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PARAMETRIC PREDICTION OF THE BURIED PIPES COOLING POTENTIAL FOR PASSIVE COOLING APPLICATIONS

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Abstract—A new parametrical model for the prediction of the thermal performance of the earth to air heat exchangers is presented. The system consists of an earth tube, buried in the ground, through which ambient or indoor air is propelled and cooled by the bulk temperature of the natural ground. The proposed model has been developed by analysing temperature data of the circulated air at the pipe's outlet using a systematic parametrical process. Four variables influencing the thermal performance of the earth to air heat exchangers were taken into account: pipe length (L), pipe radius (r), velocity of the air inside the tube (V) and depth of the buried pipe below earth surface (D). The developed algorithm is suitable for the calculation of the exit air temperature, and therefore of the cooling potential of the system. The model was validated against experimental data as well as a data set which was obtained by an accurate numerical model describing the thermal performance of the earth tube system.

1. INTRODUCTION

The use of the ground natural potential for air conditioning has gained an increasing acceptance during the last years. (Santamouris *et al.*, 1994; Antinucci *et al.*, 1994).

Earth to air heat exchangers basically consist of the underground pipes 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.

Several models to predict the thermal performance of the earth to air heat exchangers have been proposed by Agas *et al.* (1993), Puri (1986), Rondriguez *et al.* (1988), Santamouris (1981), Santamouris and Lefas (1986), Schiller (1982) and Tzaferis *et al.* (1992).

A detailed and accurate numerical model describing the simultaneous heat and mass transfer inside the pipe and into the soil accounting for the soil natural thermal stratification and predicting the humidity of the circulating air inside the tube has been presented in Mihalakakou *et al.* (1994a).

This model, was developed inside the TRNSYS (1990) environment of the simulation program.

The numerical model of earth to air heat exchangers presents serious difficulties involving complex geometry, strong non-linearities, sensitive fluid-property variations, etc. Thus, it is difficult to be used by engineers and designers taking into account that it is not a simplified model and requires apart from the experience of using the model environment, the knowledge of some principles of numerical analysis and of course a great number of parameters involved in the model simulation deck. This paper aims at developing a reliable, accurate and efficient parametrical model which can be regarded as a "chart method" and it will be capable of providing the temperature values and the energy performance of the circulating air at the pipe outlet.

Four parameters, the pipe length and radius, the air velocity inside the tube and the depth of the buried pipes below earth surface are the only necessary inputs for the model.

The whole process consists of the parabolic regression analysis of the air temperature data, and the development of the model algorithm.

2. MODELLING OF EARTH TO AIR HEAT EXCHANGERS

A transient, implicit numerical model based on coupled and simultaneous transport of heat and mass in the soil and in the pipe has been presented in every detail elsewhere (Mihalakakou *et al.*, 1994a).

This thermal model was developed inside the TRNSYS (1990) environment which is a transient system simulation program with a modular structure which facilitates the addition of other mathematical models which are not included in the standard TRNSYS library.

The numerical model was validated against an extensive set of experimental data. This indicated that the model can accurately predict the temperature and the humidity of the circulating air, the distribution of temperature and moisture in the soil as well as the overall thermal performance of the earth to air heat exchangers.

In order to calculate the overall performance of the earth to air heat exchangers the following dimensionless parameter was defined:

$$U=(T_{in}-T_{und})/(T_{out}-T_{und}) \quad (1)$$

and

$$T_{in} \neq T_{und}, \quad T_{in} > T_{und}$$

where T_{in}, T_{out} and T_{und} are the air temperature at the pipe's inlet, the air temperature at the pipe's outlet and the undisturbed soil temperature, respectively.

Taking into account that T_{in} and T_{und} are system parameters with known values, the calculations of the U values depends on a knowledge of the air temperature at the exit of the pipe.

3. PARAMETRICAL MODEL DEVELOPMENT

3.1. Reference data

In order to predict the values of the U parameter, a systematic analytical process was followed. The extended numerical code was used to calculate values of the U parameter for various sets of input parameters.

An extensive sensitivity investigation has been performed in order to analyse the impact of the main design parameters to the system cooling potential. During this investigation, the soil moisture was considered to be one variable whose influence on the system thermal performance should be examined. The other variables were the pipe length, pipe radius, the soil depth below earth surface and the air velocity inside the pipe. Therefore, the two initial soil moisture levels considered in the sensitivity analysis (Mihalakakou *et al.*, 1994b) were 30 and 20%. The soil thermal conductivities were different at these two moisture levels. Their values were 1.32 W/m°C for 30% initial moisture and 0.89 W/m°C for 20%. When the soil moisture concentration falls to 13%, the thermal conductivity falls to 0.25 W/m°C. Furthermore, the influence of the two moisture levels on the air temperature inside the earth-to-air heat exchanger was investigated and it was found that the maximum difference at the outlet of the pipe was equal to 0.36°C. This difference can not provide any significant change in the outlet air temperature distribution. From this sensitivity analysis was found that four parameters present an important effect on the outlet air temperature: the pipe length, the pipe radius, the air velocity inside the pipe and the depth of the tube below ground surface. These four parameters influencing the outlet air temperature and thus the parameter U, were used in the simplified model in the following form:

(1) Pipe length (L)
(2) Pipe grant (SV), which is defined as follows: $SV=\pi r^2 V$ where r is the pipe radius and V the air velocity
(3) Depth of buried pipe below earth surface (D).

In order to produce an extensive set of U parameter values comprehensive basic parametric studies have been performed using the detailed thermal numerical model. The simulations performed extend over a large range of values of each parameter maintaining the same basic system configuration for the other two parameters, (see Table 1). This range of values corresponds to the actual earth to air heat exchanger configuration. The U parameter value which corresponds to the three input parameters, $L=30$ m, $SV=0.393$ m^3/s and $D=2$ m, was selected as the U reference value.

3.2. Methodology—regression technique

Regression analysis was used to create a data base of U parameter data corresponding to the previously mentioned extensive set of input parameter values. The whole process can be described by the following steps:

(1) The development of the reference U parameter values using a polynomial equation and regarding the parameter U as dependent variable and the parameter L as the independent variable.
(2) The selection of U parameter data using the regression analysis in order to express U as a function of the other two parameters (D and SV) and thus to calculate the contribution of D and SV to the U actual value.
(3) The calculation of the U parameter improved predictions by correcting the U reference value.

Table 1. The system parameters values used for the performed simulations

L(m)	SV(m^3/s)	D(m)	SV(m^3/s)	D(m)
10	0.393	0.50	0.907	3.50
15	0.425	0.75	1.005	3.75
20	0.458	1.00	1.056	4.00
25	0.528	1.25	1.108	4.25
30	0.565	1.50	1.162	4.50
35	0.604	1.75	1.216	4.75
40	0.643	2.00	1.272	5.00
45	0.684	2.25	1.330	5.25
50	0.726	2.50		5.50
55	0.770	2.75		5.75
60	0.814	3.00		6.00
	0.860	3.25		

The U values corresponding to the reference values for parameters SV and D were fitted to a third-degree polynomial function regarding the parameter L as the independent variable. Thus, the equation expressing the U reference distribution is written as follows:

$$U_{ref}(L)=a_0+a_1(L)+a_2(L)^2+a_3(L)^3;$$

$$SV=0.393 \text{ m}^3/\text{s} \quad \text{and} \quad D=2 \text{ m}.$$

Furthermore, a normalization of U values as regards the system parameters and separately for each parameters was performed.

In the normalization of parameter U one parameter of the system has been considered to be the dependent variable, while the other parameters were regarded as independent variables. Then a function should be found expressing the dependent variable using the regression analysis.

The normalization technique implies that the whole set of data should be sorted into relatively small groups of input parameters' data allowing for a very high correlation factor in the curve-fitting analysis.

Analytically, the system parameters were sorted into two groups. The first group includes the depth of the buried pipe (D) as the dependent variable for the normalization of parameter U and the parameters (SV) and length (L) as the two independent variables. The second group of parameters has pipe grant (SV) as dependent variable while the depth (D) and length (L) were considered to be the two independent variables for the U normalization.

The U coefficient data in each group were normalized with respect to the reference value of the dependent variable for each value of the two independent variables. Thus, considering that the first group of $U_{SVi,Lj}(D_t)$ is a numerical predicted value of U coefficient corresponding to the i, j and t values of the parameters SV, L and D, respectively, and that the $U_{SVi,Lj}$ is the U at the reference value for the dependent variable (D) and for the given value of the two independent variables (SV) and (L), the relevant normalized U parameter value could be written in the form:

$$U\text{norm}_{SVi,Lj}(D_t)=U_{SVi,Lj}(D_t)/U_{SVi,Lj}(D_{ref}). \quad (2)$$

Similarly, for the second group the normalized U value can be stated as follows:

$$U\text{norm}_{Di,Lj}(SV_t)=U_{Di,Lj}(SV_t)/U_{Di,Lj}(SV_{ref}) \quad (3)$$

where i, j and t are values of (D), (L) and (SV) parameters, respectively, and $U_{Di,Lj}$ represents the U value at the reference value of the dependent variable (SV) and at the given values of the two independent variables (D) and (L). Then, normalized U values were expressed as third-degree polynomial using the statistical technique of the regression analysis. Thus, the fitting equations could be written in the form:

$$U\text{norm}_{SVi,Lj}(D_t)=b_0+b_1(D)^2+b_3(D)^3 \quad (4)$$

$$U\text{norm}_{Di.Lj}(SV_t)=c_0+c_1(SV)+c_2(SV)^2+c_3(SV)^3. \quad (5)$$

The coefficients of these polynomials were calculated and included in the Appendix. The regression analysis has been performed using standard regression techniques. The correlation coefficient was very high, 0.95–0.99 in all cases.

After having considered the two groups of parameters used in the regression analysis, a U correction factor for each group of parameters has been defined in order to calculate the contribution of the other two parameters (D and SV) to the parameter U and thus to improve the U reference values providing the U actual value. For the first group of parameters, the corresponding correction factor is $Cf_{SV,L}(D)$ and for the second group of parameters is $Cf_{D,L}(SV)$. Thus, the correction factor which corresponds to the first group of parameters is denoted using the equation of normalization (2) as follows:

$$Cf_{SVi,Lj,}D_t=U\text{norm}_{SVi,Lj}D_t=U\text{norm}_{SVi,Lj}(D_t) \quad (6)$$

where i and j and t are equal to values of parameters SV and L and D considered in the regression analysis. The correction factor corresponding to the second group of parameters is defined using eqn (3) as follows:

$$Cf_{Di,Lj}SV_t=U\text{norm}_{Di,Lj}SV_t=U\text{norm}_{Di,Lj}(Sv_t) \quad (7)$$

where i, j and t are the values of parameters