MODELLING THE THERMAL PERFORMANCE OF EARTH-TO-AIR HEAT EXCHANGERS

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Abstract—A new complete numerical model for the prediction of thermal performance of the earth-to-air heat exchangers is presented. The model describes the simultaneous heat and mass transfer inside the tube and into the soil accounting for the soil natural thermal stratification. The model is validated against an extensive set of experimental data and it is found accurate. The proposed algorithms are suitable for the calculation of the temperature and humidity variation of the circulating air and for the temperature and humidity distribution inside the ground. The presented model was developed within the TRNSYS environment and can be easily coupled with building or greenhouse simulation codes in order to describe the impact of the earth-to-air heat exchangers to indoor environments.

1. INTRODUCTION

The use of earth-to-air heat exchangers for heating and cooling of buildings and agricultural greenhouses has gained ground during the last few years, (3,14). The design of such a system involves optimisation of its geometrical characteristics as well as of the air-flow levels and the depth of the buried pipes. In this respect various simplified and detailed models have been proposed for this purpose. Recent evaluation (21) of seven different simplified models, (5,6,8,13,15,16,18), leads to the conclusion, that almost all the proposed algorithms can predict with sufficient accuracy the temperature of the outgoing air from the tubes. However, these models are characterised by a limited applicability as they do not take into account the latent heat transfer phenomena between the air and the pipe and they cannot predict the humidity of the circulating air. Lack of knowledge on the moisture content of the circulated air does not allow for a complete evaluation of the comfort conditions in the building.

Furthermore, most of the simplified models ignore heat transfer phenomena (sensible and latent) in the ground and, therefore, the distribution and the variation of the ground cannot be predicted. The ground temperature is of importance especially for agricultural greenhouse applications where this parameter plays a basic role.

Detailed simulation models of the thermal performance of the earth-to-air heat exchangers are mainly based on algorithms describing the simultaneous transfer of heat and mass in soils with a temperature gradient (1,2,10,11,12,17,20). However, most of the models consider an axially symmetric heat flow into the ground. This heat flow does not take into account the natural thermal stratification in the soil which alters this symmetry.

The objective of this paper is to present a more accurate and validated, transient, implicit numerical model based on coupled and simultaneous transfer of heat and mass into the soil and the pipe. The model includes a complete mathematical description of moisture migration through a soil with a temperature and, therefore, a moisture gradient which tends to redistribute the moisture content. The two inter-related phenomena are also described and since the final outcome depends on both the magnitude of the temperature and the moisture gradients. The natural thermal stratification in the soil is also considered while the soil boundary conditions are applied at the ground surface.

The model was validated against a long set of experimental data. The present model can accurately predict the temperature and the humidity of the circulating air as well as the distribution of the temperature and humidity into the soil. The proposed model is developed inside the TRNSYS programme environment, in order to be easily coupled with algorithms describing the dynamic performance of buildings as well as any other algorithm developed inside this code.

2. MODELLING OF EARTH-TO-AIR HEAT EXCHANGERS

The transient earth-to-air heat exchanger axisymmetric system has been expressed in polar coordinates with three independent variables (r, φ, t) and two dependent variables (T, h). A typical earth tube system is shown in Fig. 1.

The equation of energy balance, as it has been proposed by Ahmed (1980) and Puri (1986), can be written as follows:

$$\rho \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{\sin \phi} \frac{\partial}{\partial \phi} \left( \sin \phi \frac{\partial T}{\partial \phi} \right) - \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{\partial h}{\partial r} \right) - 4 \rho \phi \frac{\partial}{\partial \phi} \left( \frac{\partial h}{\partial \phi} \right)$$

(1)
The initial conditions are the following:

\[ T(r, y, t) = T_0(r) \]
\[ h(r, y, t) = h_0(r) \]

where \( T_0 \) and \( h_0 \) are the initial temperature and moisture content, respectively. The specific conditions are:

1. At \( r = R_o \), where \( R_o \) is the radius of the soil, the temperature and moisture distributions are not influenced by the coupled and simultaneous transfer of heat and mass into the soil caused by the presence of the earth-to-air heat exchanger system. This far-field boundary for temperature and moisture profiles in the soil has been used by Schiller (1982), Puri (1986), and Ahmad (1980). Thus, the temperature at \( r = R_o \) is the undisturbed soil temperature. The moisture profile was determined using an extensive set of moisture measurements and predictions for dry and very dry soils presented in Ahmed and Shapiro (1975). The component of moisture flux due to temperature gradient and

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( D_r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial y} \left( D_y \frac{\partial T}{\partial y} \right) \]

is the component of moisture flow due to temperature gradient and

\[ T(r, y, t) = T_0(r) \]

The calculated heat transfer in the soil is equal to the amount of heat losses as air flows along the pipe.

\[ G(T_s(y) - T(R_p, y, t)) - m_C \frac{dT_s(y)}{dy} \]

where \( G \) is the overall thermal conductance of the earth-to-air heat exchanger system including air, pipe, and soil. Thus, \( G \) can be expressed as:

\[ \lambda \frac{\partial T}{\partial y} \]

The boundary conditions are:

1. co-ordinate \( r \):
   a. at \( r = R_o \)
   \[ \frac{\partial T}{\partial r}(R_o, y, t) = 0 \]
   \[ T(R_o, y, t) = T(R_o) \]

2. co-ordinate \( y \):
   a. at \( y = y_a \)
   \[ T(r, y_a, t) = T(r) \]
   \[ h(r, y_a, t) = h_0(r) \]
   b. at \( y = y_b \)
   \[ T(r, y_b, t) = T(r) \]
   \[ h(r, y_b, t) = h_0(r) \]

The discretization equations were derived by integrating the differential eqns (1) and (2) over each control-volume and over the time interval from \( t \) to \( t + \Delta t \). The order of this integration was chosen according to the nature of the term. For the representation of the terms \( \Delta T/\Delta t \) and \( \Delta h/\Delta t \) it was necessary to make a profile assumption or an interpolation formula. The simplest possibility was to assume that the value of \( T \) or \( h \) at a grid point prevails over the control-volume surrounding it. For this profile, the slope \( \Delta T/\Delta r \) or \( \Delta h/\Delta y \) was not defined at the control-volume faces. A profile that does not suffer from this difficulty is the piecewise-linear profile. In this study, linear interpolation functions were used between the grid points.

The time dependency was best handled using implicit integration techniques. The fully implicit scheme satisfies the requirements of simplicity and of physically satisfactory behaviour. It should be noted that, while constructing the discretization equations, it was not assumed that a particular method would be used for their solution. It was useful to consider the derivation of the equations as two distinct operations, and was not necessary for the choices in one to influence the other.

In this study the algebraic equations were solved using the Gauss-Seidel iterative method. According to this method the values of the variable were calculated using each grid point in a certain order.

The programme has been developed inside the TRNSYS environment. TRNSYS is a transient system simulation programme with a modular structure which facilitates the addition to the programme of mathematical models not included in the standard TRNSYS library.
Fig. 4. Measured and predicted soil temperature (°C) at a distance of 3 m from the pipe's inlet.

Fig. 5. Comparison of the measured and predicted soil temperature (°C) at 30 cm distance from the soil surface, 80 cm above the pipe, and 7 m y-distance from the pipe inlet.

Fig. 6. Comparison of the measured and predicted soil temperature (°C) at 60 cm below the ground surface, 50 cm above the pipe, and 7 m y-distance from the pipe inlet.

this research in order to provide a basis for the verification of the accuracy of the mathematical model. For this purpose, a plastic pipe of 0.150 m in diameter and 14.8 m in length was buried in the soil at about 1.10 m in depth. The air velocity in the pipe was 10.5 m/ sec. The temperature of the air and soil were monitored at different depths below and above the buried pipe. It was not possible to take moisture measurements for this experiment but the soil was very dry. A drawing of this experiment can be found in Fig. 1.

The experiments were performed during the summer and last 15 days. Data of the air temperature as well as the temperature of the soil below and above the pipe were recorded at 10 minute intervals throughout the experiments. In addition, hourly outdoor air temperature measurements were taken every day during the experiment.

The results of the experiment are compared with the theoretical calculations. Figure 2 shows the variation of the measured and calculated air temperature at the outlet of the pipe as well as the fluctuation of the outdoor temperature during the experiment. As shown in this figure, there is an excellent agreement between the theoretical and the measured data while the outdoor air temperature has been fluctuated between 17 and 33.5°C. Also, from the same figure, it can be seen that the fluctuation of the air temperature at the pipe outlet follows the fluctuation of the outdoor temperature. In order to show that the variation of the air temperature inside the pipe is accurately predicted, Fig. 3 compares the observed with the calculated values of the air temperature at a distance of 3 m from the pipe entry. As shown, there is an excellent agreement between the observed and the predicted values.

In Fig. 4 the variation of the soil temperature as recorded at a depth of 0.9 m below the ground surface and 0.2 m above the pipe is compared with the theoretical predictions. The y-distance from the pipe inlet was equal to 7 m. As shown, there is an excellent agreement between the predicted and the measured values for the soil temperature. The maximum difference between the predicted and the measured values rarely exceeds 0.3°C. The same agreement between the predicted and the observed temperatures is obtained for two points located at a depth of 0.3 and 0.6 m below earth's surface and at a distance from the pipe of 0.8 and 0.5 m, respectively, while the y-distance from pipe inlet remained equal to 7 m (Figs. 5 and 6).

4. CONCLUDING REMARKS

An accurate, transient, implicit numerical model based on coupled heat and mass transfer has been developed to describe earth-tube system thermal performance. The superposition technique was used to analyse the influence of the temperature field due to the ground surface temperature on the soil temperature at any point in the pipe vicinity.

The proposed model was validated against experimental data and was found to accurately predict the temperature of the circulated air and the temperature distribution of the ground, as well as the overall thermal performance of the earth-to-air heat exchangers.

NOMENCLATURE

Greek characters

\[
\begin{align*}
\alpha & \quad \text{thermal diffusivity (m}^2/\text{s}) \\
\beta & \quad \text{specific heat capacity (kJ/kgK)} \\
\rho & \quad \text{density of moisture (kg/m}^3) \\
\mu & \quad \text{density of soil (kg/m}^3) \\
\end{align*}
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