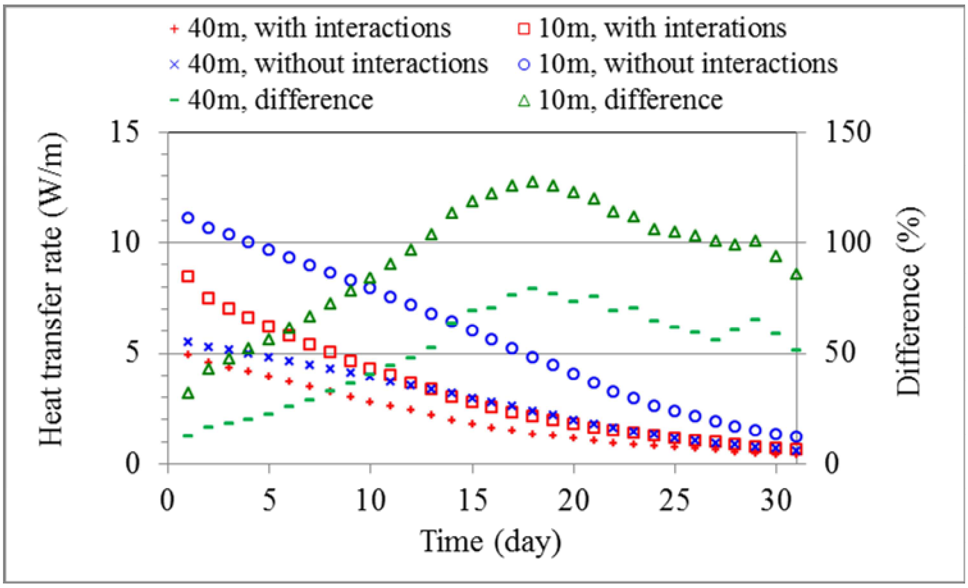


Fig. 18 Comparison of the daytime mean heat transfer rate predicted with and without interactions for 12-hour intermittent operation in January

3.2.2 Ventilation between 8am and 2pm

When the operating period is reduced from 12 hours to six hours, the daily mean heat transfer rate per unit length is increased by about 1 W/m and 0.5 W/m for 10 m and 40 m long heat exchangers, respectively, for the first half of the month. The percentage increase is almost linear from 12% on Day 1 to 25% on Day 15 for the 10 m long heat exchanger and 9% on Day 1 to 22% on Day 15 for the 40 m long heat exchanger.

The difference between the predicted heat transfer with and without considering the interactions decreases on average by about 26% to 29% when the operating period is reduced from 12 hours to six hours. The percentage difference in the daily mean heat transfer rate for 6-hour intermittent operation increases from 9% on Day 1 to 28% on Day 10 for a 40 m long heat exchanger and from 26% for Day 1 to 62% for Day 10 for a 10 m long heat exchanger. The difference increases further, e.g., to 89% and 49% for Day 15 for 10 m and 40 m long heat exchangers, respectively. The difference on Day 15 is already higher than that for continuous operation. Hence, the maximum percentage difference between the predictions with and without consideration of the interactions is still larger for this reduced duration of intermittent operation than that for continuous operation.

4 CONCLUSIONS

A three dimensional numerical model has been developed for simulation of the dynamic thermal performance of earth-air heat exchangers for preheating of supply air. The effects of the heat exchanger length and dynamic interactions between the heat exchanger, soil and ambient environments have been investigated for continuous and intermittent operation. It has been found that the heat transfer rate decreases along the heat exchanger and the rate of decrease is non-linear. Consequently, the heat transfer rate and temperature rise of supply air per unit length decrease with increasing length of the heat exchanger for preheating. However, the overall amount of heat gain and temperature rise of supply air increase with the length.

It has also been found that direct thermal and moisture interactions between a heat exchanger, soil and atmosphere have a significant impact on the heat transfer through the heat exchanger. Neglecting the interactions between the heat exchanger and surrounding environments or between soil and atmosphere would significantly over or under predict the heat transfer rate. Using an analytical expression for the annual soil temperature variation which neglects the interactions between the heat exchanger, soil and ventilating air would over predict the thermal performance of an earth-air heat exchanger. The larger the preheating potential of a system of ground heat exchanger, soil and atmosphere, the larger the over-prediction. Design of a building ventilation system based on this method would lead to more in-use heating energy than predicted. An axi-symmetric model that neglects the interactions between the soil surface and atmosphere would fail to produce reliable data for long-term operational performance of the earth-air heat exchanger installed in shallow ground and such a model is not suitable for system design.

The impact of over-prediction with regard to long term performance without considering the interactions is found to be larger for intermittent operation than for continuous operation when applied to climate conditions such that the potential heat transfer rate is lower in a period of a day when there is a need for heating than the rest of the day. As intermittent operation is more likely an operating regime in practice, it is imperative to use dynamic thermal simulation based on a three-dimensional numerical model that takes account of all the thermal and moisture interactions in order to provide accurate data for design and analysis of an earth-air ventilation system.

The computer program will be used for assessing the effects of other parameters on the performance of earth-air heat exchangers such as the heat exchanger size, installation depth and distance between parallel pipes, building load, ventilation rate, type of soil and climate.

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