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Dynamic interactions between the ground heat exchanger and environments in earth–air tunnel ventilation of buildings

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ABSTRACT

Earth–air tunnel ventilation is an energy efficient method of preheating or cooling of supply air to a building. The purposes of this study are to investigate the performance of earth–air heat exchangers under varying soil and atmosphere conditions and the interactions between the heat exchanger and environments. A computer program has been developed for simulation of the thermal performance of an earth–air heat exchanger for preheating and cooling of supply air, taking account of dynamic variations of climatic, load and soil conditions. The program solves equations for coupled heat and moisture transfer in soil with boundary conditions for convection, radiation and evaporation/condensation that vary with the climate both at the soil top surface and inside the heat exchanger. The importance of dynamic interactions between the heat exchanger, soil and atmosphere is illustrated from the comparison of the heat transfer rates through the heat exchanger. The predicted heat transfer rate varies with operating time and decreases along the passage of air in the heat exchanger. Neglecting the interactions would significantly over-predict the heat transfer rate and the amount of over-prediction increases with operating time.

1. Introduction

Earth–air tunnel ventilation is considered to be an energy efficient means of preheating and cooling of supply air to a building. A key component of a tunnel ventilation system is a ground or earth–air heat exchanger (EAHX) composed of a series of pipe or duct buried below ground for transferring heat between the supply air in the pipe and the surrounding soil with a relatively stable temperature. The heat exchanger can be made of concrete, metal or plastic and the most commonly used material is plastic such as high density polyethylene for small pipes and concrete for large pipes.

The concept of using the stable soil temperature for preheating or cooling of air for building ventilation has been tested since the ancient Greek and Persian times. One of the first modern applications of EAHX was for agricultural buildings such as greenhouses [1–4]. In recent years, the EAHX system has been applied to different types of building in different climates. Breesch et al. [5] used an EAHX for winter preheating and summer precooling of an office building in Belgium. Al-Ajmi et al. [6] showed that an EAHX could potentially reduce cooling energy demand by 30% over the peak summer season for a typical house in a hot and arid climate in Kuwait. The thermal behaviour of EAHXs has also been studied for a unique building called 'Casa Ventura' in Brazil [7] and for buildings under three different climatic conditions in Mexico [8]. Because EAHX systems alone are often insufficient to meet the thermal comfort requirements in summer conditions, Misra et al. [9] used a hybrid EAHX to enhance the efficiency of an air conditioner in India whereas Bansal et al. [10] integrated an evaporative cooler with an EAHX to minimise the use of an air conditioner.

The performance of earth–air heat exchangers has been investigated by many researchers using analytical or numerical techniques validated with experimental measurements. Bisoniya et al. [11] have recently provided a review on experimental and analytical studies of EAHX systems. The simplest analytical model is based on the thermo-hydraulic analysis of the EAHX for given soil and air properties [12]. To take account of the daily and seasonal variations of soil and air temperatures, a set of analytical equations representing the effects of climate and soil properties can be incorporated into this type of model [13]. Analytical models are generally based on the simplified solution of one dimensional (axi-symmetrical) heat transfer in a circular pipe or the surrounding soil of homogeneous properties. Different forms of analytical models have been developed to predict the heat transfer through the ground heat exchanger systems [14–16]. However, heat and moisture transfer in shallow soil surrounding a heat exchanger is neither axi-symmetric normal to the pipe nor varying uniformly along the

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pipe for long term operation due to the influence of daily and seasonal climatic variations and interactions between soil and the heat exchanger. For more realistic simulation, therefore, numerical solution of a three-dimensional model is required and this type of numerical heat transfer model has been developed or applied by a number of researchers [17–21] to predict the performance of EAHXs. Both analytical and numerical models allow parametric analysis to be performed such as air and soil properties and pipe size but the numerical model would also enable additional parameters such as non-uniform soil properties and pipe configurations to be analysed. Tzaferis et al. [22] compared eight different heat transfer models for evaluating the performance of EAHXs and found that most of them gave rise to similar results and that all of them were able to predict the general trend of the performance in terms of the outlet air temperature but none of them was accurate for predicting the patterns of daily variation.

In an earth–air tunnel ventilation system, simultaneous heat and moisture transfer could occur in soil and in the pipe. Hollmuller and Lachal [23] developed a numerical model for the sensible and latent heat transfer inside the ground pipe and examined the potential of the ground pipe systems for winter preheating and summer cooling. Gauthier et al. [24] not only developed a three-dimensional model for heat transfer in soil but also accounted for the sensible and latent heat transfer in the heat exchanger. Based on the work of Puri [25], Santamouris et al. [2] and Mihalakakou et al. [26] developed an axi-symmetric model of heat and mass transfer for the calculation of temperature and moisture in the pipe and soil and this was used for the prediction of the thermal performance of EAHXs. Darkwa et al. [27] also presented equations for axi-symmetric heat and moisture transfer in soil but did not provide the solution. Instead, the soil temperature was obtained from the analytical model developed by Lee and Strand [13] for evaluating the performance of an earth–air ventilation system.

This study aims to develop a numerical model for the simulation of transient heat and moisture transfer in soil with a horizontally coupled EAHX for preheating and cooling of buildings. The model takes account of interactions of heat and moisture transfer in soil and between the soil, heat exchanger, supply air (air passing through the heat exchanger) and ambient conditions.

2. Theory

Simulation of simultaneous heat and moisture transfer in a system of earth, air and heat exchanger is carried out through numerical solution of energy and mass conservation equations for soil together with the heat and mass balance as the boundary conditions at the interfaces between earth and atmosphere and between the heat exchanger and supply air.

2.1. Model equations

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

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

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

where ρ, C and k are the density (kg/m^3), specific heat (J/kg K) and thermal conductivity (W/m K) of soil, respectively; T is the temperature of soil (K); t is the time (s); 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 (i.e. water) (kg/m^3); Θ is the volumetric moisture content (m^3/m^3); q_v is the volumetric heat production/dissipation rate (W/m^3); $D_{T,l}$ and $D_{T,v}$ are the thermal liquid and vapour moisture diffusivities, respectively, (m^2/s K); $D_{\Theta,l}$ and $D_{\Theta,v}$ are the isothermal liquid and vapour moisture diffusivities, respectively, (m^2/s); K is the hydraulic conductivity of soil (m/s); z is the vertical coordinate (m); Θ_v is the source/sink of moisture (m^3/m^3 s).

The moisture diffusivities are defined as follows:

$$D_{T,l} = K\frac{\partial\Psi}{\partial T} \quad (3)$$

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

$$D_{\Theta,l} = K\frac{\partial\Psi}{\partial\Theta} \quad (5)$$

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

The matric potential Ψ (in m) and hydraulic conductivity of soil K are given by the following pedo-transfer functions of moisture content [28,29]

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

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

In Eqs. (3)–(8), b is constant dependent on the type of soil, D_v is the diffusion coefficient of water vapour in air (m^2/s), $f(\Theta)$ is the fractional volume of gas-filled pores ($f(\Theta) = \Theta_s - \Theta$), K_s is the saturated hydraulic conductivity (m/s), α is the tortuosity factor for diffusion of gases in soil, Ψ_s is the saturated matric potential or capillary pressure (m), Θ_s is the saturated volumetric moisture content (m^3/m^3) and ρ_v is the density of water vapour (kg/m^3).

The thermal and physical properties of a soil mixture can vary with temperature, location and time as well as its constituents such as the moisture content. The density, specific heat and thermal conductivity of a soil mixture are represented by the following functions of the volumetric composition of dry solid matter and three phases of moisture–liquid water, water vapour and solid ice:

$$\rho = \rho_d\theta_d + \rho_l\theta_l + \rho_i\theta_i + \rho_p\theta_p \quad (9)$$

$$\rho C = \rho_d C_d\theta_d + \rho_l C_l\theta_l + \rho_i C_i\theta_i + \rho_p C_p\theta_p \quad (10)$$

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

where θ is the volumetric fraction of a constituent; subscripts d, l, i and p represent dry soil, liquid moisture, ice and gas-filled pores, respectively, and m is the mth component of dry soil. f_i, f_p and f_m are the ratios of the average temperature gradient of the constituent (ice, pores and the mth component of n types of dry soil grains) to that of water and are given by the following equation [30]:

$$f_x = \frac{1}{3}\sum_{j=a}^{c}\left[1 + \left(\frac{k_x}{k_l} - 1\right)g_j\right]^{-1} \quad (12)$$

where subscript x is i, p or m; g_a, g_b and g_c depend on the ratios of the axes of the grains and the sum of them equals to unity.

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

$$k_p = k_a + LD_v\phi\frac{p_{atm}}{p_{atm} - p_v}\frac{d\rho_{vs}}{dT_v} \quad (13)$$

where ϕ is the relative humidity of soil air, p_{atm} is the atmospheric pressure (Pa), p_v is the partial pressure of water vapour (Pa), ρ_{vs} is