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On the heating potential of buried pipes techniques — application in Ireland

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Abstract

The heating potential of a single earth-to-air heat exchanger as well as of a multiple parallel earth tubes system has been investigated in this paper using real climatic data. The heating system consists of a single tube or multiple parallel tubes, buried in the ground, through which ambient air is propelled and heated by the bulk temperature of the natural ground. The dynamic thermal performance of the system during the winter period and its operational limits have been calculated in Ireland using an accurate numerical model. For this reason multi-year ambient air and soil climatic measurements for the city of Dublin have been used as inputs to the model. Furthermore, an extensive sensitivity investigation was carried out in order to evaluate the effect of the main design parameters on the system's heating capacity. The key variables influencing the performance of earth-to-air heat exchangers were considered to be pipe length, pipe radius, air velocity inside the tube and pipe depth below the surface of the earth. Cumulative frequency distributions of the air temperature at the pipe's exit have been developed as a function of all the input parameters.

Keywords: Heating potential; Buried pipes; Ireland

1. Introduction

The use of passive and hybrid cooling techniques involving dissipation of the remaining excess heat of a building to a natural heat sink, like the ground, has gained an increasing acceptance during recent years [1].

Earth-to-air heat exchangers basically consist of pipes which are buried in the ground coupled with an air system which forces the air through the pipes and eventually mixes it with the indoor air of the building.

Various simplified models have been proposed in order to describe the thermal performance of the earth tubes system [2–7]. The majority of these models 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. For this reason they are unable to predict the humidity of the circulating air. Lack of knowledge on the humidity content of the circulated air does not allow for a complete evaluation of the comfort conditions in the building. On the other hand, these models cannot predict the temperature distribution in the ground as they do not take into account the coupled and simultaneous movement of heat and mass into the ground due to the pipes' presence. The ground temperature is quite important especially for agricultural greenhouses where this parameter is very significant.

Detailed simulation models of the thermal performance of earth-to-air heat exchangers are based on algorithms describing the coupled and simultaneous transfer of heat and mass in the soil under a temperature gradient [8–11]. Most of these models consider an axially symmetric heat flow into the ground neglecting the natural thermal stratification in the soil which alters the symmetry.

The use of accurate simulation models, although providing detailed results on the performance of the system, cannot be regarded as a practical tool for the design of a particular application. Therefore, for a large number of applications it is necessary to know the impact of the main system parameters on the thermal performance of the earth-to-air heat exchangers as well as the energy potential under real climatic conditions.

This paper aims primarily at investigating the dynamic heating potential of a single earth-to-air heat exchanger and of a multiple parallel pipe system under real climatic conditions in Ireland and, in this respect, to determine the feasibility of the whole system. Furthermore, the sensitivity of a single earth-to-air heat exchanger to different design parameters,

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6.7. Closing comments

The tremendous effects of fuel and heating system selection are clearly demonstrated in this work. Most of the conclusions are not restricted to the geographic regions of Turkey considered here for calculation purposes. As the detailed analyses presented here illustrate, a casual comparison simply on the basis of unit prices of fuels, boiler efficiencies or sulfur percentages could not provide sufficiently dependable results.

Faster growth in natural gas utilization should be encouraged with emphasis because of comfort and economy (i.e. personal) as well as energy and environment (i.e. national) interests. A closer control on imported coal is advisable because at present it provides no advantage over fuel oil. As already done in several cities, the use of lignite for heating should be stopped, and its use be limited to power generation, gasification or other similar conversions that could be done away from towns and with more control. Despite its clean and comfortable appearance, direct heating with electricity should be discouraged severely.

7. Nomenclature

a	annual, annum
A	annual cost (10^6 TL/a)
B14	building with 14 flats
B_a	total annual fuel consumption for space and/or water heating (unit of fuel/a)
C	central heating system
CO	coal (imported)
COP	coefficient of performance
CRF	capital recovery factor
C_w	specific heat of water (kJ/kg °C)
D	district heating system
DD	degree day (°C day/a)
DE	direct electric heating
E_{base}	total energy requirement of the selected base, I-NG (MJ/a)
E_{sys}	total energy requirement of the system (MJ/a)
e	escalation (inflation) rate
EUAC	equal uniform annual cost (10^6 TL/a flat)
F_0	a general adjustment factor
F_1	automatic control factor
F_2	dirt factor of the heat exchanger surface
F_3	utilization time factor
F_4	calcination factor
F_5	building size factor
FO	fuel oil
H_o	upper heating value of fuel (MJ/unit of fuel)
HP	heat pump
H_u	lower heating value of fuel (MJ/unit of fuel)
I	individual heating system
i	interest rate
LG	lignite
M_w	amount of hot water consumption (kg/flat)
NG	natural gas
n	service life (year)
P	present value of the cost elements
Q_n	heat loss of one flat (kJ/h)
R	real rate of interest
R_1	first heating region (warmest)
R_2	second heating region
R_3	third heating region
R_4	forth heating region (coldest)
TL	Turkish Lira (currency unit)
T_{od}	outside design temperature (°C)
UA	heat loss-area product of one flat (kJ/h °C)

Greek letters

δT	inside–outside design temperature difference
ϵ_b	maximum boiler efficiency
ϵ_d	distribution efficiency
ϵ_{eff}	overall (effective) performance factor of the boiler and system combination
ϵ_s	stoppage efficiency

Subscripts

s	space heating
w	water heating

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such as pipe length, pipe radius, air velocity inside the pipe and the depth of the buried pipe below the earth's surface has been evaluated.

Therefore, the effectiveness and the heating potential of the earth-to-air heat exchanger system are investigated and presented in a format suitable for designers' use.

2. Modelling of earth-to-air heat exchangers

A numerical, transient, implicit model based on coupled and simultaneous transfer of heat and mass into the soil and the pipe has been developed and presented in Ref. [12]. This model includes a complete mathematical description of moisture migration through the soil under a thermal gradient from higher to lower temperature regions and, simultaneously, tending to redistribute itself in reverse under the created moisture gradient. 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. On the other hand, the soil's natural thermal stratification was taken into account and soil surface boundary conditions were applied in order to predict the ground temperature distribution. The numerical method of control-volume formulation was used to discretise the partial differential equations describing the heat and mass transfer inside the tube and into the soil. This method, which can be regarded as a special and new version of the method of weighted residuals, looks like the finite difference method but it employs many ideas that are typical of the finite element methodology. The time dependency was best handled using implicit integration techniques. The fully implicit scheme satisfies the requirements of simplicity and of physically satisfactory behaviour.

Furthermore, the discretised algebraic equations were solved using the Gauss–Seidel iterative method.

The whole problem was considered a heat conduction problem. The overall thermal conductance of the whole earth-to-air heat exchanger system including air, pipe and soil (G) can be expressed by the following equation :

$$G=2lM/(1/r_{\mathrm{in}}h_{\mathrm{c}})+[\ln(R_{\mathrm{p}}/r_{\mathrm{in}})/K_{\mathrm{p}}]$$

where l is the pipe length (m), r_{in} the inner pipe radius (m), h_{c} the heat transfer coefficient (W/m^2 K), R_{p} the outer pipe radius (m), K_{p} the thermal conductivity of the pipe (W/m K).

Furthermore, the technique of superposition was used to calculate the thermal performance of multiple, parallel earth-to-air heat exchangers. Thus, the formulae calculating 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 [13] using the thermal conductance theory [14].

The whole model was developed inside the TRNSYS environment [15], which is a transient system simulation program with a modular structure that facilitates the addition of other mathematical models not included in the standard TRNSYS library. Thus, a separate module describing the thermal performance of a single pipe as well as of multiple parallel buried pipes was developed and connected with the main structural components of the TRNSYS program.

Finally, the proposed model has been successfully validated against an extensive set of experimental data [12,13]. Therefore, it has been substantiated that it 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 system of earth-to-air heat exchangers.

3. Assessment of the heating potential of the system

3.1. The heating potential of a single earth-to-air heat exchanger

The heating potential of a single 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 pipe below the earth's surface and the air flow velocity inside the tube.

In order to assess the thermal performance of the system using these input parameters, an extensive set of basic parametric studies was performed.

The thermal model described in the previous section was used to simulate the performance and the feasibility of a typical earth-to-air heat exchanger configuration [16,17].

Thus, the thermal performance of a plastic pipe of 125 mm in radius and 30 m in length buried in the ground at about 1.20 m below short-grass covered soil was simulated. The air velocity inside the pipe was equal to 8 m/s while the temperature rise due to the fan was considered to be 0.1 °C.

The calculations cover the time period 1974–1984 for December, January, February and March using hourly values of air and ground temperatures for Dublin Airport. The Irish Meteorological Service provided the data used in the present study. At this station, soil measurements are performed at the depths of 50, 100 and 200 mm below bare soil as well as at 0.3, 0.6 and 1.20 m depths under short-grass covered soil.

The soil thermal conductivity values used in the present study were obtained from Ref. [18] while the soil density and specific heat capacity were taken from Ref. [10].

The calculated cumulative frequency distributions of the air temperature at the pipe's inlet as well as at the pipe's outlet for January and for the whole heating period are given in Fig. 1 and Fig. 2, respectively. All hourly temperature values were collected and using a simple statistical program the frequency distribution and after that the cumulative frequency distributions of the above temperatures were calculated. From the results analysis it is estimated that the air temperature at the pipe's outlet would fluctuate in the range of 6.2 to 25.9 °C for December, 4.9 to 23.3 °C for January, 5.5 to 24.9 °C for February and 6.8 to 26.8 °C for March. The corresponding

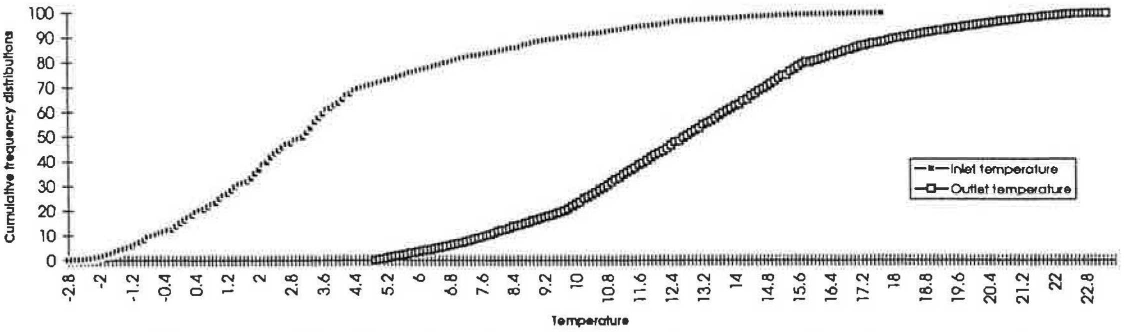

Fig. 1. The cumulative frequency distributions of the air temperature at the exit of a single earth-to-air heat exchanger for January.

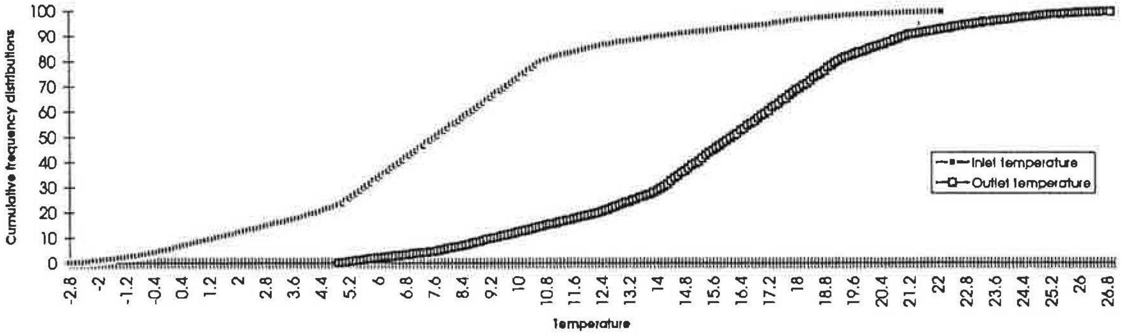

Fig. 2. The cumulative frequency distributions of the air temperature at the exit of a single earth-to-air heat exchanger for the whole winter period.

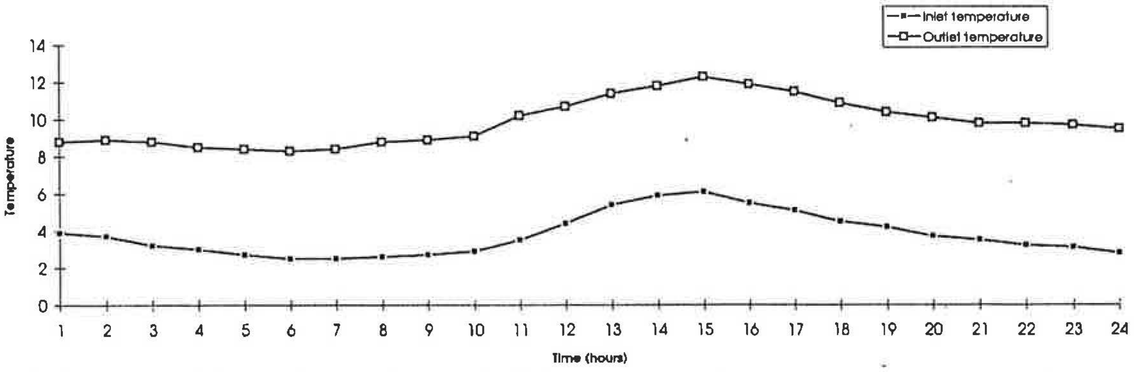

Fig. 3. Temporal variation for a typical winter day of the inlet and exit air temperature from a single earth-to-air heat exchanger.

measured inlet air temperature values are found to vary in the range of −1.5 to 20.3 °C for December, −2.8 to 17.7 °C for January, −2 to 18.2 °C for February and −1.1 to 22 °C for March.

The overall analysis indicated that a single earth-to-air heat exchanger can provide an effective method for space pre-heating in cold climates, and that the heating potential of the system during the winter is significantly important. During December, the outlet air temperature is always higher that 7 °C and for 50% of the period the temperature is above 15 °C. For January, February and March and for 50% of the cases the outlet air temperature is higher than 13, 14 and 16 °C, respectively.

The pre-heating effectiveness of the earth-to-air heat exchanger system is 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 single pipe with the previously described system configuration and for a typical winter day. From this figure it can be observed that the air temperature at the pipe exit fluctuated in the range of 8.3 to 12.3 °C while the inlet air temperature was between 2.5 and 6.1 °C.

3.2. Heating potential of multiple earth-to-air heat exchangers

In order to assess the heating potential of multiple parallel earth-to-air heat exchangers 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 plastic pipes of 30 m in length and 125 mm in radius, buried at a depth of 1.20 m below short-grass covered soil. The air velocity inside the pipes was 8 m/s

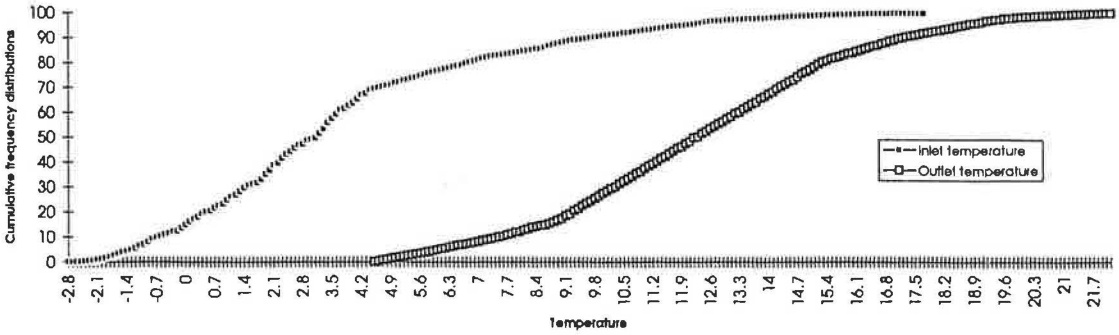

Fig. 4. The cumulative frequency distributions of the air temperature at the exit of an internal earth-to-air heat exchanger for January.

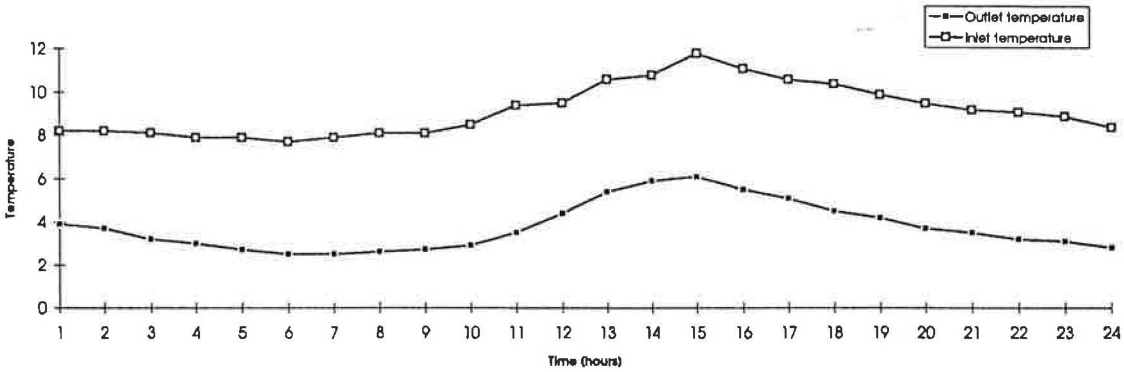

Fig. 5. Temporal variation for a typical winter day of the inlet and exit air temperature from an internal earth-to-air heat exchanger.

while the distance between the adjacent pipes was equal to 1.5 m.

The calculations cover the same time period (1974–1984) as previously, for December, January and February, using the same air and ground temperature hourly values for Dublin as inputs to the thermal model.

Cumulative frequency distribution of the air temperature at the exit of an internal pipe for January is given in Fig. 4. From the analysis it can be seen that the internal pipe's outlet air temperature varied from 5.8 to 24.2 °C for December, from 4.5 to 22.1 °C for January and from 5.1 to 23 °C for February while the inlet air temperature fluctuations were from −1.5 to 20.3 °C for December, from −2.8 to 17.7 °C for January and from −2 to 18.2 °C for February. As can be seen the outlet air temperature at the exit of the internal pipe is slightly lower than the air temperature at the exit of the single earth-to-air heat exchanger. The outlet air temperature difference is close to 0.6 °C and it is caused by the heat loss from the pipe to the adjacent pipes. This difference could be diminished by increasing the distance between adjacent pipes as shown in Ref. [13].

Finally, Fig. 5 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 and for the same typical winter's day. From this figure it can be seen that the outlet air temperatures varied in the range of 7.7 to 11.8 °C while as previously mentioned the inlet air temperature fluctuated between 2.5 and 6.1 °C.

4. Sensitivity investigation

In order to determine the impact of varying the parameters of the system on the thermal performance of a single earth-to-air heat exchanger buried under short-grass covered soil and for real climatic conditions at Dublin Airport, an extensive sensitivity analysis was performed for the time period 1974–1984, for the months of December, January, February and March. The key variables influencing the thermal performance of the system are pipe length, pipe radius, air velocity inside the pipe and the depth of the buried pipe below the earth's surface. For each variable, a sensitivity investigation was carried out for a range of values covering the existing design practice. The obtained results are discussed in the following sections.

4.1. Influence of pipe length

The simulations were performed for three different pipe lengths, 30, 50 and 70 m, maintaining the same basic system configuration for the values of the other parameters.

The cumulative frequency distribution of the air temperature at the exit of an earth-to-air heat exchanger for the three different pipe lengths for January is shown in Fig. 6. From the analysis it is estimated that for January the maximum exit air temperature was equal to 23.3 °C for 30 m pipe length, to 24.6 °C for 50 m and to 25.1 °C for 70 m. For February the exit air temperature fluctuated between 5.5 and 24.9 °C for

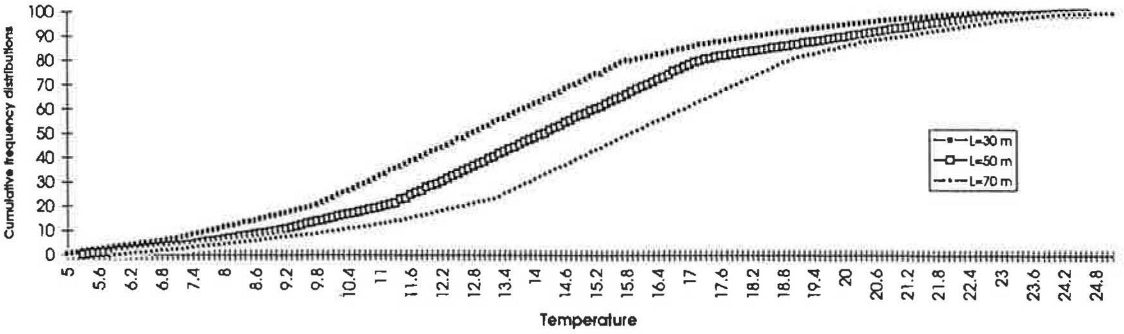

Fig. 6. The cumulative frequency distributions of the air temperature at the exit of a single earth-to-air heat exchanger for three different pipe lengths for January.

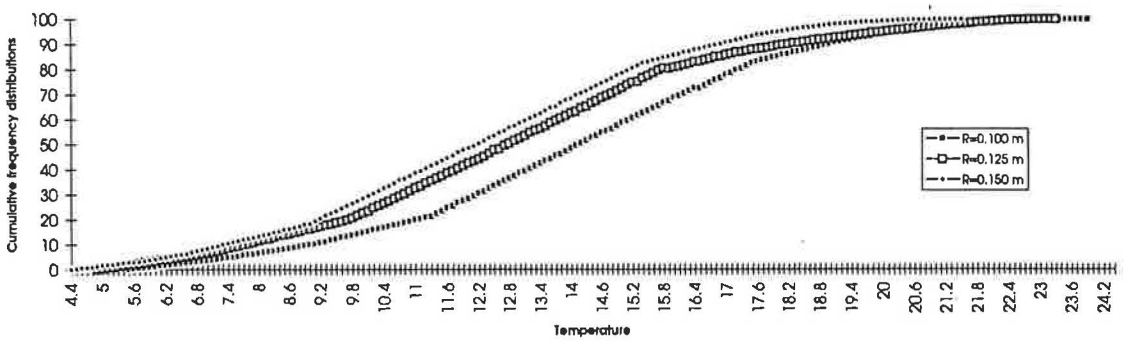

Fig. 7. The cumulative frequency distributions of the air temperature at the exit of a single earth-to-air heat exchanger for three different pipe radii for January.

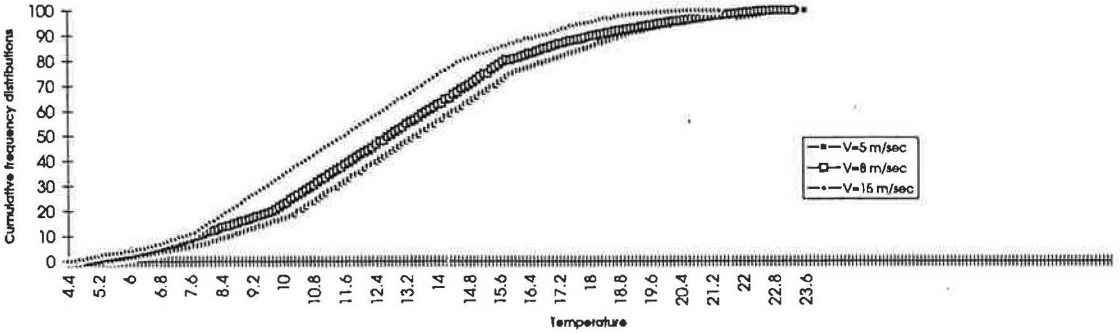

Fig. 8. The cumulative frequency distributions of the air temperature at the exit of a single earth-to-air heat exchanger for three different air velocities inside the pipe for January.

30 m pipe length, between 6.1 and 25.4°C for 50 m and between 6.8 and 25.9 °C for 70 m.

From these calculations, it can be observed that an increase of pipe length from 30 to 70 m provides a significant increase of the exit air temperature and, therefore, an improvement of the system's heating capacity.

4.2. *Influence of pipe radius*

The simulations used three different values of pipe radius, 100, 125 and 150 mm, while the other input parameters of the system remained unchanged.

Fig. 7 shows the cumulative frequency distributions of the air temperature at the three different pipe radii for January.

It is calculated that a reduction of the pipe radius from 150 to 100 mm increases the air temperature at the pipe's exit by 0.9–1.8 °C. However, in general terms, an increase of the buried pipe's radius represents a reduction of the convective heat transfer coefficient and an increase of the pipe surface so providing a lower air temperature at the pipe's outlet, thus reducing the heating capacity of the system.

4.3. *Influence of air flow velocity*

Three different air velocities inside the pipe (5, 8 and 15 m/s) were used for the investigation of the impact of air speed on the thermal behaviour of the system. The simulations were performed for these three air velocity values while the values of the other parameters remained as in the basic system configuration.

The cumulative frequency distributions of the air temperature at the pipe exit for the three different air velocities in

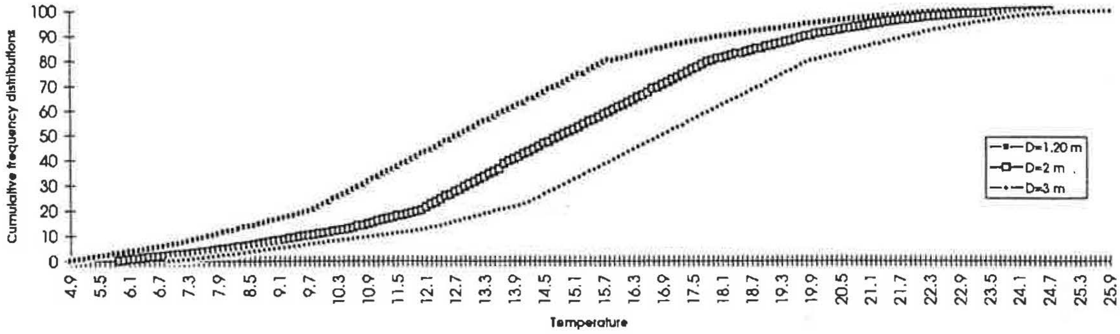

Fig. 9. The cumulative frequency distributions of the air temperature at the exit of a single earth-to-air heat exchanger for three different burial depths for January.

January are presented in Fig. 8. The outlet air temperature values fluctuated in the range of 5.5 to 23.6 °C for January and 6 to 25.4 °C for February for an air speed of 5 m/s.

When the air velocity was increased to 15 m/s, the range of temperatures at the pipe outlet decreased slightly for January (4.4–21.4 °C) and for February (5.1 to 22.3 °C).

The overall analysis demonstrated that a higher air velocity leads to a slight decrease of air temperature at the pipe exit and then to a reduction of the system's heating capacity. This outlet air temperature decrease is mainly caused by the increased mass flow rate inside the pipe as the air velocity is increased.

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-to-air heat exchanger system. Diurnal, seasonal and annual temperature variations, which vary with depth, should be taken into account in the storage design.

The undisturbed temperature field $T(z,t)$ at any depth z in the ground and at any time t can be written, using the analytical solution of the one-dimensional, transient, heat conduction equation, as [14]

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

where a is the ground thermal diffusivity, A_s is the amplitude of the temperature fluctuation at the ground's surface, T_m is the mean annual temperature at the ground's surface and t_0 is the phase lag.

Simulations were carried out for 1.2, 2 and 3 m depths, while all the other input parameters were the same as those of the basic configuration settings.

The effect of different soil temperature values on the temperature profiles for the month of January is clearly shown in Fig. 9. It is obvious that there is a considerable increase of the system's heating capacity potential with depth.

For a pipe buried at a depth of 1.2 m, it was estimated that the outlet air temperature fluctuated between 4.9 and 23.3 °C for January and between 5.5 and 24.9 °C for February. Accordingly, for a depth of 2 m the temperature variation is between 5.9 and 24.7 °C for January and 6.4 and 25.7 °C for February. Finally, for a depth of 3 m the exit air temperature varied in the range of 6.9 to 25.9 °C for January and of 7.3 to 26.4 °C for February.

5. Conclusions

The dynamic heating potential of a single earth-to-air heat exchanger as well as of multiple parallel pipes under real climatic conditions in Ireland has been investigated through realistic examples. Cumulative frequency distributions of the exchangers' performance were developed for the whole heating period.

Moreover, the sensitivity of the earth tube systems to different design parameters, such as pipe length, pipe radius, air velocity inside the tube and soil depth below the earth's surface was analysed. Therefore, a set of curves was created to simulate parameter changes in pipe length, pipe radius, air velocity and soil depth. Cumulative frequency distributions of the exchangers' performance were developed as a function of all the input parameters.

From the overall analysis it was demonstrated that the system can effectively be used for heating and especially for preheating the indoor air of a building.

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