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Analysis of the accuracy and sensitivity of eight models to predict the performance of earth-to-air heat exchangers

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Abstract

Eight different algorithms predicting the performance of earth-to-air heat exchangers are evaluated. The sensitivity of the methods to the inlet air temperature, air velocity, pipe length, pipe radius and the pipe depth is examined. Two different types of experiments have been designed and performed, and experimental results have been compared with the set of the predicted values. The relative accuracy of each algorithm is estimated and reported for both cases.

1. Introduction

Passive and hybrid cooling systems and techniques can contribute decisively to the cooling of buildings reducing therefore the peak electricity load of utilities and preserving the environment [1].

The use of the ground as a sink for dissipation of the excess heat of buildings is a well-researched area [2–4]. Hybrid ground cooling systems and especially earth-to-air heat exchangers have gained an increasing acceptance during the last years [5–15]. Here air is circulated through buried pipes using fans. Due to the temperature difference between the ground and the air, the air temperature decreases. The main advantages of the system are its simplicity, high cooling potential, low capital, operational and maintenance cost and environmental protection.

The use of such a system requires a quite difficult dimensioning process, involving optimization of its length, diameter, depth and airflow. For this purpose various algorithms have been proposed. Each algorithm is deduced from and is validated for a specific set of parameters, i.e., a certain depth, a flow rate, a length, a diameter, etc.

However there is an important dependence and variability of the system's performance as a function of its thermal and geometrical characteristics. Consequently such algorithms are not automatically accurate for every set of parameters and therefore a more detailed validation is required.

The aim of the present paper is to contribute to the validation of the algorithms by examining their accuracy for various data sets, and also to investigate their sensitivity upon the more important parameters. For this purpose experiments have been undertaken and two sets of experimental data have been obtained and used for validation. The overall work offers a complete analysis of the subject and contributes towards a more accurate design of earth-to-air heat exchangers.

2. The algorithms

The eight examined algorithms can be classified in two groups:

- Those algorithms which first calculate the convective heat transfer from the circulating air to the pipe and then the conductive heat transfer from the pipe to the ground and inside the ground mass [16]. The necessary input data are:

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— the geometrical characteristics of the system;
— the thermal characteristics of the ground;
— the thermal characteristics of the pipe;
— the undisturbed ground temperature during the operation of the system.

• Those algorithms which calculate only the convective heat transfer from the circulating air to the pipe [17–21]. In this case the necessary input data are:
— the geometrical characteristics of the system;
— the thermal characteristics of the pipe;
— the temperature of the pipe surface.

A. The Schiller algorithm [16]

In this algorithm, the two heat transfer processes determining the behaviour of the buried pipe as a heat exchanger are treated separately. The first process is the convective heat transfer between the air circulating in the pipe and the internal surface of the pipe. The second process is the heat transfer by conduction from the internal surface of the pipe to the ground. The ground is thus divided theoretically into coaxial cylindrical elements.

In order to better simulate the heat transfer process in the ground, the thermal resistance of the ground was considered to be time-dependent, in order to take into account the variation of its thermal properties with temperature.

The air temperature at the outlet of an element of the pipe can be obtained by the following relation:

$$T_{f,\,x+1}=T_{f,\,x}-\frac{Q_x}{\dot{m}c_f} \qquad (1)$$

with x, $x+1$ the axial positions of the inlet and the outlet of the element. The air temperature at the outlet of the pipe is obtained by applying this relation for all the elements of the pipe in order to cover its entire length.

B. Santamouris algorithm [17]

According to this algorithm, the air temperature at the outlet of a buried pipe is given by the following expression:

$$T_{f,\,o}=(T_{f,\,i}-T_{pwo})\exp(-Sa)[1+(Bi\,Sa)^{0.5} \times\int_0^{Fo}\exp(-Bi\,Fo)I_1(2[Bi\,Sa\,Fo]^{0.5}) \times Fo^{0.5}\mathrm{d}Fo]+T_{pwo} \qquad (2)$$

The dimensionless parameters Bi, Sa and Fo depend on the thermophysical properties of the pipe and of the air and on the characteristics of the airflow.

C. The Rodriguez et al. algorithm [18]

This model allows the prediction of the air temperature circulating in the pipe at any position x from the inlet. The relation is:

$$T_{f,\,x}=T_{pwo}+(T_{f,\,i}-T_{pwo})\exp\left(-\frac{4hx}{\rho_f c_f V 2R_i}\right) \qquad (3)$$

This relation is based on the assumption that the temperature of the external wall of the pipe is maintained constant during the process. The air temperature at the outlet of the pipe is calculated by eqn. (3) with $x=L$, L being the length of the pipe.

D. The Levit et al. algorithm [19]

The air temperature in the pipe at a distance $x+1$ from the inlet is calculated by solving the steady-state heat balance equation between the air and the ground at a distance D from the pipe, through a finite differences scheme. The resulting relation is:

$$T_f^{x+1}=T_f^x\,\frac{\dot{m}c_f-UAdx}{\dot{m}c_f}+\frac{UAdx}{\dot{m}c_f}\,T_g(x,D) \qquad (4)$$

with $A=2\pi D$, U=the overall heat transfer coefficient, $T_g(x, D)$=the ground temperature at length x at a distance D from the pipe and dx the length of the elementary part of the pipe.

The air temperature at the outlet of the pipe is calculated by applying eqn. (4) consecutively for all the elements of the pipe.

E. The Seroa et al. algorithm [20]

The buried pipe is divided in elementary parts. The air temperature at the outlet of each element is given by the relation:

$$T_{f,\,o}=\frac{[(1-U/2)T_{f,\,i}+UT_{pwo}]}{(1+U/2)} \qquad (5)$$

where

$$U=(2\pi R_i\,dxU_w)/\dot{m}c_f$$

U_w is the overall heat transfer coefficient between the air and the external wall of the pipe. The air temperature at the outlet of the pipe is calculated by applying eqn. (5) consecutively for all the elements of the pipe.

F. The Elmer and Schiller algorithm [21]

Again the pipe is divided in elementary cylinders of length dx. The air temperature at the outlet of each element is given by the relation:

$$T_{f,\,x+1}=T_{f,\,x}-Q_x/\dot{m}c_f \qquad (6)$$

where the heat flow rate per unit length of the element at a distance x from the inlet of the pipe equals:

$$Q_x = U_w(T_{f,x} - T_{pwo})2\pi R_i dx \tag{7}$$

The air temperature at the outlet of the pipe is calculated by applying eqn. (6) consecutively for all elements of the pipe.

G. The Sodha et al. algorithm [22]

In this case the air temperature at the outlet of the pipe is given by the relation:

$$T_{f,o} = T_{pwo}\Phi_a(n) \tag{8}$$

where

$$\Phi_a(n) = (\Phi_j - 1)\exp(-\beta n) + 1 + F(n, \beta) \tag{9}$$

$$\Phi_j = T_{f,i}/T_{pwo} \tag{10}$$

$$\beta = \frac{2\pi R_i L U}{\dot{m} c_f} \tag{11}$$

$$n = (x/L) \tag{12}$$

When the air temperature at the outlet of the pipe has to be calculated, $x = L$ consequently $n = 1$. Knowing β, the parameter $F(n, \beta)$, eqn. (8) the air temperature at the outlet of the pipe is obtained.

H. The Chen et al. algorithm [23]

This algorithm solves the three-dimensional transient heat balance equation between the air and the external wall of the pipe. The Neumann-type boundary condition at the external surface of the pipe is also taken into account. By applying a finite differences scheme, the following equation giving the air temperature at the outlet of an element of the pipe is obtained:

$$T_f^{x+1} = \frac{2U_w}{\rho_f c_f R_o V} T_{pwo} dx + T_f^x \left(1 - \frac{2U_w}{\rho_f c_f R_o V} dx\right) \tag{13}$$

The air temperature at the outlet of the pipe is calculated by applying eqn. (13) consecutively for all the elements of the pipe.

3. Sensitivity analysis

The algorithms presented above have been introduced into computer programs in order to simulate the behaviour of the earth-to-air heat exchangers and to investigate the impact of each input parameter, by means of a sensitivity analysis. The sensitivity of all the models, regarding the inlet air temperature, the ground temperature, the air velocity, the length of the pipe, and the internal pipe radius and the depth, has been investigated. Some of the algorithms require the pipe wall temperature as an input. In that case, the pipe wall temperature has been calculated first by the Schiller algorithm and then used as an input for the studied algorithm.

The main parameter determining the outlet air temperature is the inlet air temperature. The outlet air temperature has been calculated using all the algorithms, with the inlet air temperature ranging from 25 °C to 75 °C. For the other input data, typical values used during the operation of the earth-to-air heat exchangers have been selected. These values are $T_g = 25$ °C, $V = 5$ m s^{-1}, $R_i = 125 \times 10^{-3}$ m, $L = 30$ m, $z = 1.5$ m. The results obtained are illustrated in Fig. 1. From the results it can be seen that all models present a similar linear behaviour regarding the inlet temperature variations. All models except the Schiller and Sodha *et al.* algorithms predict almost the same value of the outlet air temperature. The Schiller and Sodha predictions are also linear functions of the inlet air temperature but the Schiller algorithm (A) gives significantly higher temperatures while the Sodha *et al.* algorithm (G) gives lower values.

Figure 2 illustrates the outlet air temperature vs. ground temperature at the depth of the exchanger, using the same input data as before, but assuming a constant inlet air temperature of 35 °C. As it can be seen, the outlet temperature is predicted as a linear function of the ground temperature. All models predict almost the same outlet temperature except the Schiller model that predicts values higher of about 1.5 °C for low ground temperatures and the Sodha *et al.* model which predicts lower values of about 0.5 °C. The differences between the mean predictions decrease for the Schiller model and increase for the Sodha *et al.* model as temperature increases.

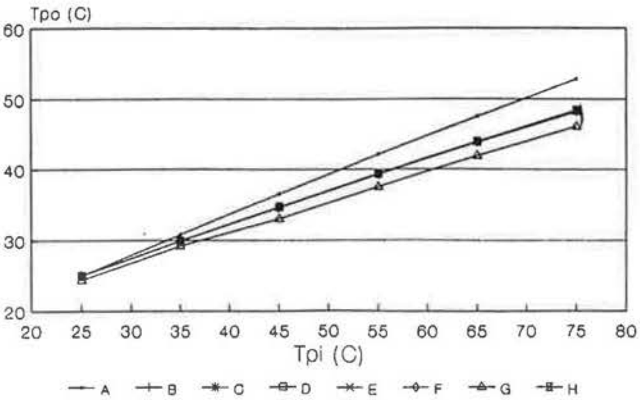

Fig. 1. Outlet air temperature variation vs. inlet air temperature.

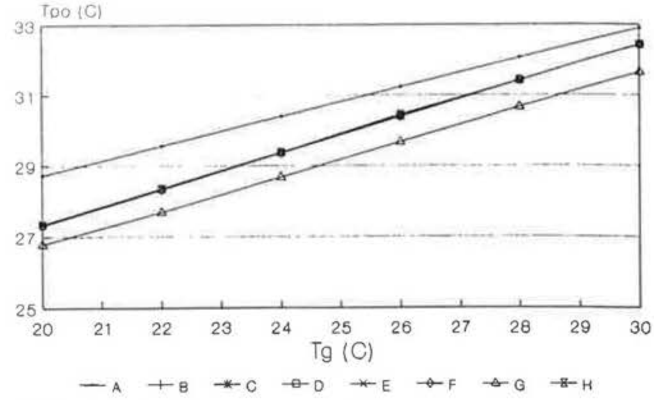

Fig. 2. Outlet air temperature variation vs. ground temperature, at the depth of the exchanger.

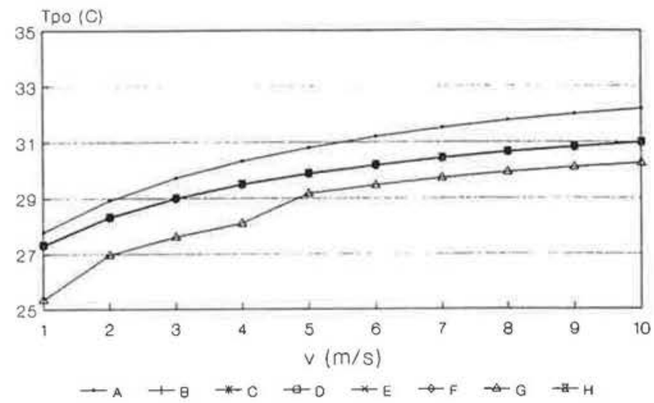

Fig. 3. Outlet air temperature variation vs. air velocity inside the exchanger.

The variation of the outlet air temperature as a function of the air velocity inside the exchanger is illustrated in Fig. 3. All models have in general the same behaviour: the outlet temperature increases quickly with velocity for values of about 6 m s^{-1} with a tendency to become practically stable after this value. The Schiller and Sodha algorithms present, here also, a particular behaviour by predicting higher and lower values respectively of the outlet air temperature. The difference between Schiller and mean predictions are about 0.5 °C for low air velocities, increasing up to 1.2 °C at high air velocities. The Sodha *et al.* algorithm has the opposite behaviour; the difference is important as the air velocity increases, becoming equal to 1 °C for the highest air velocity. It must be noted here that the heat transfer coefficient between the air and the wall of the pipe has been calculated using the Dittus–Boelter relation.

The opposite phenomenon is observed in Fig. 4 where the effect of changing the length of the pipe on the outlet air temperature is illustrated. In this case the outlet temperature drops rapidly with the length of the pipe and tends to a constant value

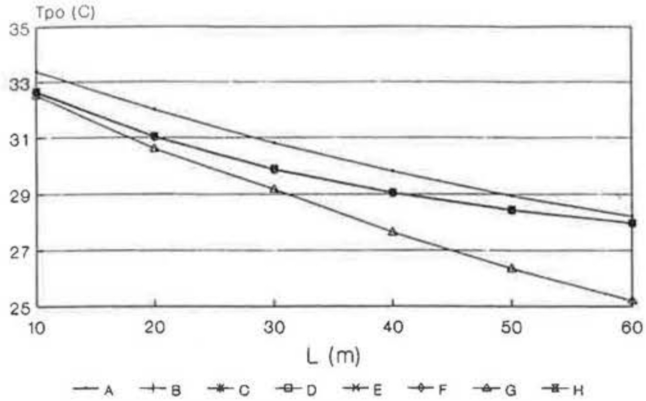

Fig. 4. Outlet air temperature variation vs. pipe length.

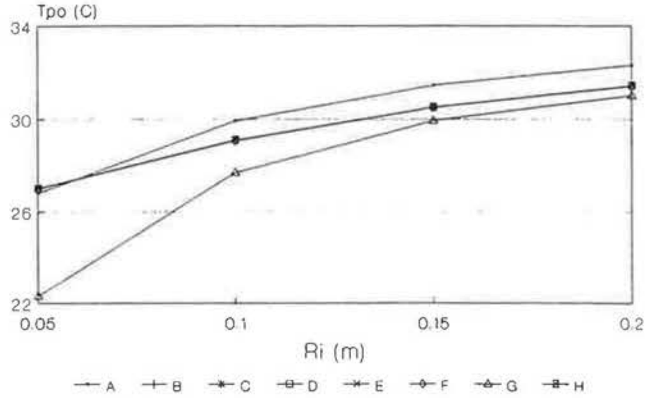

Fig. 5. Outlet air temperature variation vs. pipe radius.

after a length of about 50 m. The behaviour of the Sodha *et al.* algorithm is sensitive to length variations and the outlet temperature drop predicted with this model is higher. All the other algorithms give almost the same predictions for the outlet air temperature for all the tested lengths.

Figure 5 illustrates the outlet temperature variation as a function of the internal radius of the pipe, while the air velocity in the pipe is maintained constant. The outlet temperature increases rapidly with the radius, for radii up to 0.15 m, but for radii higher than 0.20 m, the outlet temperature remains practically constant. The Schiller and Sodha *et al.* models give in this case also higher and lower predictions respectively, compared to the other models. Exceptionally in this case, the Schiller model gives a prediction slightly lower than the mean prediction when the internal radius takes its lower value, i.e. 0.05 m.

The dependence of the predicted air temperature upon the depth variation for the various models is illustrated in Fig. 6. Here also the Schiller and Sodha *et al.* models give predictions significantly different from all the other models. As it can be seen, the outlet air temperature decreases exponentially as depth increases. This decrease is important for low

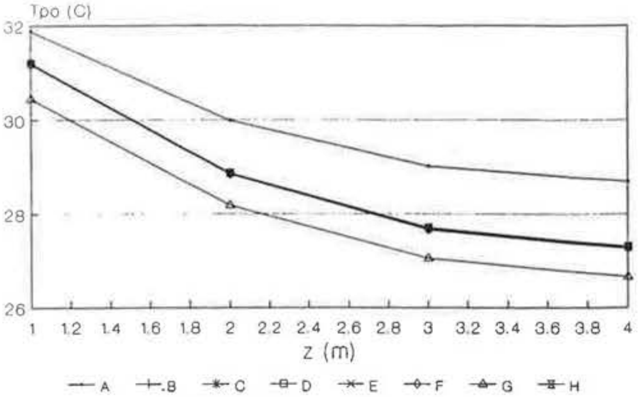

Fig. 6. Outlet air temperature variation vs. depth.

depths; the outlet temperature drop is about 5 °C for the first 3 m, but between 3 and 4 m the decrease is only about 0.5 °C. It must be noted here that the difference between the Schiller model mean predictions increases with depth, while the difference between the Sodha model and the mean predictions remains practically constant for all depths.

4. Comparison with experimental data

In order to evaluate and validate the predicted performance of the algorithms discussed above, the performance of a PVC horizontal pipe, buried at a depth of 1.1 m, was measured. The pipe was 14.8 m long, with a diameter of 0.15 m. The thickness of the pipe wall was 0.01 m. Ambient air, heated by a 2 kW electric heater, circulated in the pipe by means of a fan. Two experiments have been performed.

During the first experiment the air circulated continuously for 9 days, in June 1982, with a velocity of 4.5 m s^{-1}. The inlet and outlet air temperatures, ground surface temperature and ground temperature at various depths were measured [24].

The aim of the second experiment was to test the behaviour of the system by applying an intermittent air circulation. The air circulated from 08:00 until 20:00, with a velocity of 10.5 m s^{-1}. Measurements were performed for 15 days, during June and July, 1983. The temperature was measured at the same experimental points as for the first experiment [25]. The thermal diffusivity of the ground was determined experimentally and used as input data for the models [26].

Figure 7 illustrates the measured inlet air temperature and the ground temperature at the depth of the pipe, 1.1 m, for the first experiment. Figure 8 illustrates the outlet air temperature obtained by this experiment (solid line) and the simulation results obtained by the various algorithms as a function of time. The curve representing the experimental data presents oscillations on a daily period. This is due to the fact that the inlet air temperature is not thermostatically controlled, but ambient air was heated by applying a constant heating power. In this graph it can be observed also that the mean daily outlet temperature increases with time. This is due to progressive heating of the ground layers close to the pipe (see Fig. 7), which reduces the heat transfer rate between the air circulating in the pipe and the ground.

As can be seen from Fig. 8, while the models can follow the long-term dynamic behaviour of the outlet air temperature, their predictions of the maximum and minimum values on a daily basis is much less accurate. In order to quantify the accuracy of the various models regarding the experimental results, the root-mean-square error between experimental data and calculated values was calculated (Fig. 9) for all days of the experiment. It is observed that except for the Schiller and the Sodha algorithms which present the highest r.m.s. error, all the other algorithms present an r.m.s. error of the same order, i.e., of about 3.4%.

The comparison between measured data of a typical day during the second experiment and the corresponding simulation results is illustrated in Fig. 10 and the corresponding inlet air and ground temperature are given in Fig. 11. From this Figure it is observed that the results from all models are very close to the curve, except the Schiller and the Sodha models. The Schiller algorithm gives outlet air temperature values which are about 3–4 °C higher than the error band, while the Sodha algorithm gives values which are located in the middle of the error band. Comparisons between measurements and calculated values were made for all the days of the experiment and results obtained were similar to the ones already discussed.

The r.m.s. error between measurements and calculated values is illustrated in Fig. 12. The error was calculated for all the measurements obtained during the 15 days of the experiment, for both the upper and lower limits of the error bands. These results are illustrated in Fig. 12. The Schiller algorithm presents the highest r.m.s. error. The error of all other models regarding upper and lower limit of measurements is respectively of about 2.98% and 4.7%, except the Sodha algorithm which gives an error of the same order in both cases, i.e., 3.53% and 3.25% respectively.

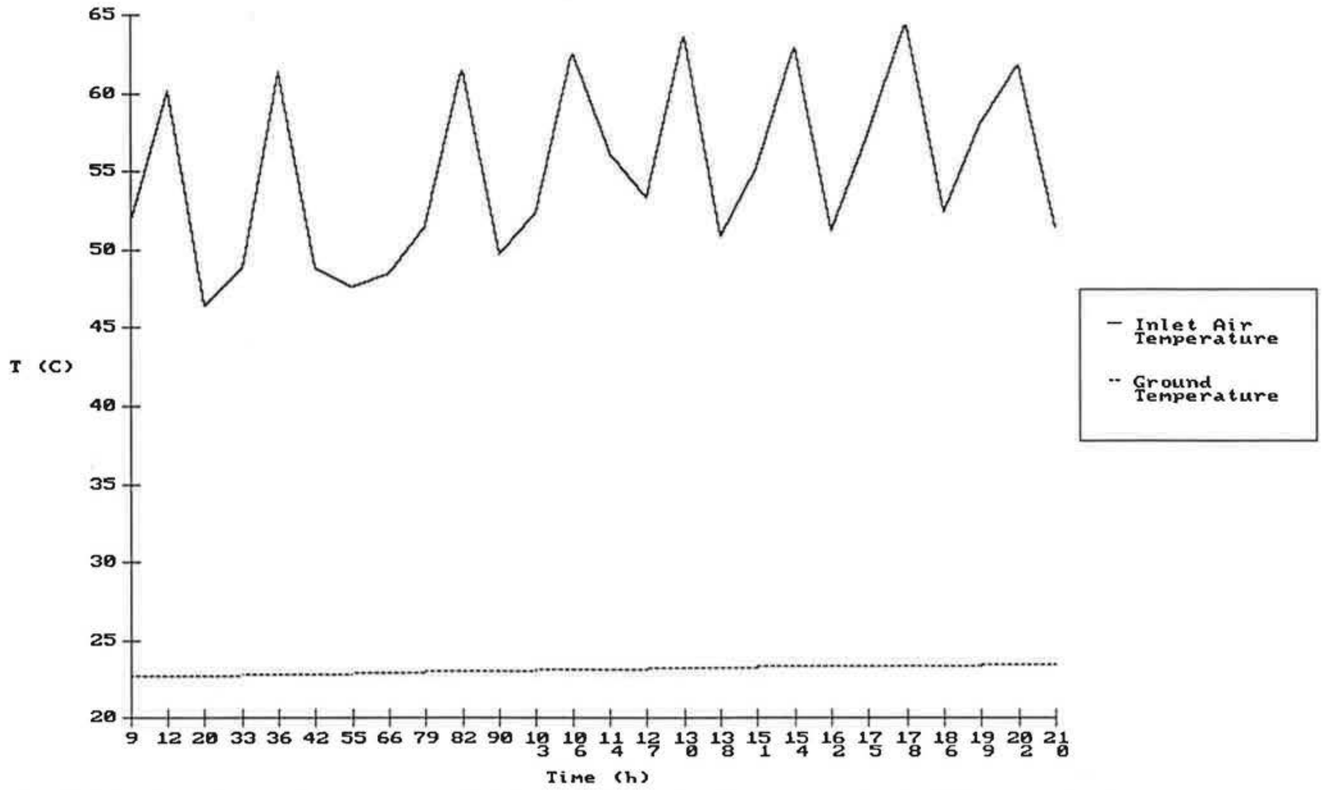

Fig. 7. Inlet air and ground temperatures (at 1.1 m depth) during the constant air circulation experiment.

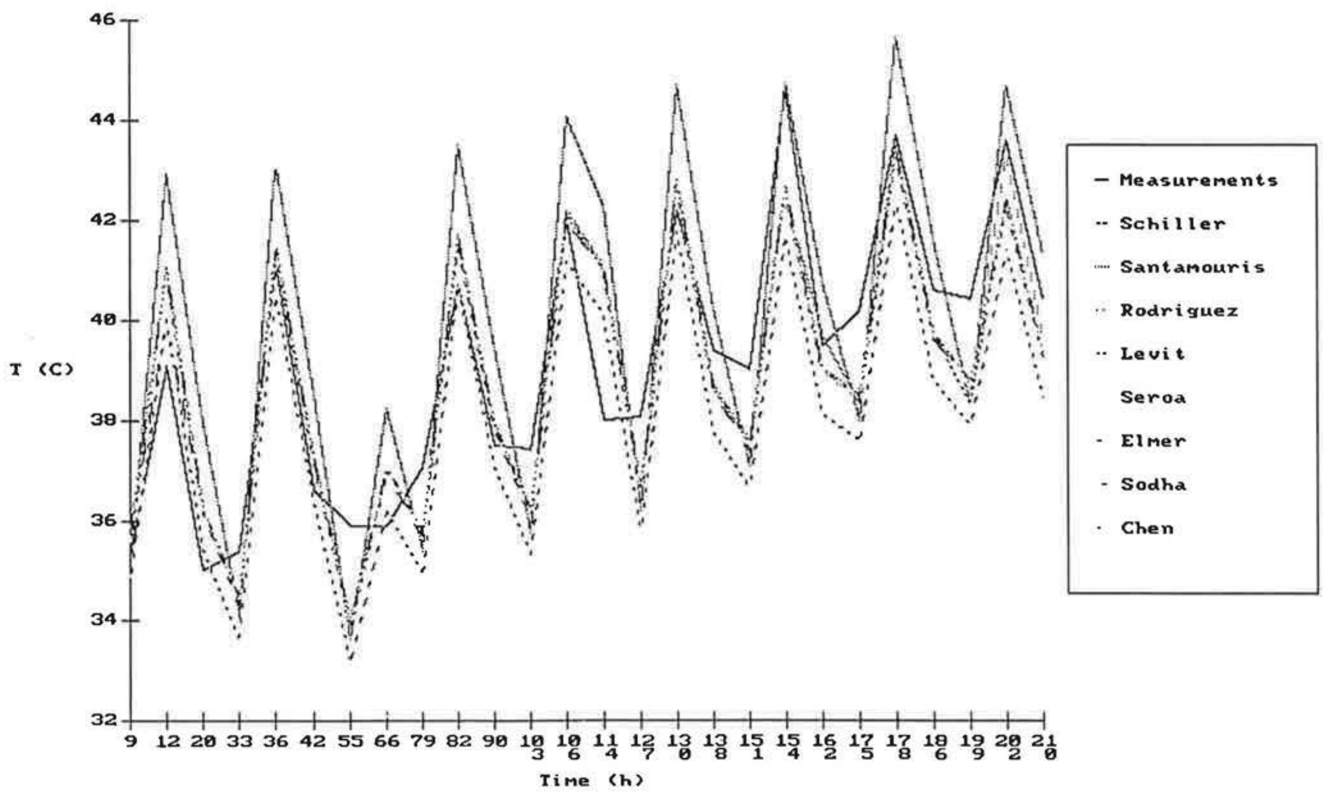

Fig. 8. Measured and predicted outlet temperature during the constant air circulation experiment.

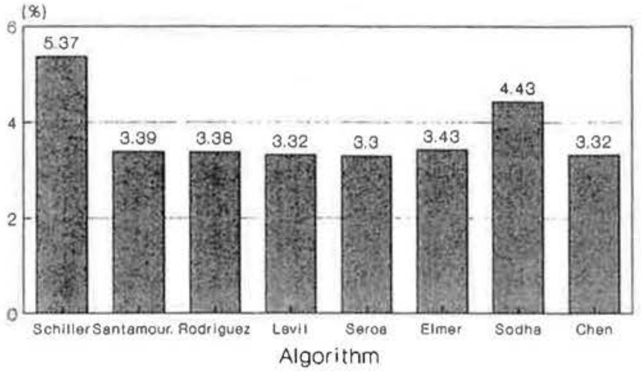

Fig. 9. The r.m.s. errors between measured and predicted values for the constant air circulation experiment.

5. Conclusions

In this paper, eight algorithms for the prediction of the performance of cylindrical earth-to-air heat exchangers have been examined. A sensitivity analysis has shown that the main parameters determining the air temperature at the outlet of the exchanger are the inlet air temperature and the ground temperature which is a function of the depth at which the exchanger is placed. The sensitivity analysis has shown also that only changes up to a certain limit of length and of the diameter of the pipe and of the air velocity in the pipe can modify the outlet air temperature. After that limit, the changes do not influence the performance of the system. The models have been used to simulate the performance of a heat exchanger, operating under two different experimental conditions. The r.m.s. error in each case has been calculated. The mean value of this error was found to be of about 3.5% for all cases except for the models, which gave higher r.m.s. errors.

Nomenclature

c_f	specific heat at constant pressure of the air (J kg^{-1} °C^{-1})
h	convective heat transfer coefficient inside the pipe (W m^{-2} °C^{-1})
I_1	modified Bessel function of the first kind of order 0
L	length of the pipe (m)
$\dot{m}$	air mass flow rate (kg m^{-3})
Q_x	heat flux per unit length of the pipe at length x (W m^{-1})
R_o	outer radius of the pipe (m)
t	operating time (s)
T_g	ground temperature (°C)
$T_{f,x}$	air temperature in the pipe at a distance x from the inlet of the pipe (°C)

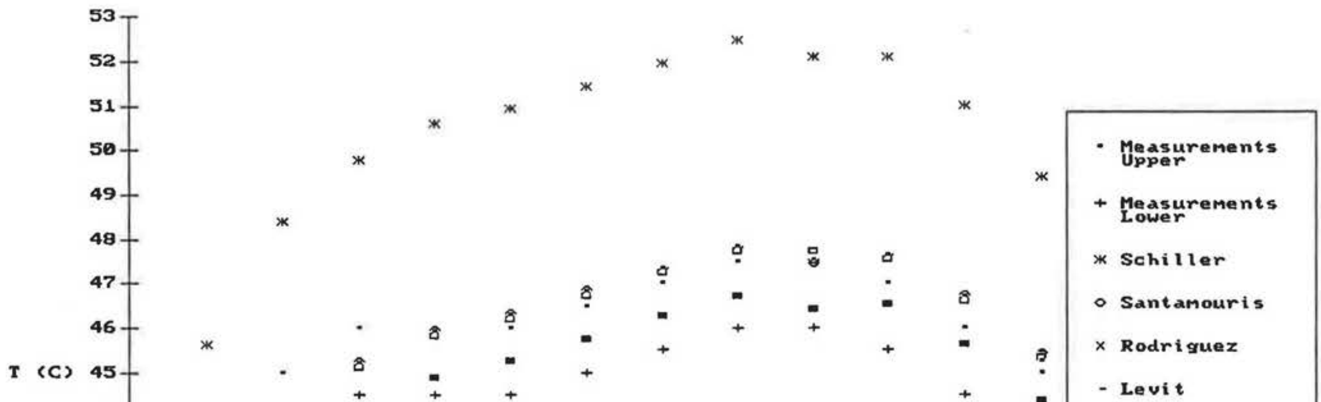

Fig. 10. Measured and predicted outlet temperatures during the intermittent air circulation experiment.

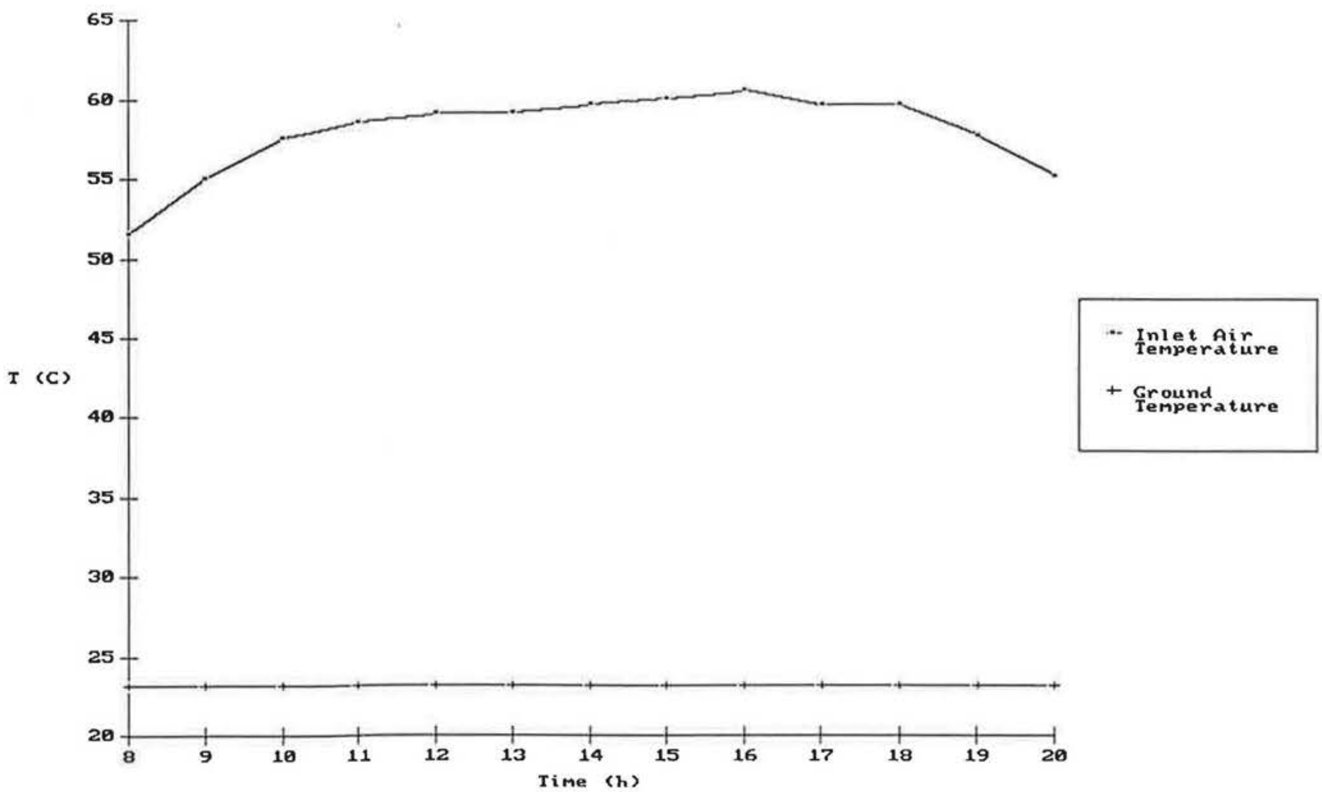

Fig. 11. Inlet and ground temperatures (at 1.1 m depth) during the intermittent air circulation experiment.

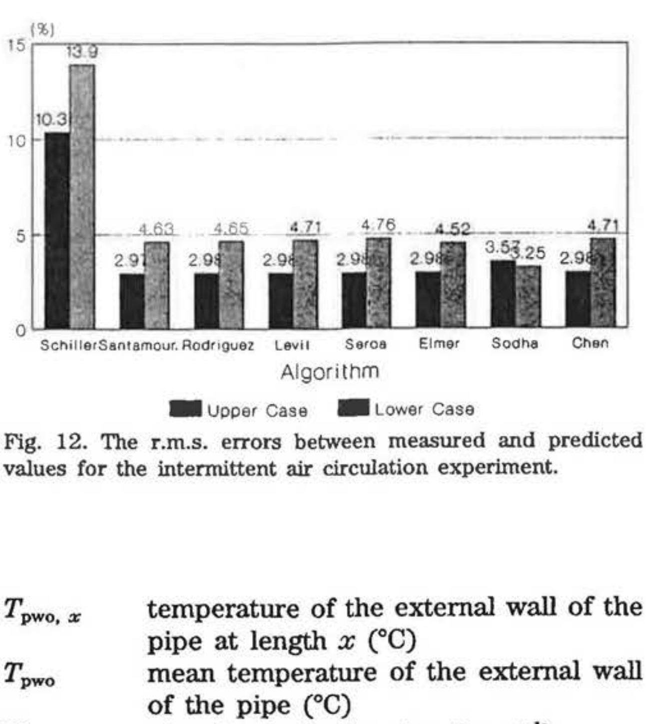

Fig. 12. The r.m.s. errors between measured and predicted values for the intermittent air circulation experiment.

$T_{pwo,x}$	temperature of the external wall of the pipe at length x (°C)
T_{pwo}	mean temperature of the external wall of the pipe (°C)
V	air velocity in the pipe (m s^{-1})
z	depth of the pipe (m)

Greek symbol

ρ_f	density of the air (kg m^{-3})

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