errors. In some cases, however, especially when P was not known, a maximum ± 0.5% error occurred. In the other cases, errors considerably smaller than this were obtained.

The results of different combination sets are given in Table 6. In combination set no. 6, the properties are calculated without any numerical analysis procedures. In combination sets 12, 19, 27 and 33, however, numerical analysis techniques were employed (see Table 5). In the columns of Table 6, '*' following the data indicates the known psychrometric properties. The calculated values are shown with three digits for comparison. However, no significant differences between any combination sets were found.

CONCLUSION

When humid air is used as a working fluid, it is essential to use reliable data for any necessary calculations. A good method to perform these calculations is by the use of computer software embodying the properties of perfect gases. In this study such software has been developed and utilised to obtain the psychrometric properties of humid air. It was found that given three input parameters, the remaining four parameters could, except in three cases, be calculated with negligible error.

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Impact of Ground Cover on the Efficiencies of Earth-to-Air Heat Exchangers

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ABSTRACT

The influence of different ground surface boundary conditions on the efficiency of a single earth-to-air heat exchanger as well as of a multiple parallel earth tubes system has been investigated. The cooling potential of both these systems buried under bare soil has been assessed and compared with the cooling potential of the same systems buried under short-grass covered soil. The results revealed that soil surface could be a controllable factor for the improvement of the performance of earth-to-air heat exchangers.

The cooling system consists of a single tube or multiple tubes, buried in the ground and through which ambient or indoor air is circulated and cooled: it is then mixed with the indoor air of a building or an agricultural greenhouse. An accurate numerical model has been used to assess the dynamic thermal performances and operational limits of the earth-to-air heat exchangers. Finally, a sensitivity investigation was carried out in order to evaluate the effect of the main design parameters on the system's cooling capacity. Cumulative frequency distributions of the air temperature at the pipe's exit have been developed as a function of the input parameters.

1. INTRODUCTION

The use of the ground for heating and cooling of buildings has gained an increasing acceptance during recent years. Underground cooling tunnels is a concept that can be traced back several centuries. Applications of these at different times and in different parts of the world have been described.[1,2]

The impact of different ground covers on the thermal performances of earth-to-air heat exchangers depends upon the surface temperatures of the soil.

Although this observation has been mentioned in various papers,[6,7] few assessments of the energy potential of the earth-to-air heat-exchanger systems are available. Complete assessment of the cooling potentials of a single earth-to-air heat exchanger as well as of multiple parallel pipes buried under short grass-covered soil are given in Refs. 5 and 6 respectively.

The main objective of this paper is primarily to investigate the dynamic cooling potential of a single earth-to-air heat exchanger and of a multiple-pipe system, buried under bare soil, for real climatic conditions, and secondly to compare the cooling capacity of the previous systems with the energy potential of the same systems buried under short grass covered soil. This comparison has been realised in order to improve the earth tubes performance by using different soil-surface boundary conditions.

Furthermore, the sensitivities of a single earth-to-air heat exchanger to different design parameters, such as pipe length, speed of the air flow in the pipe, pipe radius and depth of buried pipe below the earth's surface, have been evaluated, while the results of a comparison between the sensitivity analyses of the system buried under bare soil and under soil with short grass have been presented.

2. MODELLING OF EARTH-TO-AIR HEAT EXCHANGER

A transient, implicit, numerical model based on coupled and simultaneous transfer of heat and mass into the soil and the pipe taking into account the soil's natural thermal stratification, has been presented in every detail in Ref.7. This thermal 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 interrelated phenomena were described and it was found that the final outcome depends on both the magnitude of the temperature and the moisture gradients.

Furthermore, the technique of superposition was used to calculate the thermal performance of multiple, parallel, earth-to-air heat exchangers. Thus, the formulae for the performance of N parallel pipes buried in the ground are directly obtained from the thermal analysis of a single pipe by the method of superposition.[6]

The whole model was developed inside the TRNSYS environment,

which is a transient system simulation program with a modular structure that facilitates the addition to the programs of other mathematical models which are not included in the standard TRNSYS library.[8]

Finally, the proposed model has been successfully validated against an extensive set of experimental data. Thus, it has been proved that this model could accurately predict the temperature and the humidity of the circulating air, and the distribution of the temperature and moisture in the soil, as well as the overall thermal performance of the earth-to-air heat exchanger.

3. ASSESSMENT OF THE COOLING POTENTIAL OF THE SYSTEM

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

The cooling effectiveness of a single earth-to-air heat exchanger buried under bare soil was compared with that of the same system buried under soil with a short-grass cover. The energy potential of the earth-to-air heat exchanger has been assessed using a broad range of input parameters such as the pipe length and radius, the depth of the buried exchanger below the earth's surface and the air flow velocity. Thus, an extensive set of basic parametric studies has been performed. The thermal model ,[9,10] was used to simulate the performance and the feasibility of a typical earth-to-air heat exchanger configuration.

The calculations cover the time period 1981–1990 for June, July and August using hourly values of air and ground temperatures from 09.00 to 19.00 LST. The air and ground temperatures were collected by the National Observatory of Athens network and include ground temperatures (available from 1917) at the ground surface over bare and short-grass covered soils and at 0.3, 0.6, 0.9 and 1.2 m depths under the short-grass-covered soil. Based on these measurements an accurate model to predict the annual and daily variations of the ground temperature was developed.[11]

Thus, the undisturbed temperature field $T_u(z, t)$ any depth z in the ground and time t can be written as follows:

$$T_u(z,t) = T_m - A_s \exp\left[-z(\pi/365a)^{1/2}\right] \cos\left\{2\pi/365\left[t - t_0 - z/2(365/\pi a)^{1/2}\right]\right\}$$

where a is the thermal diffusivity, A_s is the amplitude of the temperature fluctuation at the ground's surface and T_m is the mean annual temperature at the ground's surface.

From the multiyear variation of the average annual earth's temperature and the temperature amplitude for bare and short-grass-covered soil, presented in Ref. 11, it was found that, for the bare soil, the multiyear average annual temperature was close to 21°C, while the multiyear amplitude was about 14.7°C. For the short-grass-covered soil the multiyear average annual temperature was close to 18.5°C while the multiyear amplitude was close to 11.5°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. 5. 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 cooling capacity and the cooling capacity of the same system buried under short-grass soil has been developed.

Cumulative frequency distributions of the air temperature at the pipe's inlet and at the pipe's outlet for bare and short-grass soil and for June, July, August as well as for the whole summer period are given in Fig. 1. As shown in this figure, the outlet air temperature fluctuated in the range of 20.7 – 23.7°C, 23.3 – 27.0°C and 25.1 – 28.5°C for June, July and August 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 of 20.8 – 25.9°C, 23.8 – 28.9°C and 25.3 – 29.6°C for June, July and August accordingly.

The overall analysis indicated that an earth-to-air heat exchanger can provide an effective method for space cooling even when the system was buried under bare soil.

Certainly, the system must be more efficiently used for earth tubes buried under short-grass-covered soil because of the observed lower temperature values at the ground's surface. Thus, during June the outlet air temperature is always lower than 26°C for the bare soil while for the short-grass soil the temperature at the pipe exit is lower than 24°C. During July for 80% of the time, the exit air temperature is lower than 27.5°C for bare soil and 26.0°C for short-grass soil. Finally for 70% of August the exit air temperature is lower than 28°C and 26°C for bare and short-grass soil respectively.

Cooling 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 of four parallel

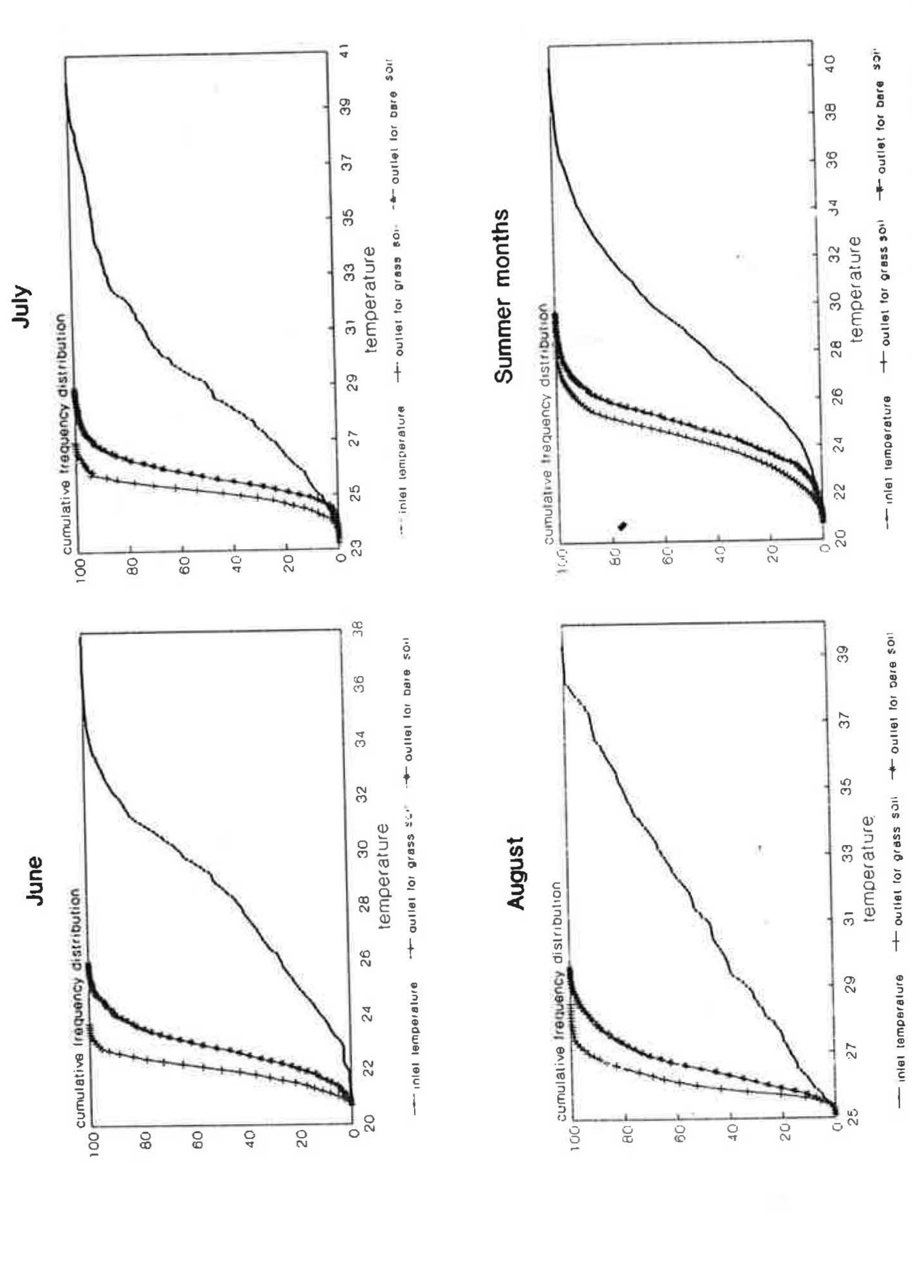

Fig. 1. Cumulative frequency distributions of the inlet and outlet air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass covered soil for June, July, August and for the whole summer period.

plastic pipes of 0.125 m radius and 30 m length buried at a depth of 1.50 m under bare soil . The air velocity in the pipes was 10 m/sec while the distance between the adjacent pipes was 1.5 m.

The calculations cover the same time period (1981–1990) as previously, for July and August, using the same air and ground temperature hourly values as inputs to the thermal model. The cooling potential of the same system buried under short-grass-covered soil has been presented and discussed in Ref. 6.

Cumulative frequency distributions of the air temperature at the second pipe outlet for bare and short-grass soil and for July and August

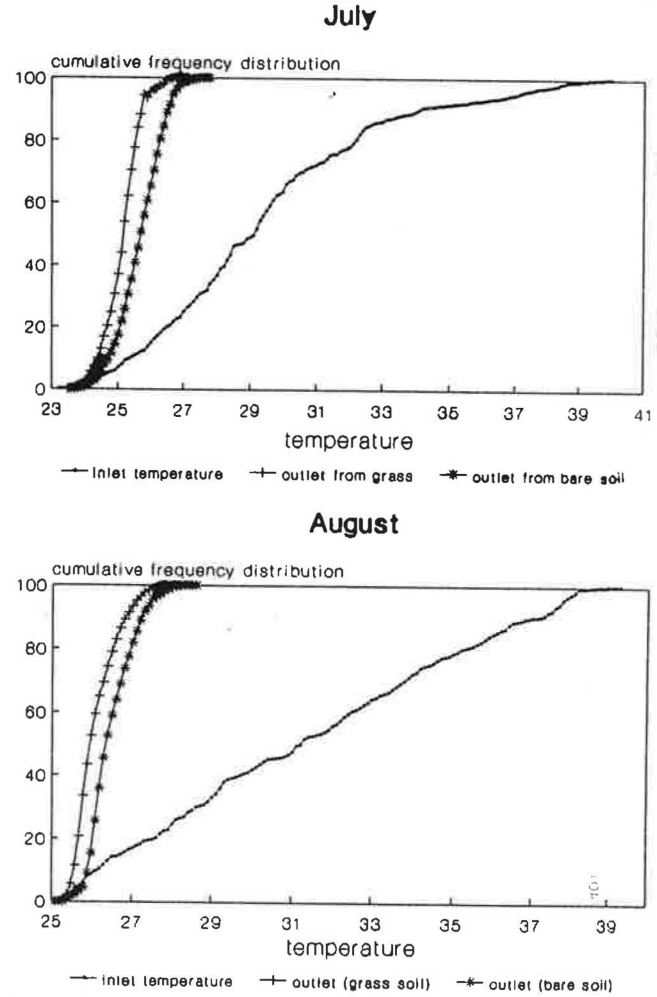

Fig. 2. Cumulative frequency distributions of the exit air temperature (in °C) from an internal pipe of multiple parallel earth-to-air heat exchangers buried under bare and short-grass covered soil for July and August.

are given in Fig. 2. From this figure it can be seen that the second pipe's outlet air temperature varied from 24.3–29.0°C and 25.6–30.8°C for July and August respectively and for the system buried under bare soil while for the short-grass-covered soil the exit air temperature fluctuated between 24.1–28.2°C and 25.4–29.7°C for July and August accordingly.

This comparison between the effectivenesses of the earth-to-air heat exchangers buried under bare and short-grass-covered soil could be more emphatically presented in Fig. 3. This figure shows the temporal variation of the air temperature at the inlet as well as at the exit of a

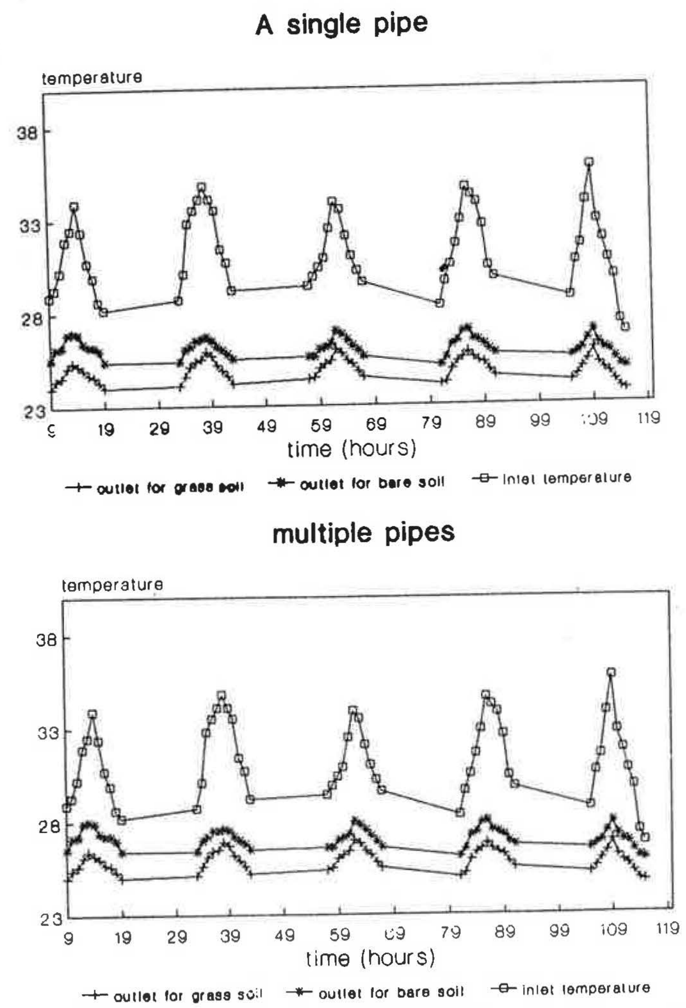

Fig. 3. Temporal variations for the five first days ofJuly the inlet and exit air temperature (in °C) from a single and an internal earth-to-air heat exchanger buried under bare and short-grass covered soil.

single pipe buried under bare and short-grass-covered soil, for the period of 1st–5th July, and secondly the temperature variation at the exit of an internal pipe of the four parallel pipes buried under bare and short-grass soil and for the same time period. Thus, taking the second day of July it can be observed that the air temperature at the single pipe exit fluctuated in the range of 24.1– 25.9°C for the system buried under short-grass-covered soil and between 25.4–26.7°C for the system buried under bare soil. In this case, the exit air temperature difference was close to 1.1°C.

For the same day, the air temperature at the exit of the internal pipe varied in the range of 25.1°C –26.9°C for short-grass soil while in the range of 26.4 C to 27.7 C for bare soil. Thus, the exit air temperature difference remained close to 1.1°C.

The loss of effectiveness observed for both a single pipe and multiple-pipe systems buried under bare soil can provide an important controllable factor for the improvement of the earth-tubes thermal performance optimising the soil surface boundary conditions. This could be obtained by burying the pipe under a surface of low temperature such as where the soil is covered by short grass.

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 and for real climatic conditions, an extensive sensitivity analysis was performed

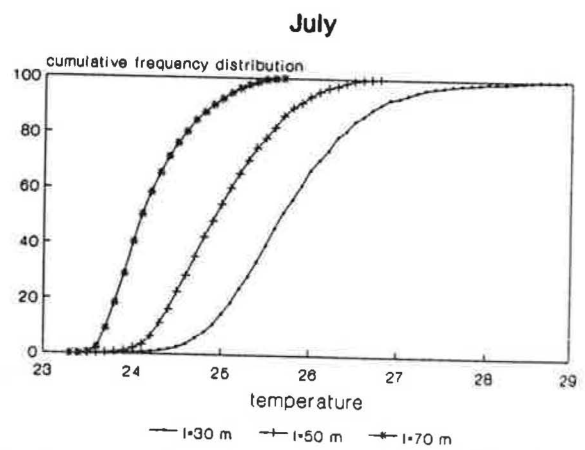

Fig. 4. For July, the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger for 30, 50 and 70 m long pipes.

for the time period 1981–1990 for all the summer months. The variables influencing the thermal performance of the system are pipe length, pipe radius, air velocity in the pipe 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 the existing design practice while the obtained results were compared with the results of a sensitivity analysis performed for the same system buried under short-grass-covered soil.

4.1 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 4 shows the cumulative frequency distributions of the air temperature at the pipe exit for the three different pipe lengths for the month of July. As can be seen, an increase of the buried-pipe's length results in a reduction of the exit air temperature this represents an increase of the system potential cooling capacity.

Figure 5 shows the cumulative frequency distributions of the air temperature at the exit of an earth-to-air heat exchanger buried under short-grass soil and at the exit of an earth-to-air heat exchanger buried under bare soil for July. As shown 97% of the outlet air temperature values for the bare soil are lower than 26.3°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 25.2°C.

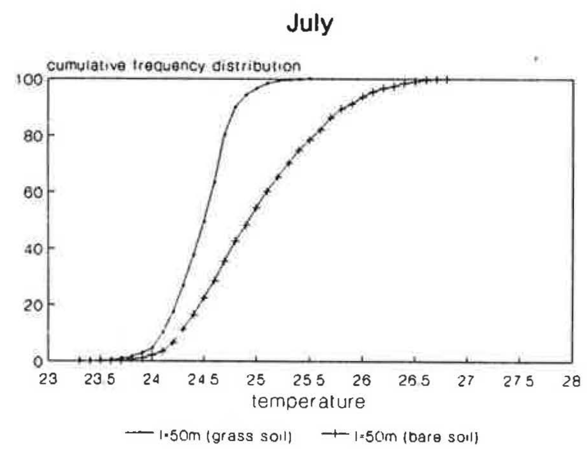

Fig. 5. For July the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass covered soil for a pipe length of 50 m.

4.2 Influence of pipe radius

The simulations 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. 6 for July. An increase of the buried-pipe's radius leads to a reduction of the convective heat-transfer coefficient so providing a higher air temperature at the pipe's outlet, thus reducing the system cooling capacity.

Figure 7 presents the cumulative frequency distributions of the outlet air temperature for bare and short-grass soil, for a pipe radius equal to 0.180 m and for the month of July. 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 24.2 – 29.6°C, while the air temperature at the exit of the pipe buried under short-grass soil varied from 24.1 – 28.7°C.

4.3 Influence of air velocity

The performed simulations include those for three different air velocities, namely 5, 10 and 20 m/s, while the other input parameter values remained unchanged. Figure 8 presents the calculated cumulative frequency distributions of the air temperature at the pipe outlet for July and for the three air speeds. As shown, an increase of the air velocity in the pipe leads to a slight increase of the outlet air temperature. This is mainly due to the increased mass flow rate .

Figure 9 shows the cumulative frequency distributions of the air

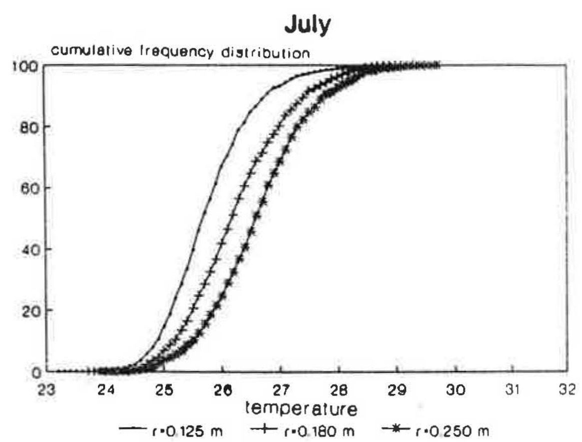

Fig. 6. For July the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger for 0.125, 0.180 and 0.250 m pipe radius.

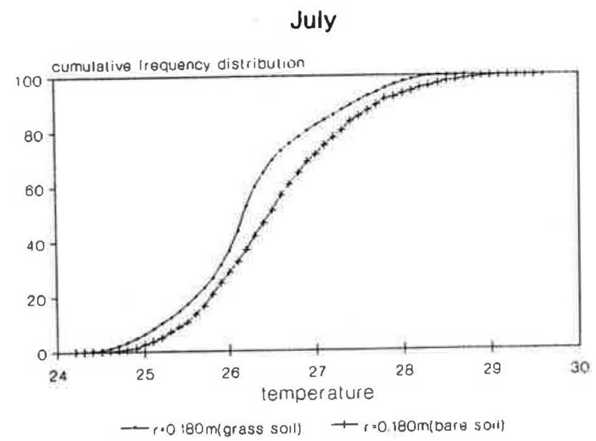

Fig. 7. For July the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass covered soil for pipe radius 0.180 m.

temperature at the exit of a pipe buried under bare soil and at the exit of a pipe buried under short-grass soil, for an air velocity equal to 10 m/s and for July. As can be seen from this figure, having the short-grass soil surface improves the system's cooling capacity by about 1.2°C.

4.4 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 tubes system. Diurnal, seasonal and annual temperature variations, which vary with soil depth, should be taken into account in the storage design.

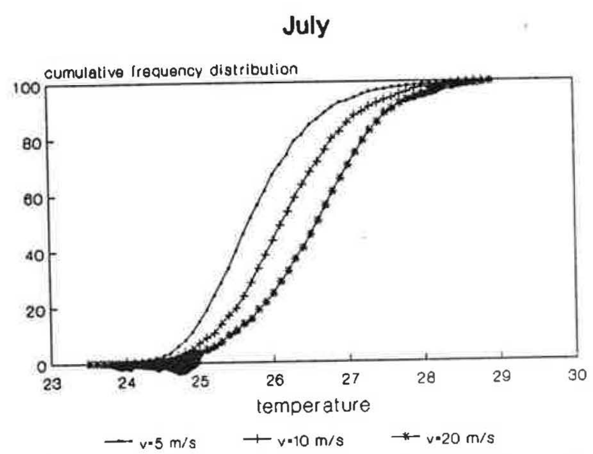

Fig. 8. For July the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger for 5, 10 and 20 m/s air velocities.

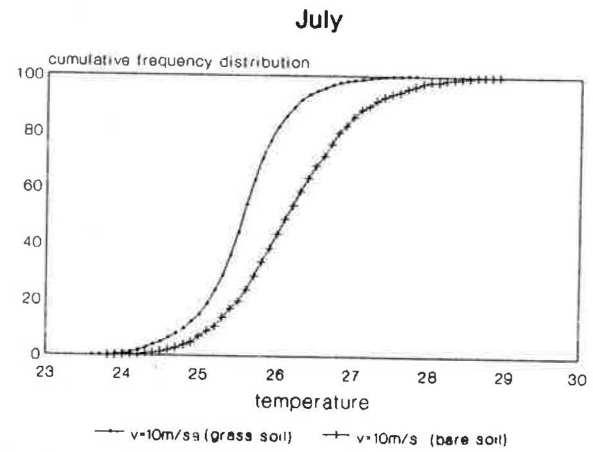

Fig. 9. For July the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass covered soil for an air velocity of 10m/s.

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 settings. The effect of different soil temperatures on the exit air temperature profile can be seen in Fig. 10. As shown, an increase of soil height above the pipes provides a considerable increase in the system's potential cooling capacity.

Figure 11 shows the outlet air temperature for bare and short grass soil, for a soil depth equal to 2 m and for July. The exit air temperature for the system buried under bare soil was about 25.5°C while the exit air temperature for the same system buried under the same height of soil but with a short grass covering was about 23.5°C.

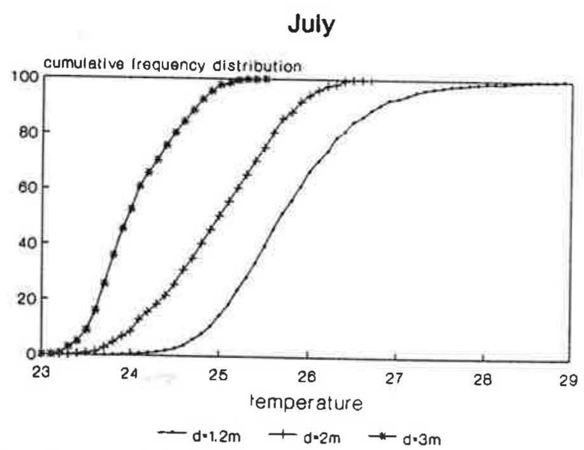

Fig. 10. For July the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried at 1.20, 2.0 and 3.0 m pipe burial depths.

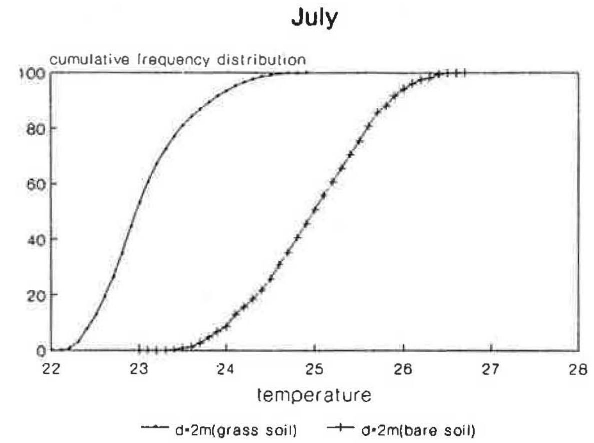

Fig. 11. For July the cumulative frequency distributions of the exit air temperature (in °C) from a single earth-to-air heat exchanger buried under bare and short-grass covered soil at the depth of 2 m.

CONCLUSIONS

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

Furthermore, a sensitivity investigation of a single earth-to-air heat exchanger, buried under bare soil, to different parameters such as pipe length, pipe radius, air velocity and soil depth has been 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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Absorbers in the Open Absorption System

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ABSTRACT

This paper describes an experimental study of four different absorber designs in this type of system: cross-current and counter-current packed-bed absorbers, the spray absorber and fluid-bed absorber.

In a laboratory pilot, plant, working lines for the absorbers were determined under adiabatic conditions. The influences of internal solution flow, gas flow, pressure drop and dissipation are discussed.

The working lines represent the efficiency for each absorber. The highest performance occurs with the packed-bed absorbers, followed by the fluid-bed absorber and finally the spray absorber.

For open absorption systems in air-conditioning applications (small scale), the cross-current absorber is preferable, and for industrial utilization (large scale) the fluid-bed absorber should be chosen.

INTRODUCTION

The open absorption system[1] (Fig. 1) consists of three parts: absorber, generator and condenser. The working medium (moisture in drying processes) is produced by an external system, which is a substitute for the evaporator in the closed cycle and is absorbed by the weak solution in the absorber. the strong solution goes to the generator, where evaporation occurs as a result of the primary-heat supply. Only the solution is recirculated; the working medium is separated from the system after the condenser.

Compared with the closed system, the open system has several advantages. Direct contact with an external system results in an increased overall heat-transfer coefficient. A large contact-surface is created because the solution medium exists as droplets. Hence, a more effective absorber is