was conducted based on questionnaires (for the employees) and on-site visits of a trained panel of engineers and scientists. Monitoring of specific pollutants has been performed for a central hospital in Athens.

It appears from this investigation that the office buildings clearly exhibit an indoor air quality problem, which is the direct cause of a number of employees' health symptoms. The highest percent of reported symptoms were the following: eye irritation, headaches, dizziness, drowsiness and unusual fatigue. The indoor air quality problem in most of the N/V buildings is also influenced by the poor outdoor air quality, which is a major problem in the area of Athens. A significant number of employees also complained for disturbed concentration, which is directly related to the location of the audited buildings in areas of heavy traffic and high outdoor noise levels.

A number of other correlations which were attempted between the reported employee health symptoms and the buildings' energy consumption and thermal comfort did not prove significant. It appears, that the information one may collect from conducting a study based on standard questionnaires has been exhausted.

For the next stage of the investigation, the study will include on-site measurements of the air pollutants in office buildings in Athens, which will then be extended to other major Hellenic cities.

Monitoring of the NO_2 and SO_2 levels in a hospital building did not exceed the WHO limit values for ambient air. However, the NO_2 concentrations found in this study were higher than the corresponding concentrations measured in buildings without known indoor sources. This is primarily due to the high concentration of pollutants in the outdoor environment.

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ON THE COOLING POTENTIAL OF EARTH TO AIR HEAT EXCHANGERS

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Abstract—The present paper deals with the cooling potential of earth to air heat exchangers. The cooling system consists of an underground pipe laid horizontally where ambient or indoor air is propelled through and cooled by the bulk temperature of the natural ground.

The dynamic thermal performance of the system during the summer period and its operational limits have been calculated using an accurate transient numerical model. Multiyear soil and ambient air climatic measurements have been used as inputs to the model.

An extensive sensitivity investigation has been performed in order to analyze the impact of the main design parameters on the cooling potential of the system. Cumulative frequency distributions of the exchanger's performance have been developed as a function of all the input parameters.

The present paper aims to simplify the procedure for accurate design and performance evaluation of earth to air heat exchangers and to provide information on their cooling potential.

Passive cooling Earth to air heat exchangers Cooling potential Energy performance of buildings

NOMENCLATURE

C_p = Specific heat capacity (J/kg °C)
$D_{u,vap}$ = Isothermal diffusivity of moisture in vapour form (m/s)
D_T = Thermal moisture diffusivity (m/s °C)
D_u = Isothermal moisture diffusivity (m/s)
h = Moisture content (kg of moisture/kg of moist soil)
k = Soil thermal conductivity (W/m °C)
l_s = Moisture heat of vaporization
r = Polar co-ordinate, radial distance from the tube axis (m)
T = Soil temperature (°C)
t = Time (s)
y = Polar coordinate, axial distance from the pipe inlet (m)

Greek characters

ϱ = Soil density (kg/m^3)
ϱ_m = Density of moisture (kg/m^3)

INTRODUCTION

The energy consumption of buildings for cooling purposes has increased considerably during the last decade. Especially in selective hot climate countries, the penetration of conventional air conditioning units is extremely important, having a serious impact on the peak electricity load.

Use of passive and hybrid cooling techniques involving dissipation of the remaining excess heat of the building to a natural heat sink, like the ground, have gained increasing acceptance in recent years.

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

Detailed simulation models of the thermal performance of earth to air heat exchangers are based on algorithms describing the simultaneous transfer of heat and mass in soils under a temperature gradient [1–5]. 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. An accurate and validated model, based on a complete mathematical description of moisture migration and heat conduction, taking into account the thermal stratification in the soil is given elsewhere.

The use of accurate simulation models, although providing detailed results on the performance of the system, cannot be considered as a practical tool for the design and dimensioning of a particular application. Simplified models to assess the effectiveness of the system have also been proposed [8–11]. However, for a number of practical applications, it is necessary to know the impact of the main input parameters on the thermal performance of the system as well as its cooling potential under real climatic conditions.

The main objective of this paper is, primarily, to investigate the energy potential of the earth to air heat exchanger under real climatic conditions in Greece and, in this respect, to determine the feasibility of the whole system. Furthermore, it is intended to contribute to the analyses of the system's sensitivity to different design parameters, such as the pipe's length, the depth of the buried pipe below the earth's surface, the pipe's radius and the air velocity. Therefore, the effectiveness and the cooling potential of the earth to air heat exchanger is investigated and presented in a format suitable for designers' use.

MODELLING OF EARTH TO AIR HEAT EXCHANGERS

A new, transient, implicit, numerical model based on coupled and simultaneous transfer of heat and mass into the soil and the pipe has been developed and presented in detail elsewhere [6, 7]. This model includes a complete mathematical description of the moisture migration through the soil under a thermal gradient from higher to lower temperature regions and, at the same time, tending to redistribute itself in reverse under the created moisture gradient.

The equations used for the description of the energy and mass balance of the system are written in the form:

$$\varrho c_{\mathrm{p}} \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) - l_{\mathrm{g}}\varrho_{\mathrm{m}}\frac{1}{r}\frac{\partial}{\partial r}\left(D_{\mathrm{u,vap}}r\frac{\partial h}{\partial r}\right) - l_{\mathrm{g}}\varrho_{\mathrm{m}}\frac{\partial}{\partial y}\left(D_{\mathrm{u,vap}}\frac{\partial h}{\partial y}\right) \quad (1)$$

$$\frac{\partial h}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(D_{\mathrm{T}}r\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial y}\left(D_{\mathrm{T}}\frac{\partial T}{\partial y}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(D_{\mathrm{u}}r\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial y}\left(D_{\mathrm{u}}\frac{\partial h}{\partial y}\right). \quad (2)$$

The numerical method of the control volume formulation was used to discretise equations (1) and (2), while the time dependency was best handled using implicit integration techniques.

The basic programme has been developed inside the TRNSYS environment. TRNSYS is a transient system simulation programme with a modular structure which facilitates the addition of other mathematical models which are not included in the standard TRNSYS library.

The model was validated against an extensive set of experimental data, and it was found that it predicts accurately the temperature of the circulated air, the temperature of the ground, as well as the overall thermal performance of the earth to air heat exchanger.

ASSESSMENT OF THE ENERGY POTENTIAL OF THE SYSTEM

Previous applications of earth to air heat exchangers [12–14], as well as their modelling [15–17], have indicated a broad range of input parameters, such as the tube length and diameter, the depth of placement of the exchanger, the speed of the air flow, etc.

In order to assess the thermal performance of earth to air heat exchangers using these ranges of values, comprehensive basic parametric studies have been performed. The calculation procedure followed to obtain the corresponding cooling potential of the exchanger is given here.

The thermal model described in the previous section is used to simulate the performance and the feasibility of a typical earth to air heat exchanger configuration [13–17]. Thus, the thermal

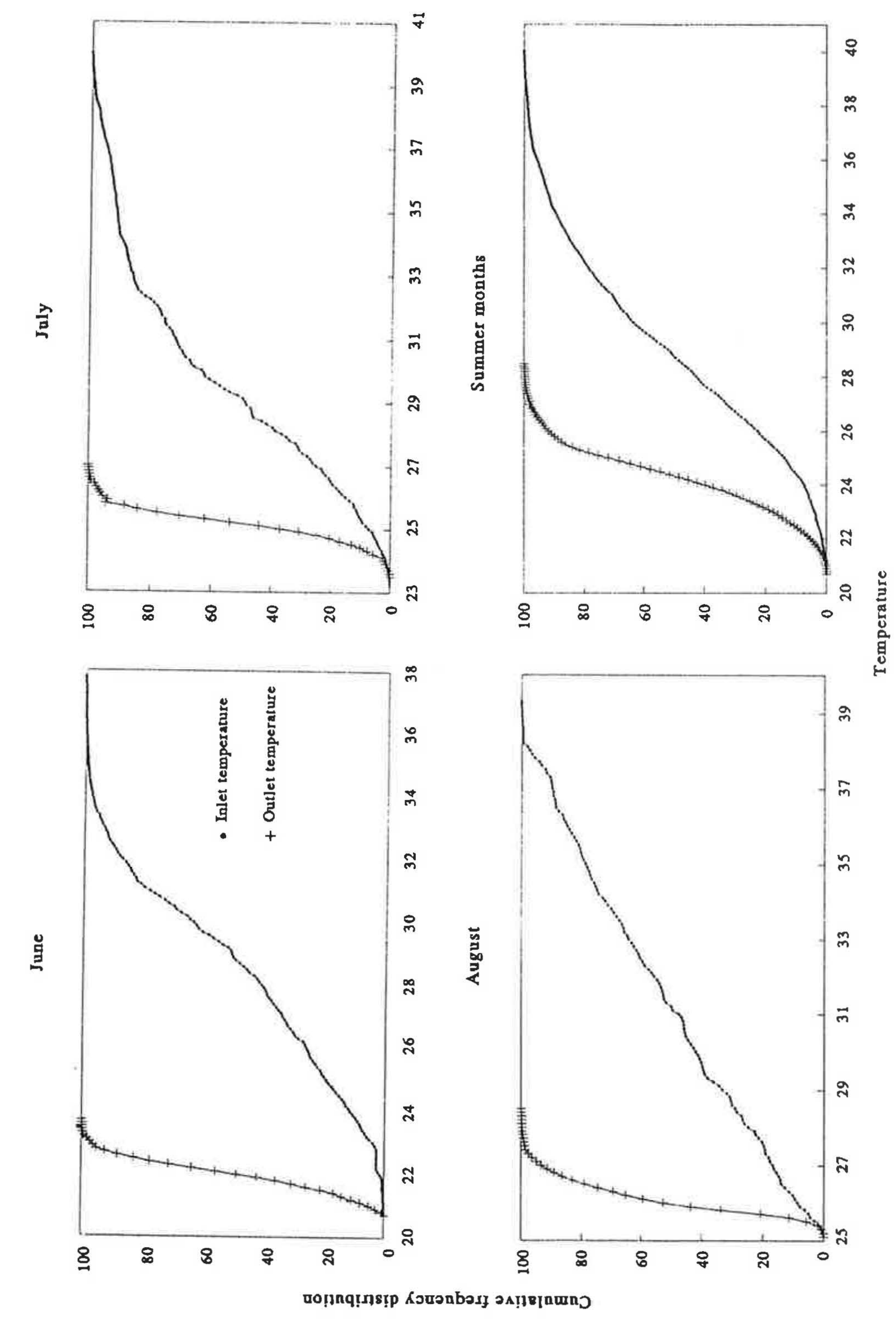

Fig. 1. Cumulative frequency distributions of the inlet and outlet air temperature from an earth to air heat exchanger for June, July, August and the whole summer period.

performance of a plastic pipe of 0.125 m in radius and 30 m in length buried in the ground at about 1.20 m and guiding air at a speed of 5 m/s was simulated. Calculations extend over the time period 1981–1990 for the months June, July and August using hourly values of the air and ground temperature and from 9 a.m. to 9 p.m.

The National Observatory of Athens station provided the data used in the present study. At this station, ground measurements are available from 1917 and are performed at the ground's surface over bare and short grass covered soil as well as at 0.3, 0.6, 0.9 and 1.2 m depths under the short grass covered soil. Based on these measurements, an accurate prediction model for the annual and daily variation of the ground temperature has been developed [18]. The soil thermal conductivity and diffusivity values used here were obtained from Refs [19] and [20], respectively, using an integration time step of 0.1 h for the computations.

The calculated cumulative frequency distributions of the air temperature at the pipe's inlet as well as at the pipe's outlet, for June, July, August and the whole summer period are given in Fig. 1. It is estimated that the air temperature at the pipe's outlet fluctuates in the range of 20.7–23.7, 23.3–27.0 and 25.1–28.5 for June, July and August, respectively. The corresponding measured inlet air temperature were found to vary in the range of 20.9–37.8, 23.2–40 and 25.3–39.3 for June, July and August, accordingly.

The overall analysis has shown that the cooling potential of the earth to air heat exchangers during the summer period is very important. During June, the outlet air temperature is always lower than 24°C, and therefore, the heat exchanger system can be used throughout the month, while for

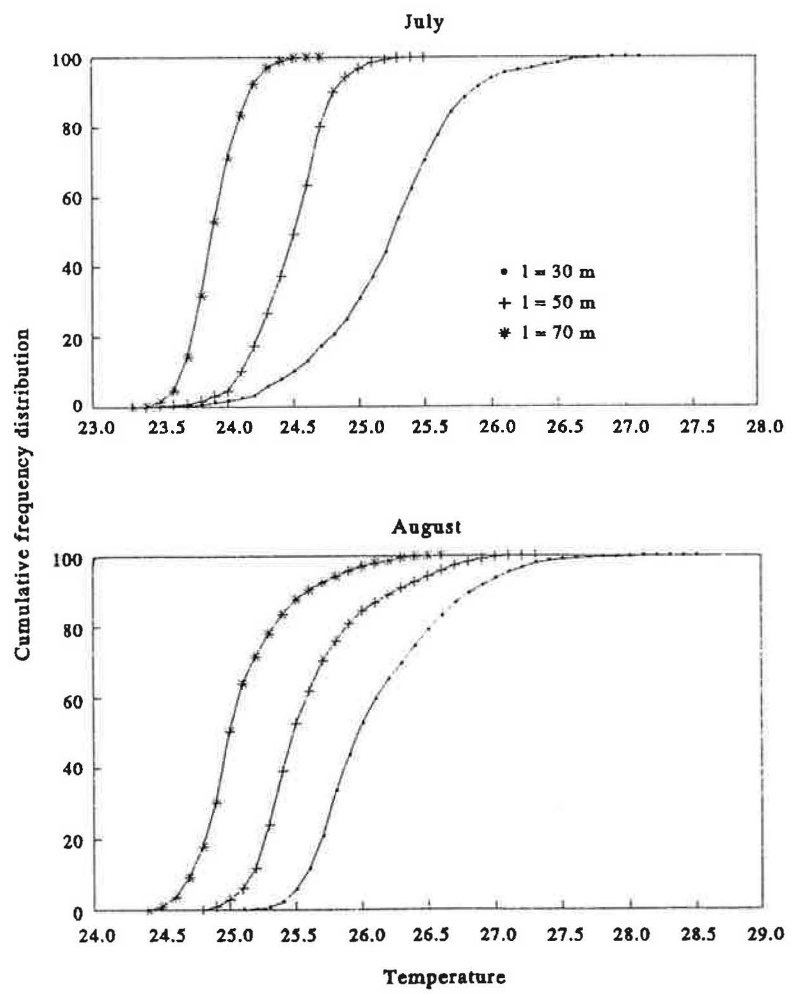

Fig. 2. Cumulative frequency distribution of the exit air temperature from an earth to air heat exchanger for 30, 50 and 70 m long pipes.

July, for almost 90% of the cases, it is lower than 25.5°C and for August is lower than 26°C for 70% of the period. Therefore, the system could be used efficiently for almost all the critical summer period covering the cooling load of the building.

In order to evaluate the effect of parameter variations on the system's performance under real climatic conditions, an extensive sensitivity analysis was carried out. In this respect, the influence of different pipe lengths, the depth of the buried pipe, the pipe's radius and the air velocity on the thermal efficiency of the whole system was investigated for the 1981–1990 period and for all the summer months.

SENSITIVITY ANALYSIS RESULTS

The key variables influencing performance are pipe length, pipe radius, air velocity and soil depth. For each variable, a sensitivity analysis has been carried out for a range of values covering existing design practice. The obtained results are discussed in the following sections.

Influence of pipe length

The simulations extend over three different values of pipe lengths, 30, 50 and 70 m, maintaining the same basic system configuration for the values of the other parameters. The cumulative frequency distributions of the air temperature at the exit of the exchanger for the three different pipe lengths for July and August are shown in Fig. 2. It is estimated that almost 97% of the outlet

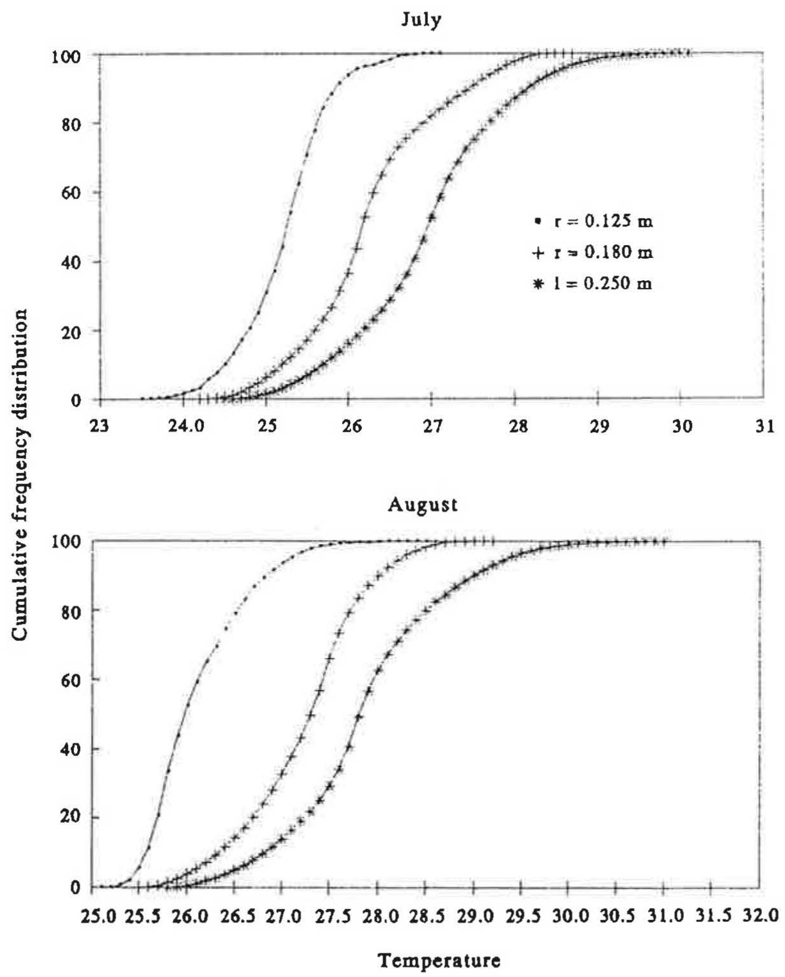

Fig. 3. Cumulative frequency distribution of the exit air temperature from an earth to air heat exchanger for 0.125, 0.18 and 0.25 m pipe radius.

temperature values are higher than 26.9°C for July and 28.2°C for August for a 30 m pipe length. Furthermore, for a length of 50 m, the temperature at the pipe's outlet was estimated to be 25.5 and 26.5°C for July and August respectively. Finally, for a 70 m pipe length, the outlet temperature of the air was found to be 24.7°C for July and 25.9°C for August.

From these calculations, it can be observed that, although the inlet air temperature is higher during July than August, the temperature at the pipe's outlet during August is consistently higher. This is mainly caused by the time lag of the ground temperature, which characterizes the retardation time of the temperature wave at various depths below the earth's surface through the year.

Influence of pipe radius

The performed simulations include three different pipe radii, 0.125, 0.180 and 0.25 m, while the other input parameters of the system remained unchanged. Figure 3 shows the cumulative frequency distributions of the air temperature at the three different pipe outlet radii for July and August.

It is calculated that a reduction of the pipe radius from 0.250 to 0.125 m lowers the air temperature at the pipe's outlet by 1.5–2.5°C. However, in general terms, an increase of the pipe's radius represents a reduction of the convective heat transfer coefficient, providing a higher air temperature at the pipe's outlet and thus, a reduction of the system cooling capacity potential.

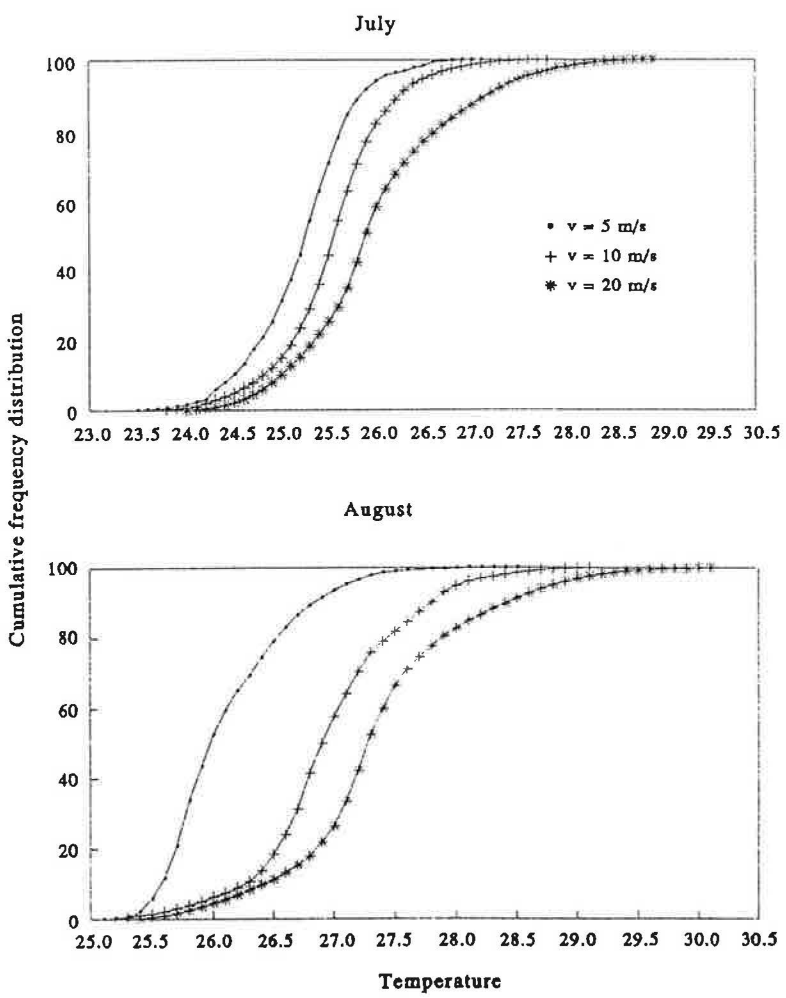

Fig. 4. Cumulative frequency distribution of the exit air temperature from an earth to air heat exchanger for 5, 10 and 20 m/s air velocities.

Influence of air flow velocity

Simulations have been carried out for 5, 10 and 20 m/s air velocities while the pipe length and radius as well as the soil depth remained unchanged, as in the basic configuration.

Figure 4 presents the calculated cumulative frequency distributions of the outlet air temperature for July and August for the three pre-selected air speeds.

It is found that the outlet air temperature values varied in the range of 23.8–27.8°C for July and 25.2–28.9°C for August, for 10 m/s air velocity.

Moreover, when the air velocity increased to 20 m/s, the range of temperatures at the pipe outlet shifted slightly, (23.8–28.9°C) for July and for August (25.3–30°C).

The overall analysis clearly demonstrated that higher air velocity leads to a slight increase of the outlet air temperature. In this respect, the convective heat transfer coefficient also increases, thus contributing to a more efficient heat exchange. However, the temperature increase at the pipe outlet is mainly attributed to the increased mass flow rate.

Influence of soil depth

The performance of any earth to air heat exchanger is obviously related to the earth's temperature, which varies with the soil depth. Therefore, diurnal, seasonal and annual variations have to be considered in the storage design.

Simulations have been carried out for 1.2, 2 and 3 m depths, while all the other input parameters were as those of the basic configuration settings. The effect of different soil temperatures on the

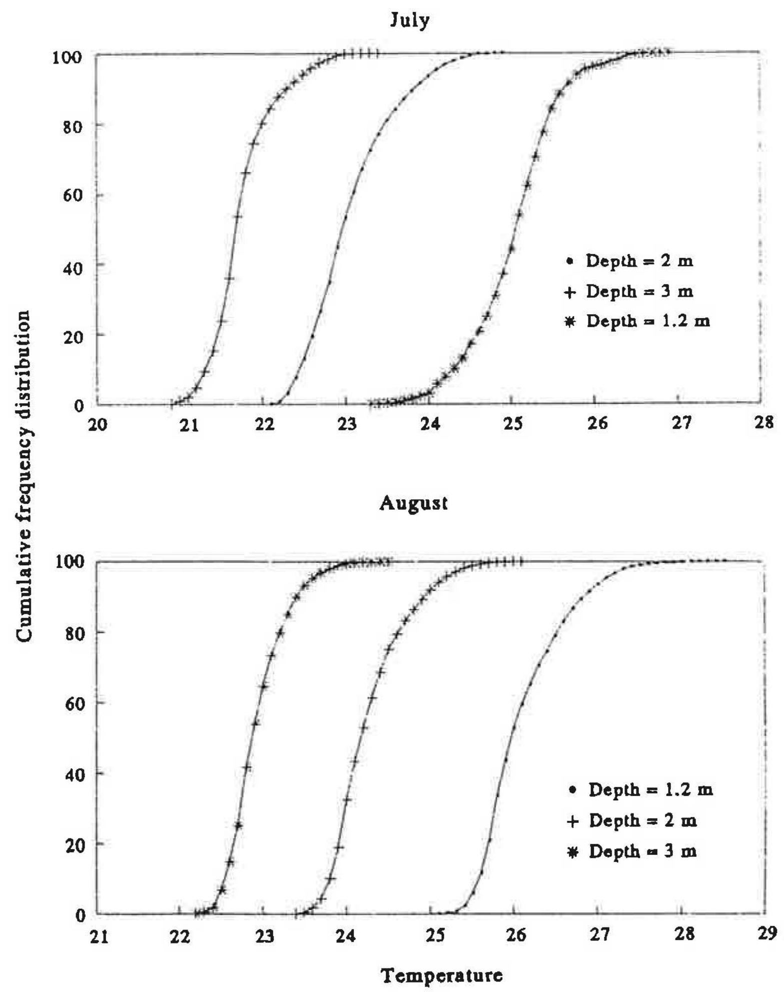

Fig. 5. Cumulative frequency distribution of the exit air temperature from an earth to air heat exchanger at 1.20, 2.0 and 3.0 m pipe burial depths.

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MULTIVARIABLE INTEGRAL CONTROL OF HYDRONIC HEATING SYSTEMS

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Abstract—State feedback control of a gas-fired hydronic heating system is studied. The system consists of a space heating circuit and a domestic hot water (DHW) circuit. Multiple input controllers are designed to regulate the mass flow rate of hot water flowing in both circuits and also to modulate the fuel firing rate in the burner. The control objective is to maintain the zone temperature and the DHW temperature close to some chosen setpoints. Comparisons are made between the output responses obtained from the state feedback controller with and without integral action.

Hydronic heating Temperature control Multivariable control Feedback Energy conservation

NOMENCLATURE

A = System matrix
a_b = Boiler exterior surface heat loss coefficient
a_w = Heat loss coefficient of DHW tank
a_z = Zone heat loss coefficient
B = Input matrix
C = Output matrix
C_b = Boiler thermal capacity
C_{pw} = Specific heat of water
C_w = Thermal capacity of DHW tank
C_z = Thermal capacity of zone air mass
D_1, D_2 = Disturbance matrices
$\underline{e}$ = Error vector
$\underline{K}_1, \underline{K}_2$ = Gain matrices
m_w = Rate of DHW consumption
t = Time
T_a = Ambient temperature
T_b = Boiler temperature
T_w = DHW temperature
$T_{w,sp}$ = DHW setpoint temperature
T_{wi} = Supply-water temperature to DHW tank
T_z = Zone-air temperature
$T_{z,sp}$ = Zone-setpoint temperature
U_1 = Control variable, space heating (dimensionless)
U_{1max} = Maximum mass flow rate of water in space heating circuit
U_2 = Control variable, boiler (dimensionless)
U_{2max} = Maximum natural gas supply rate to burner
U_3 = Control variable, DHW circuit (dimensionless)
U_{3max} = Maximum mass flow rate of hot water to DHW heat exchanger

Greek letters

ϵ_z = Heat-transfer coefficient, space heating circuit
ϵ_w = Heat-transfer coefficient, DHW circuit
α = Flue loss coefficient
θ = Servocompensator matrix
Ω = Servocompensator matrix
ξ = Output vector of the servocompensator

Superscript

t = Transpose