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THE INFLUENCE OF DIFFERENT GROUND COVERS ON THE HEATING POTENTIAL OF EARTH-TO-AIR HEAT EXCHANGERS

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Abstract—Ten years' hourly measurements of air and ground temperature values at various depths below bare and short grass soil at Dublin Airport have been used in order to investigate the impact of different ground surface boundary conditions on the efficiency of a single and a multiple parallel earth-to-air heat exchanger system. The heating potential of both these systems buried under bare soil has been assessed and compared with the heating potential of the same systems buried under short-grass-covered soil. The results of this comparison revealed that soil surface cover might be a significant controllable factor for the improvement of the performance of earth-to-air heat exchangers. The heating system consists of a single pipe or multiple parallel pipes laid horizontally, through which ambient or indoor air is propelled and heated by the bulk temperature of the natural ground. The dynamic thermal performance of these systems during the winter period and their operational limits have been calculated using an accurate numerical model. Finally, a sensitivity analysis was performed in order to investigate the effect of the main design parameters, such as pipe length, pipe radius, air velocity inside the tube and the depth of the buried pipe below the earth's surface, on the system heating capacity. Cumulative frequency distributions of the air temperature at the pipe's exit have been developed as a function of the main input parameters.

1. INTRODUCTION

The energy consumption of buildings for heating and cooling purposes has significantly increased during the last decade. The use of the ground as a heat source and for heat storage and dissipation has been accepted for passive heating and cooling applications [1, 2]. Two main strategies are defined: direct earth contact, which involves partial or total placement of the building envelope in direct contact with the soil, and indirect contact, which involves the use of an earth-to-air heat exchanger system. A buried pipes heating system consists of a single tube or multiple tubes buried in the ground and through which ambient or indoor air is circulated and heated; the air is then mixed with the indoor air of a building.

Various simplified and detailed models have been proposed to describe the thermal performance of earth-to-air heat exchangers [3–7]. However, for a large number of applications it is necessary to know the energy potential of the system under real climatic conditions, as well as the impact of the main design parameters on the thermal behaviour of earth-to-air heat exchangers. A complete assessment of the heating and cooling potential of a single earth-to-air heat exchanger, as well as of multiple parallel pipes, has been presented in detail [8–10].

The impact of different ground covers on the thermal performance of earth-to-air heat exchangers depends upon the temperature of the soil surface. The main objective of this study is to investigate the heating potential of a single earth-to-air heat exchanger and of a multiple pipe system, buried under bare soil, for real climatic conditions at Dublin Airport. Moreover, the heating capacity of such systems is compared with the potential of the same systems buried under short-grass-covered soil. This comparison aims at improving the earth tubes' performance by using

different soil surface boundary conditions. Furthermore, the sensitivity of a single earth-to-air heat exchanger to different design parameters, such as pipe length, pipe radius, air velocity inside the tube and depth of the buried pipe below the earth's surface, have been evaluated, while the results of a comparison between the sensitivity analysis of the system buried under bare soil and under short-grass-covered soil are extensively presented.

2. MODELLING OF EARTH-TO-AIR HEAT EXCHANGERS

An accurate, numerical, transient, implicit thermal model based on coupled and simultaneous transfer of heat and mass into the soil and the pipe has been presented in detail in ref. [11]. The model includes a complete mathematical description of moisture migration through soil with a temperature and, therefore, a moisture gradient which tends to redistribute the moisture content. The two interrelated phenomena were also described, since the final outcome depends on both the magnitude of the temperature and the moisture gradients. The natural thermal stratification in the soil was also considered while the soil boundary conditions were applied at the earth's surface. This model was validated against an extensive set of experimental data and it was shown that it can accurately predict the temperature and the humidity of the circulating air, as well as the distribution of the temperature and humidity in the soil.

In addition, the thermal performance of multiple parallel earth-to-air heat exchangers was calculated using the above model and the technique of superposition. The mathematical model describing the thermal behaviour of N parallel pipes buried in the ground is directly obtained from the thermal analysis of a single earth-to-air heat exchanger using the method of superposition. This mathematical analysis is extensively described in ref. [8].

The proposed models were developed within the TRNSYS program environment. TRNSYS [12] is a transient system simulation program with a modular structure which facilitates the addition to the program of mathematical models not included in the standard TRNSYS library.

3. ASSESSMENT OF THE HEATING POTENTIAL OF THE SYSTEM

Heating potential of a single earth-to-air heat exchanger

The heating effectiveness of a single earth-to-air heat exchanger, buried under bare soil, was compared with that of the same system buried under short-grass-covered soil. The energy potential of the earth-to-air heat exchanger has been assessed using a broad range of input parameters, such as pipe length and radius, the depth of the buried exchanger below the earth's surface and the air flow velocity inside the tube.

Thus, an extensive set of basic parametric studies has been performed. The thermal model presented in ref. [11] was used to simulate the performance and feasibility of a typical earth-to-air heat exchanger configuration.

The calculations cover the time period 1974–1984 for December, January, February and March using hourly values of air and ground temperatures at Dublin Airport. The air and ground temperature values were collected by the Irish Meteorological Service and include ground temperatures at the surface of bare and short-grass-covered soil and at 0.3, 0.6 and 1.2 m depths under the short-grass-covered soil. The undisturbed ground temperature field $T_u(z, t)$ at any depth z in the ground and at any time t has been calculated using the following equation [13, 14]:

$$T_u(z, t) = T_m - A_S \exp[-z(\pi/365\alpha)^{1/2}] \times \cos\{2\pi/365[t - t_0 - z/2(365/\pi\alpha)^{1/2}]\}, \quad (1)$$

where α is the soil thermal diffusivity, A_S is the amplitude of the temperature fluctuation at the soil's surface, T_m is the mean annual temperature at the surface and t_0 is the phase lag.

The soil thermal conductivity and diffusivity values were obtained from refs [15] and [16]. From the multiyear variation of the average annual earth temperature and the temperature amplitude for bare and short-grass-covered soil, it was found that for bare soil the multiyear average annual temperature was close to 12.3°C, while the multiyear amplitude was about 7.8°C. For the short-grass-covered soil the multiyear average annual temperature was close to 9.2°C, while the multiyear amplitude was close to 5.9°C. The dynamic energy potential of an earth-to-air heat exchanger buried under short-grass-covered soil has been analytically investigated and the results are presented in ref. [10]. So, apart from presenting the energy potential of a single earth-to-air heat exchanger buried under bare soil, an extensive comparison between the previous system's heating capacity and the heating capacity of the same system buried under short-grass-covered soil has been developed. Simulations have been carried out for an earth-to-air heat exchanger 30 m in length and 125 mm in radius while the air velocity inside the pipe was 8 m/s. The pipe was buried at a depth of 1.2 m below the earth's surface.

Cumulative frequency distributions of the air tem-

perature at the pipe's inlet and outlet for bare and short-grass-covered soil and for December, January, February, March as well as for the whole winter period, are given in Figs 1–5, respectively. As shown, the outlet air temperature fluctuated in the range 6.2–25.9°C, 4.9–23.3°C, 5.5–24.9°C and 6.8–26.8°C for December, January, February and March, respectively, for a system buried under short-grass-covered soil. The air temperature at the exit of the pipe, buried under bare soil, varied in the range 7.9–26.6°C, 6–23.9°C, 7.2–25.1°C and 9.1–27.4°C for December, January, February and March accordingly. The inlet

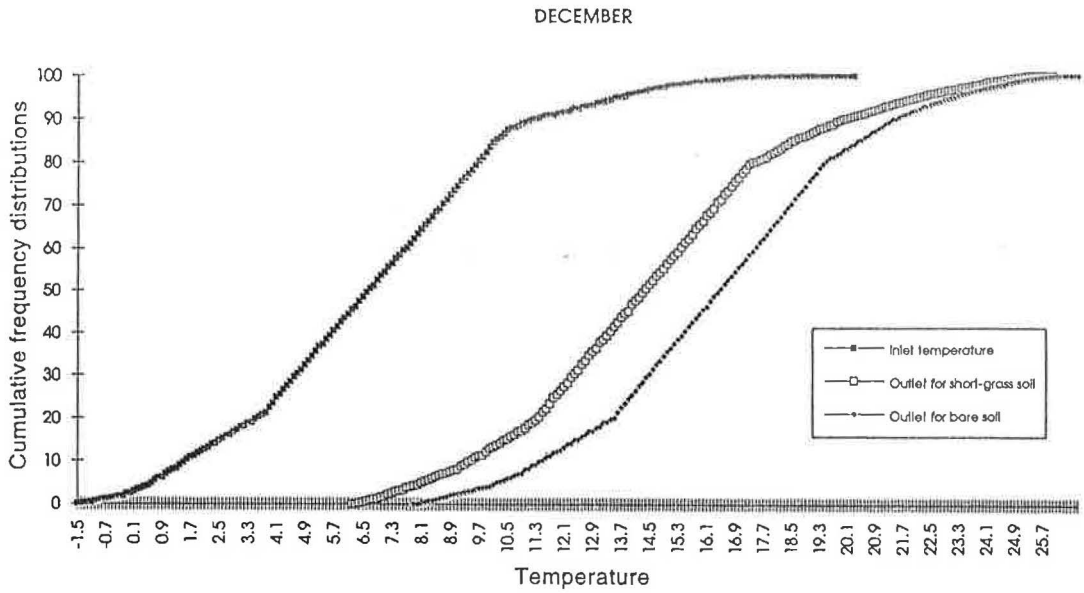

Fig. 1. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil (for December).

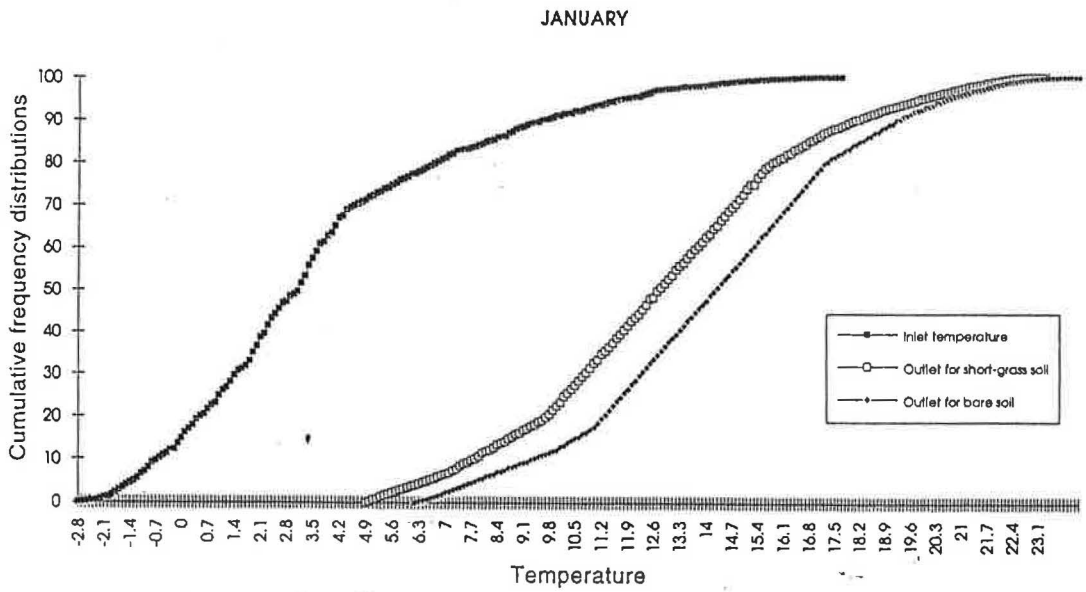

Fig. 2. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil (for January).

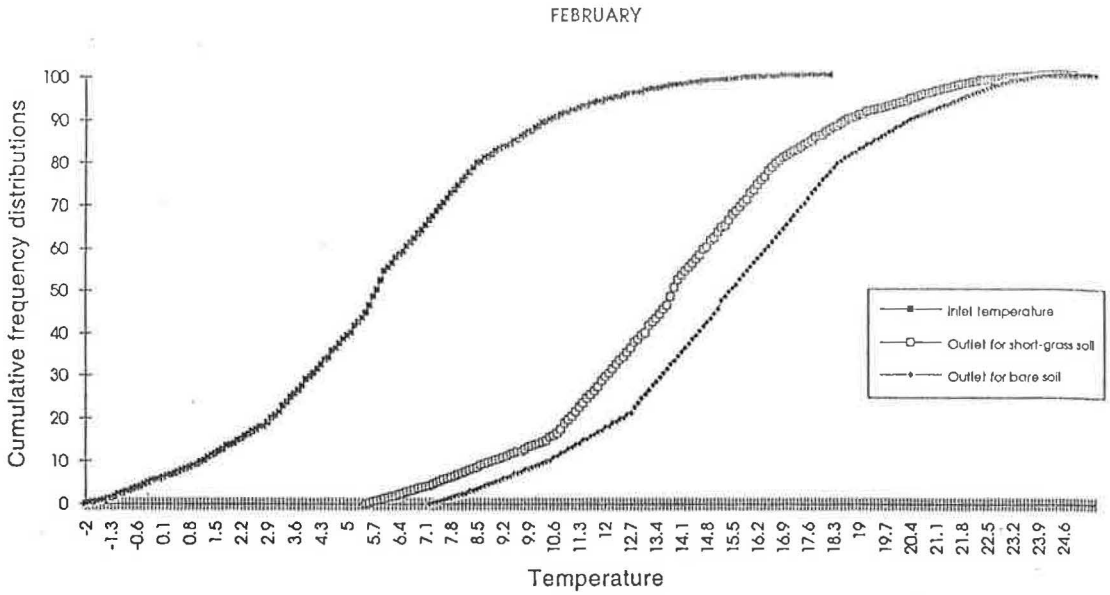

Fig. 3. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil (for February).

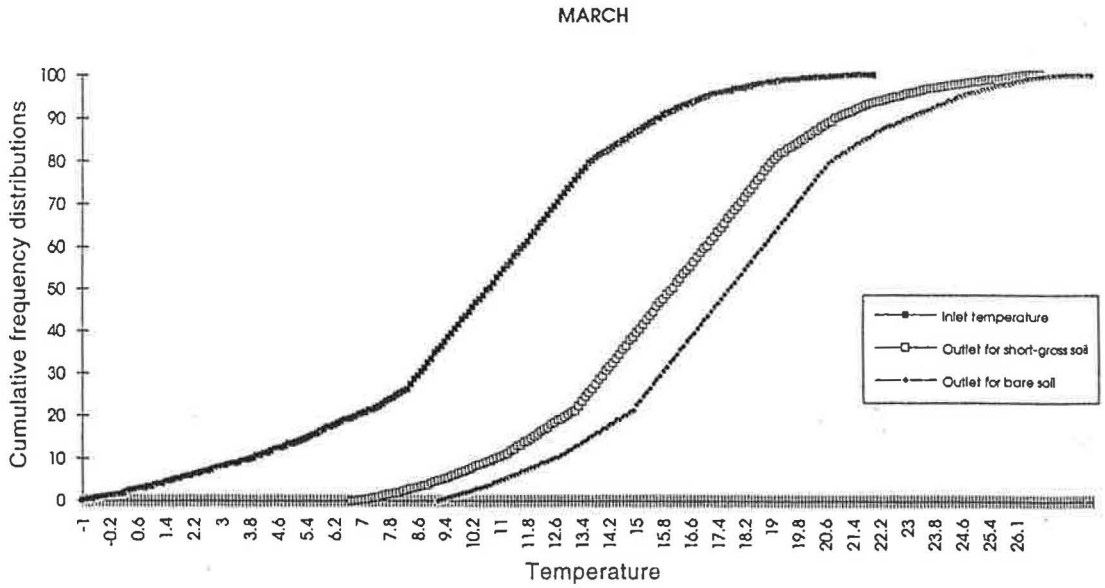

Fig. 4. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil (for March).

air temperature fluctuated in the range −1.5–20.3°C for December, −2.8–17.7°C for January, −2–18.2°C for February and −1.1–22°C for March.

Figure 6 shows the temporal variation of the air temperature at the inlet as well as the outlet of a single pipe with the previously described system configuration, buried under bare and short-grass-covered soil and for a typical winter day. From this figure it can be observed that the air temperature at the exit of the pipe buried under short-grass-covered soil fluctuated between 8.3 and 12.3°C, while the outlet air temperature for the same pipe buried under bare soil

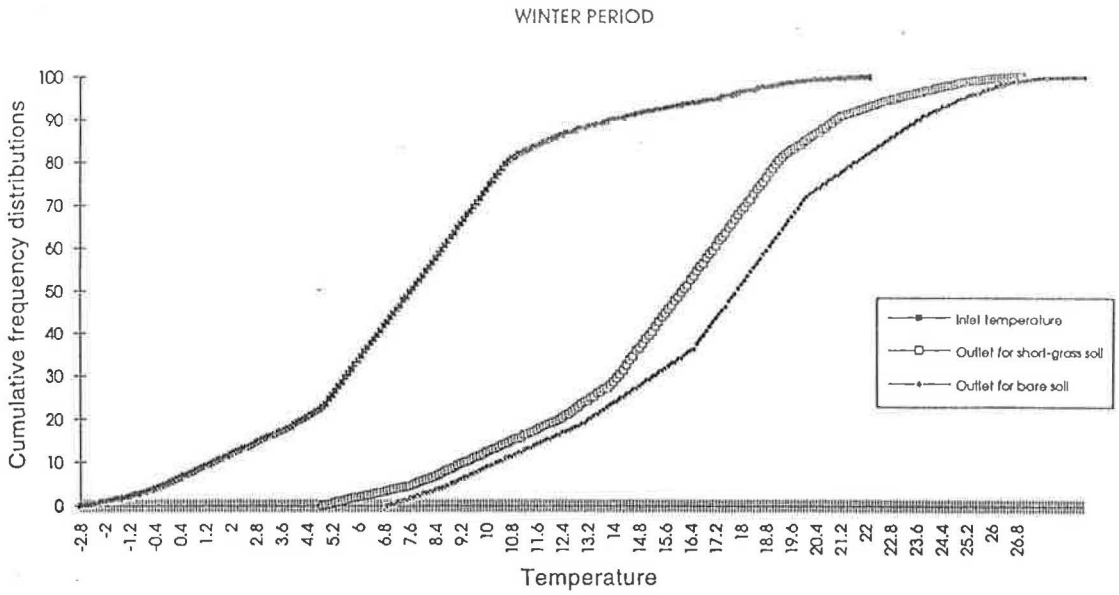

Fig. 5. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil (for the whole winter period).

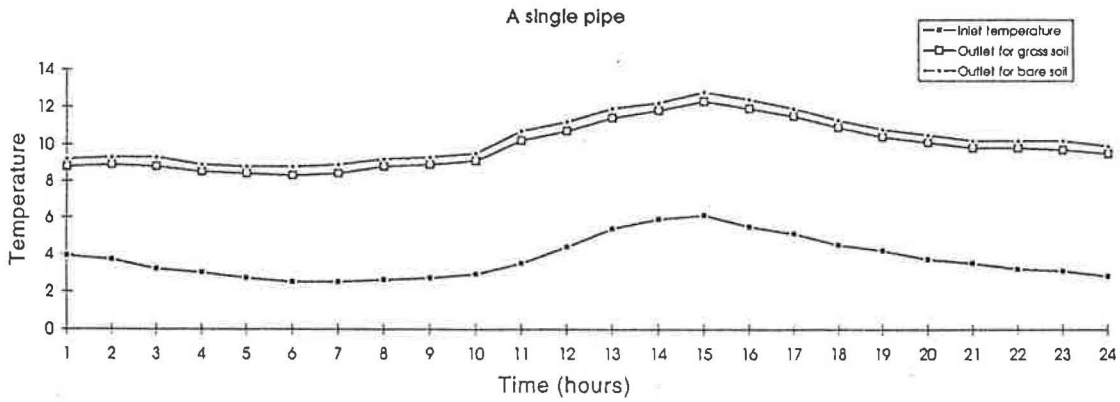

Fig. 6. Temporal variation for a typical winter day of the inlet and exit air temperature from a single pipe buried under short-grass-covered soil and bare soil.

varied in the range 8.8–12.8°C. The inlet air temperature was between 2.5 and 6.1°C.

From the above figures it can be seen that the system can be regarded as more efficient for tubes buried under bare soil because of the observed higher temperature values at the ground's surface. Thus, for December the outlet air temperature is always lower than 27°C for the bare soil while for the short-grass-covered soil the temperature at the pipe's exit is lower than 26°C. During January, for 80% of the time the exit air temperature is lower than 18.5°C for bare soil and 17°C for short-grass-covered soil. Finally, for 70% of the February time period the exit air temperature is lower than 16.6°C for bare soil and 15.5°C for short-grass-covered soil.

Furthermore, using eq. (1), the undisturbed temperature field at various depths has been calculated under a surface covered by asphalt. The heating potential of a single earth-to-air heat exchanger buried under asphalt-covered soil has been investigated. The buried pipe configuration was as previously described. The cumulative frequency distributions of the air tem-

perature at the pipe's outlet for asphalt-covered and bare soil for the month of January are given in Fig. 7. As can be seen, the exit air temperature for the system buried below asphalt fluctuated in the range 7.7–25.9°C, while the corresponding exit air temperature values for the pipe buried under bare-covered soil varied between 6.2 and 24.2°C.

Finally, in Fig. 8 the daily values of energy offered from the bare soil and the short-grass-covered soil for the month of January are presented. As shown, the energy for the bare soil fluctuated in the range of 0.063–0.08 kWh/m^2, while for the grass-covered soil the fluctuation was between 0.049 and 0.07 kWh/m^2.

Heating potential of multiple earth-to-air heat exchangers

In order to assess the energy potential of multiple parallel earth-to-air heat exchangers buried under bare soil, several basic parametric studies were performed. The thermal model describing the performance of N parallel earth-to-air heat exchangers was used to assess the feasibility as a heat source of four parallel plastic pipes of 125 mm radius and 30 m length buried at a depth of 1.20 m under bare soil. The air velocity inside the pipe was 8 m/s while the distance between the adjacent pipes was 1.5 m.

The calculations cover the same time period (1974–1984) for December, January and February, using the same air and ground temperature hourly values as inputs to the thermal model. The heating potential of the same system buried under short-grass-covered soil has been presented and extensively discussed [10].

Cumulative frequency distributions of the air temperature at the second (inner) pipe exit for bare soil and short-grass-covered soil and for December, January and February are given in Figs 9–11, respectively. From these figures it can be seen that the second pipe's outlet air temperature values fluctuated from 7.2 to

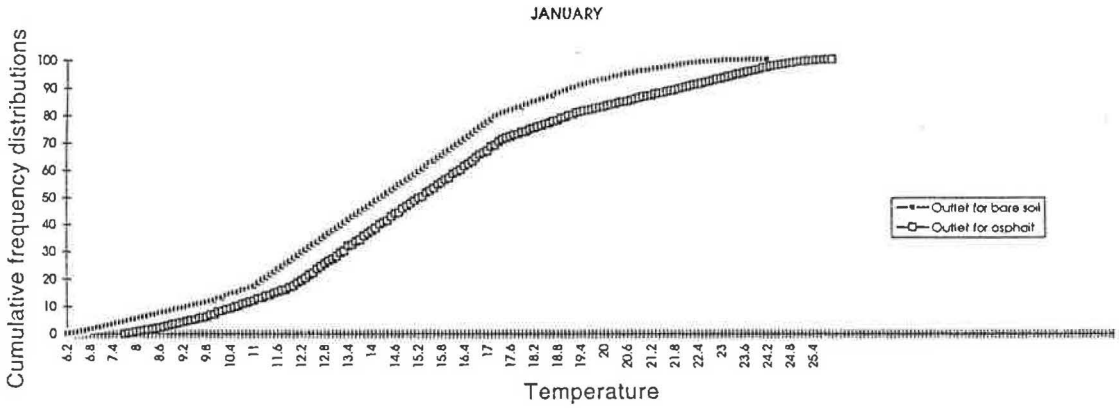

Fig. 7. The calculated cumulative frequency distributions of the outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and asphalt-covered soil.

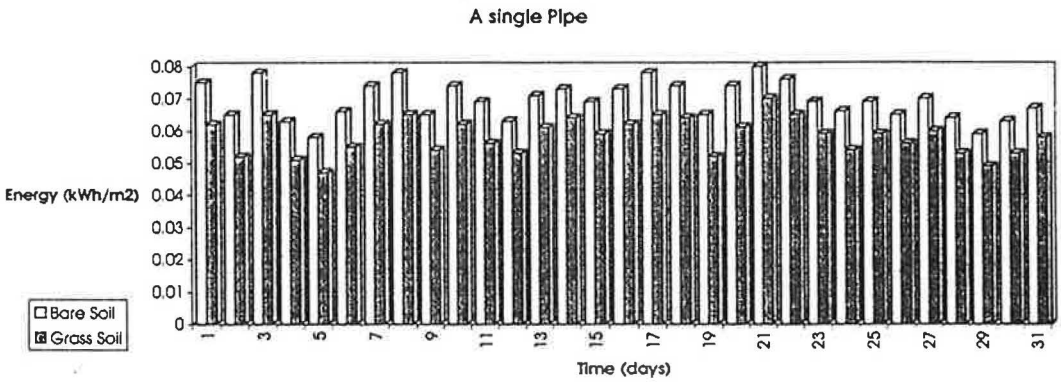

Fig. 8. Daily energy values offered from the bare and short-grass-covered soil, for the month of January for a single pipe system.

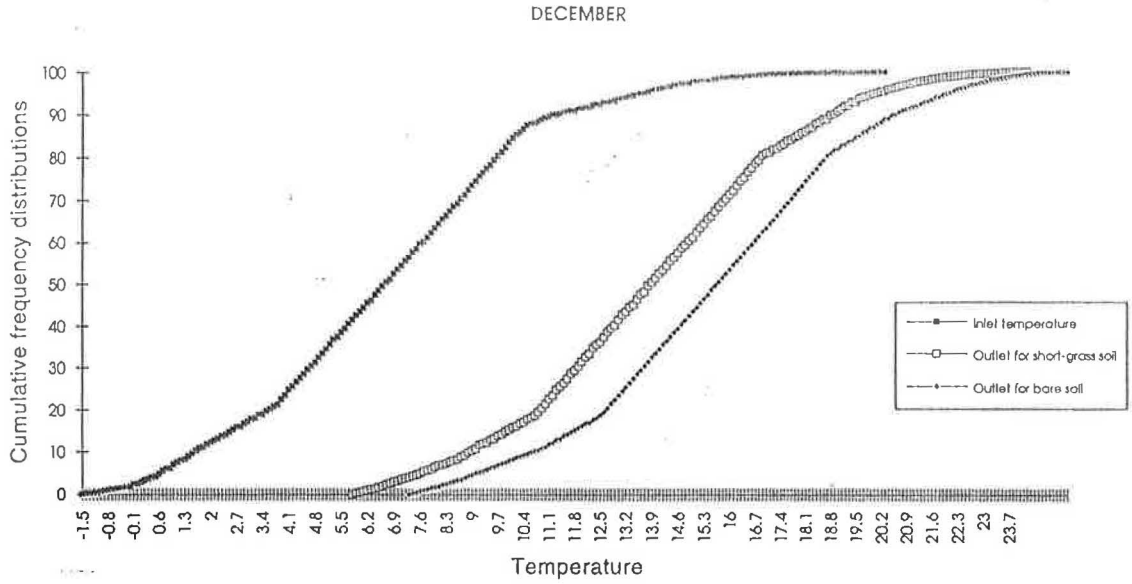

Fig. 9. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from an internal pipe of multiple parallel earth-to-air heat exchangers buried under bare and short-grass-covered soil (for December).

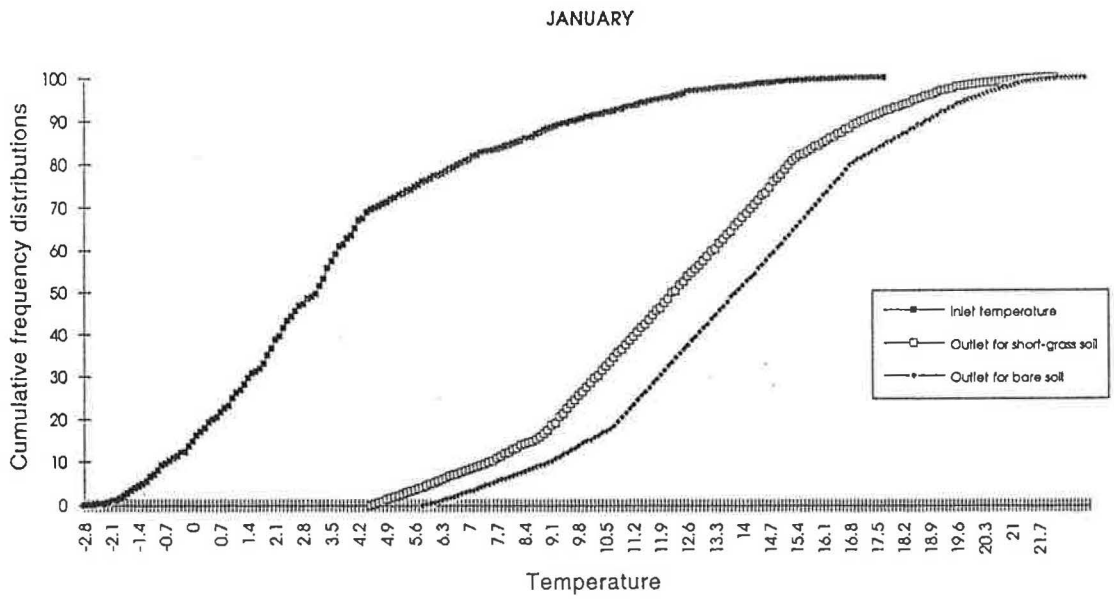

Fig. 10. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from an internal pipe of multiple parallel earth-to-air heat exchangers buried under bare and short-grass-covered soil (for January).

24.5°C, from 5.8 to 23°C and from 6.6 to 23.8°C for December, January and February, respectively for the system buried under bare soil. For the short-grass-covered soil the exit temperature varied between 5.8 and 24.2°C for December, between 4.5 and 22.1°C for January and between 5.1 and 23°C for February.

The loss of effectiveness observed for both the single pipe and multiple pipe systems buried under short-

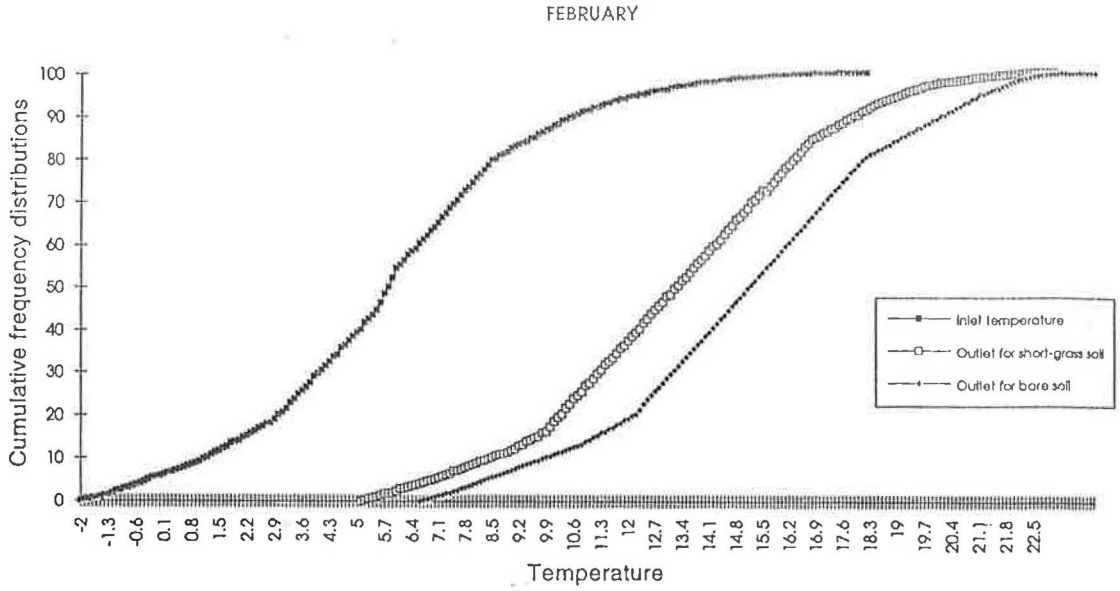

Fig. 11. The calculated cumulative frequency distributions of the inlet and outlet air temperature (in °C) from an internal pipe of multiple parallel earth-to-air heat exchangers buried under bare and short-grass-covered soil (for February).

grass-covered soil, can provide an important controllable factor for the improvement of the heating capacity of earth tubes by optimising the soil surface boundary conditions. This improvement could be obtained by burying the pipes under high temperature surface, such as a bare surface or one with very little grass.

Figure 12 presents the temporal variation of the air temperature at the inlet and at the exit of an internal pipe of the previous four parallel pipes, buried under short-grass-covered soil and bare soil and for the same typical winter day. From this figure it can be seen that the outlet air temperature for the pipe buried under short-grass-covered soil varied in the range 7.7–11.8°C, while the air temperature at the exit of the pipe buried under bare soil fluctuated between 8 and 12.3°C. The inlet air temperature, as previously mentioned, was between 2.5 and 6.2°C.

Finally, Fig. 13 shows the daily values of energy offered from the bare and the short-grass-covered soil

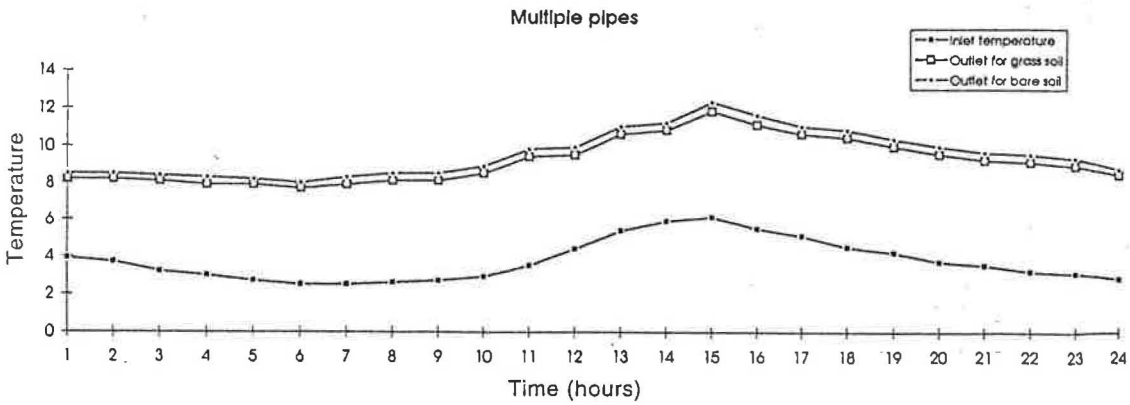

Fig. 12. Temporal variation for a typical winter day of the inlet and exit air temperature from an internal pipe buried under short-grass-covered soil and bare soil.

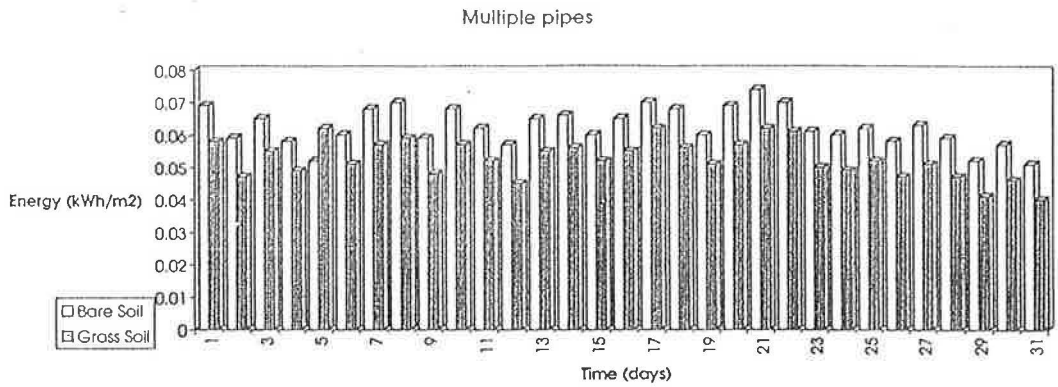

Fig. 13. Daily values of energy offered from the bare and short-grass-covered soil, for January for the multiple pipe system.

for the month of January. As can be seen, the energy was between 0.052 and 0.074 kWh/m^2 for the bare soil and between 0.040 and 0.062 kWh/m^2 for the short-grass-covered soil.

4. SENSITIVITY ANALYSIS

To determine the impact of parameter variations on the performance of a single earth-to-air heat exchanger buried under bare soil for real climatic conditions, an extensive sensitivity analysis was performed for the time period 1974–1984 for all the winter months. The variables influencing the thermal performance of the system are pipe length, pipe radius, air velocity inside the tube and the depth of the buried pipe below the earth's surface. For each variable a sensitivity analysis was carried out for a range of values covering existing design practice, while the results obtained were compared with the results of a sensitivity analysis performed for the same system buried under short-grass-covered soil.

Influence of pipe length

Simulations have been performed for three different pipe lengths, namely 30, 50 and 70 m, while the other parameter values remained unchanged. Figure 14 shows the cumulative frequency distributions of the air temperature at the pipe exit for the three different pipe lengths for the month of January. It can be seen that an increase of the buried pipe's length from 30 to 70 m results in an increase of the exit air temperature, representing an increase of the system's potential heating capacity. Figure 15 shows the cumulative frequency distributions of the air temperature at the exit of an earth-to-air heat exchanger buried under short-grass-covered soil and at the exit of an earth-to-air heat exchanger buried under bare soil. As shown, 97% of the outlet temperature values for the bare soil are below 24.6°C for the 50 m pipe length, while the same percentage of the outlet air temperature values for the short-grass-covered soil system are lower than 23.9°C.

Influence of pipe radius

The simulations performed extend over three different values of pipe radius, namely 0.125, 0.180 and 0.250 m, while maintaining the same basic configuration for the values of the other parameters. The cumulative frequency distributions of the outlet air temperature for the three different pipe radii are given in Fig. 16 for January. An increase in the buried pipe's radius leads to a reduction in the convective heat transfer coefficient, so providing a lower air temperature at the pipe's outlet, thus reducing the system's heating capacity. Moreover, the outlet air temperature reduction is associated with the pipe surface increase as the pipe radius increases.

Figure 17 presents the cumulative frequency distributions of the outlet air temperature for bare soil and short-grass-covered soil, for a pipe radius equal to 0.180 m and for the month of January. From this figure, it can be estimated that the air temperature at the outlet of the pipe buried under bare soil varied in the range of 5–22.2°C, while the air temperature at the exit of the pipe buried under short-grass-covered soil varied from 3.9 to 20.7°C.

Influence of air velocity

The performed simulations include those for three different air velocities inside the earth-to-air heat exchanger, namely 5, 10 and 20 m/s, while the other parameter values remained unchanged. Figure 18 presents the calculated cumulative frequency dis-

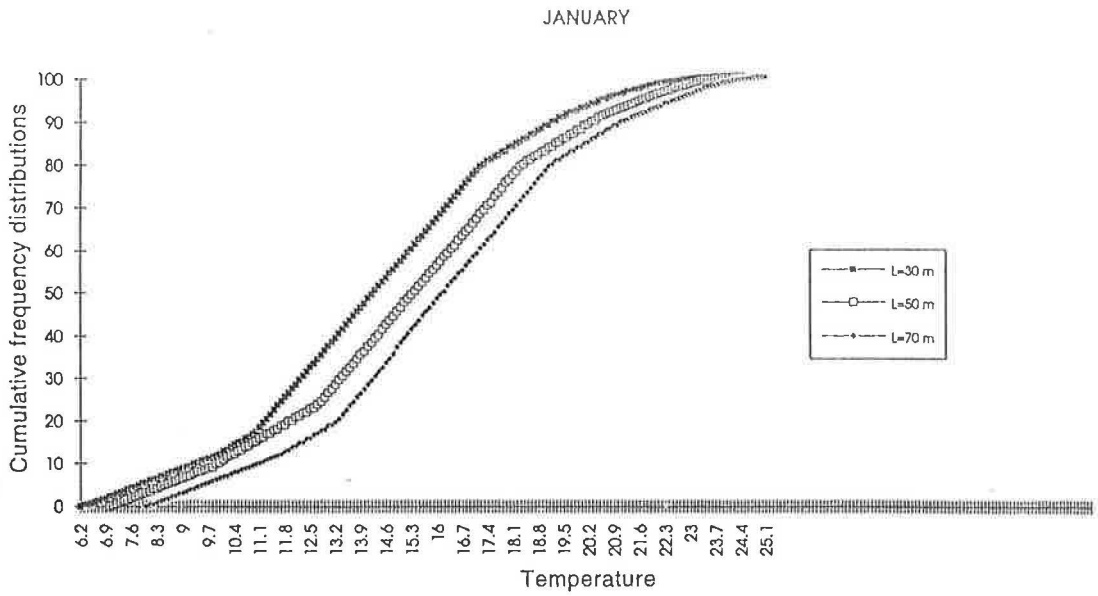

Fig. 14. For January, the calculated cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger for 30, 50 and 70 m long pipes.

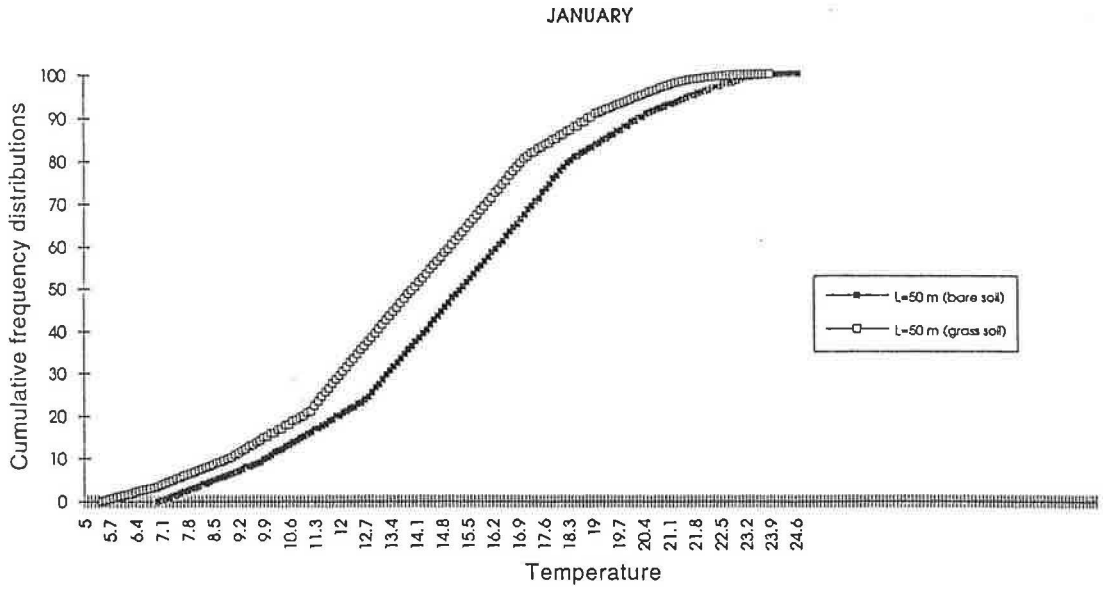

Fig. 15. For January, the calculated cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil for a pipe length of 50 m.

tributions of the air temperature at the pipe outlet for January and for the above-mentioned three air speeds. As shown, an increase of the air velocity in the pipe leads to a slight decrease of the outlet air temperature. This is mainly due to the increased mass flow rate.

Figure 19 shows the calculated cumulative frequency distributions of the air temperature at the exit of a pipe buried under bare soil and at the exit of a pipe buried under short-grass-covered soil, for an air velocity equal to 10 m/s for January. As can be seen

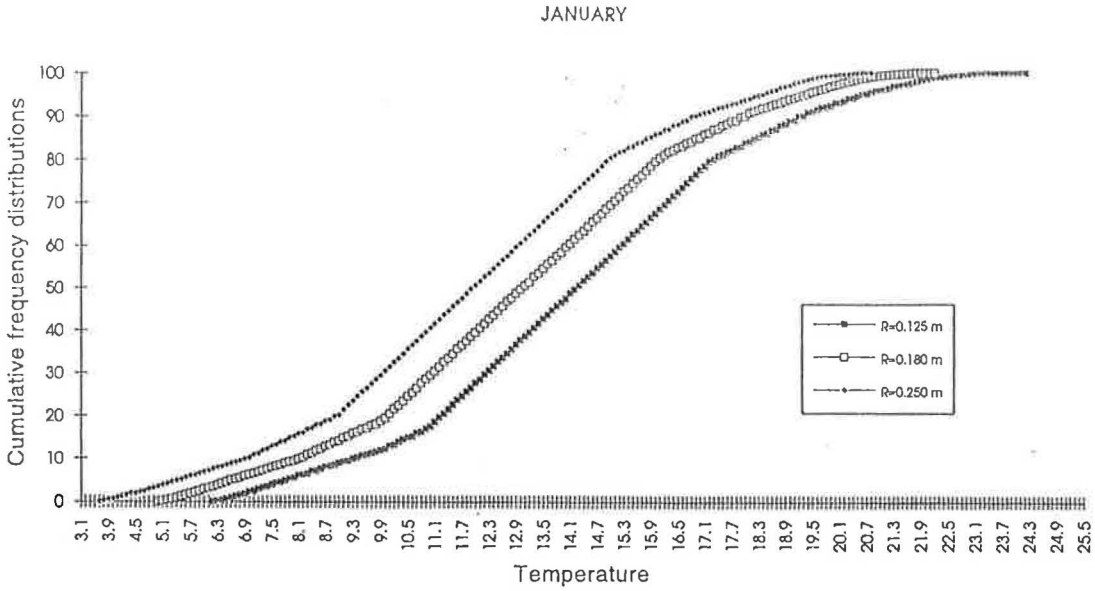

Fig. 16. For January, the calculated cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger for 0.125, 0.180 and 0.250 m pipe radii.

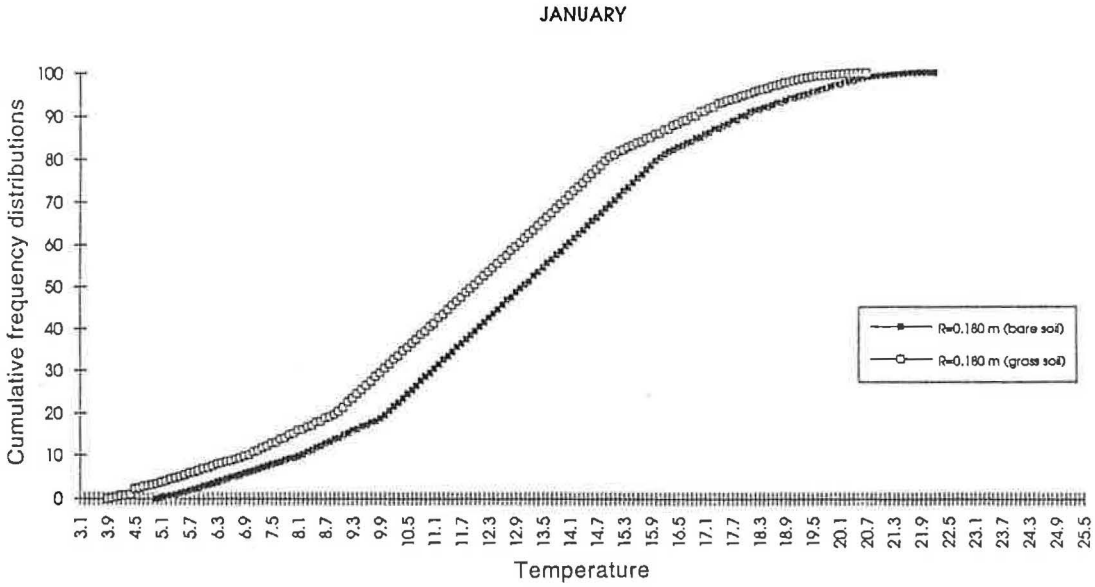

Fig. 17. For January, the calculated cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil for a pipe radius of 0.180 m.

from this figure, the bare soil surface improves the system's heating capacity by about 1.3°C.

Influence of soil depth

The depth of the buried pipe below the earth's surface is another crucial variable in the design of the earth tube system. Diurnal, seasonal and annual temperature variations, which vary with soil depth, should be taken into account in the system's design.

Simulations have been performed for 1.2, 2 and 3 m depths, while all the other input parameters were fixed at those values of the basic configuration

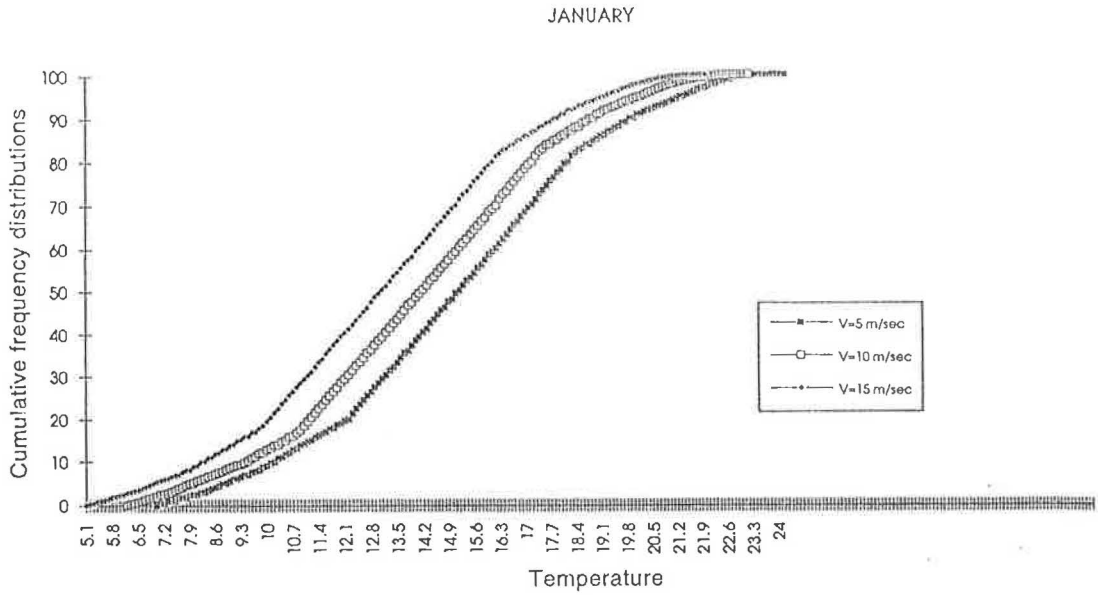

Fig. 18. For January, the calculated cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger and for 5, 10 and 15 m/s air velocities.

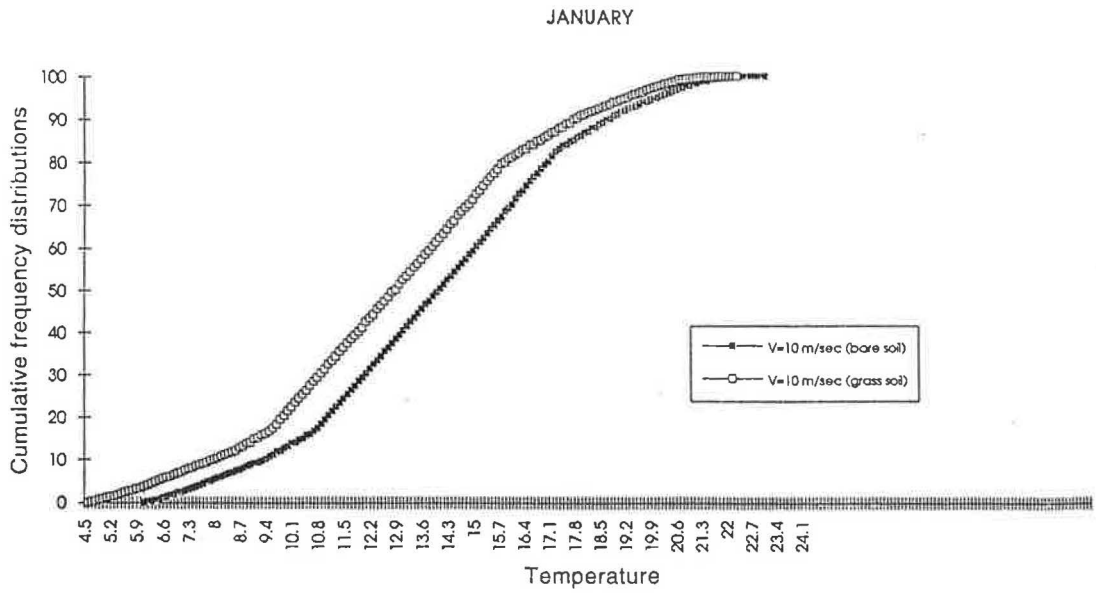

Fig. 19. For January, the calculated cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil for an air velocity inside the pipe equal to 10 m/s.

settings. The effect of different soil temperature values on the exit air temperature profile can be seen in Fig. 20. An increase of soil depth above the pipes provides a considerable increase in the system's potential heating capacity. Figure 21 shows the exit air temperature for bare soil and short-grass-covered soil, for a soil depth equal to 3 m for January. The exit air temperature for the system buried under bare soil varied between 8.5 and 25.5°C, while the outlet air temperature for the same system buried under the same depth of soil but with a short-grass covering varied in the range 7.4–24.3°C.

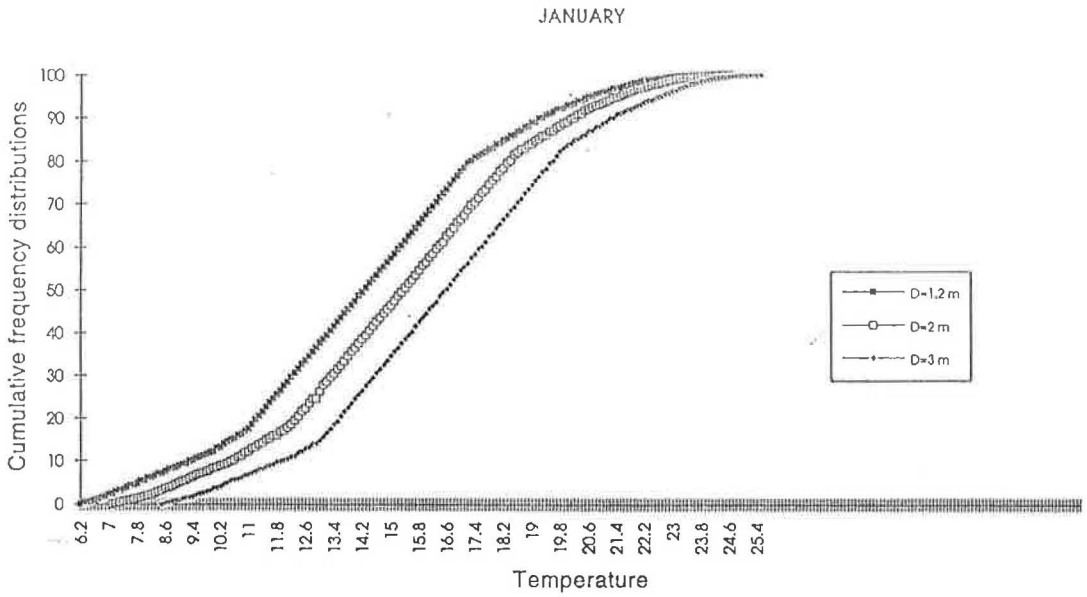

Fig. 20. For January, the calculated cumulative frequency distributions of the outlet air temperature (in °C) from a single earth-to-air heat exchanger for 1.2, 2 and 3 m pipe depths.

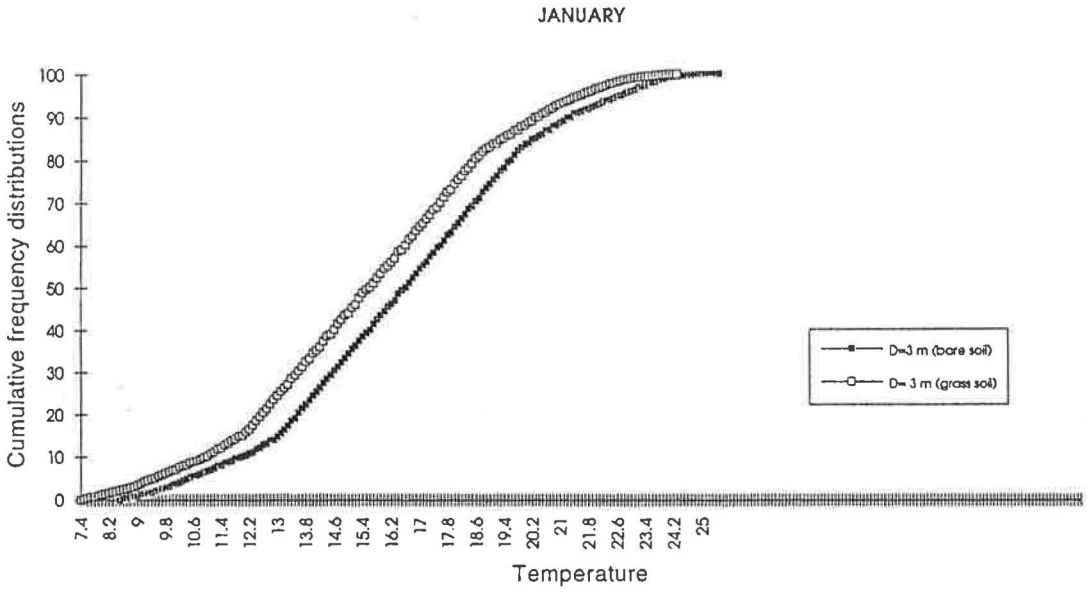

Fig. 21. For January, the calculated cumulative frequency distributions of the outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass-covered soil at a depth of 3 m.

5. CONCLUDING REMARKS

The dynamic heating potential of a single earth-to-air heat exchanger, as well as of multiple, parallel earth tubes buried under bare soil, was compared with the heating potential of the same system buried under short-grass-covered soil. The bare soil surface can increase the system's heating capacity. This observation could be helpful for the improvement of earth tube performance by creating advantageous soil surface boundary conditions.

A sensitivity investigation of a single earth-to-air

heat exchanger, buried under bare soil, to different design parameters, such as pipe length, pipe radius, air velocity inside the pipe and depth of the buried pipe below the earth's surface, was performed, while the effect of these parameters on the system performance was compared with the effect of the same parameters for the system buried under short-grass-covered soil.

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PERFORMANCE AND TESTING OF TWO MODELS OF SOLAR COOKER FOR ANIMAL FEED

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Abstract—Two simple solar cookers, one made of clay and locally available materials, and the other of exfoliated vermiculite and cement tiles, have been designed, fabricated and tested. The comparative performance of both cookers is described, and their efficiencies are 22.6 (clay) and 24.9% (vermiculite), respectively. The cookers are capable of boiling 2 kg of animal feed per day, and represent the equivalent of 1350 MJ of fuel per year at Jodhpur. Payback periods for solar cookers made of vermiculite tiles vary from 0.50 to 3.47 years, depending upon the fuel they replace. The shorter payback period suggests that the use of the cooker is economical.

1. INTRODUCTION

During a survey of rural arid areas, it was found that a huge amount of firewood, cowdung cake and agricultural waste is burnt for the boiling of animal feed [1]. The cattle population in western Rajasthan is 1.5 times the human population [2], and feed is generally given to animals in the evening, hence its boiling is only required once a day. It was therefore felt that an inexpensive solar cooker should be designed for the boiling of animal feed. Thus locally available materials, *e.g.* clay, pearl millet husk and horse excreta, have been used in the fabrication of a small [3] and a large solar cooker for animal feed [4]. By observing their success it was felt that a more durable solar cooker should be designed by using cement and vermiculite. The performance and testing of this cooker has been compared with a solar cooker made of clay and is described below.

Fig. 1. Solar cooker for animal feed made of clay.

2. DESIGN

2.1. *Solar cooker made of clay*

The cooker has been fabricated in the ground by using locally available materials, i.e. clay, horse excreta, wheat/pearl millet husk. Pearl millet husk has also been used as an insulating material. These materials are of no cost. The only material that has to be used and paid for is a mild steel sheet that acts as an absorber, and two clear window panes for the cover. The detailed design is described in ref. [3]. Actual installation of the solar cooker is shown in Fig. 1.

2.2. *Solar cooker made of vermiculite cement*

A pit of dimensions $920 \times 790 \times 170$ mm^3 was dug in the ground. The base of the pit was filled with cement concrete (1 : 2 : 4). Exfoliated vermiculite and cement were mixed together (4 : 1) and 40 mm thick tiles were made. The pit was filled with three layers of 40 mm thick tiles which were also used to construct the sides of the cooker. The 20 s.w.g. mild steel sheet was put in the base of the cooker and painted with blackboard paint.

Two clear window panes were fixed on a suitable frame and put on the cooker. The schematics of the cooker are shown in Fig. 2 and actual installation in the ground is shown in Fig. 3.