USE OF RESPONSE FACTOR METHOD TO MODEL EARTH-TO-AIR HEAT EXCHANGER BEHAVIOUR. INTEGRATION IN A WHOLE BUILDING SIMULATION INTO SIMSPARK PLATFORM

Pierre Tittelein[1], Etienne Wurtz[1], Gilbert Achard[1]
[1]LOCIE, CNRS FRE 3220, INES-RDI, Université de Savoie, Campus Scientifique Savoie Technolac, 73376 Le Bourget du Lac, Cedex, France

ABSTRACT

This paper shows the numerical model of an earth-to-air heat exchanger. The system is discretized into "n" sections perpendicular to the exchanger pipe. In each section, conduction is solved using response factor method in order to reduce computational time. Each response factor is calculated using a finite element program that solves 2D conduction problems. The particularity of this problem is that time-constants are very high, making it impossible to use classical properties of response factors to reduce the number of calculations. We will set out a new approach to solve this particular problem. Heat flux entering the pipe is then expressed as a function of the temperature of the air that circulate in the pipe and the external thermal driving forces. A heat balance is then applied for each layer to find the resulting outlet air temperature. The model is then compared to an analytical model and a 3D model based on the dynamic finite volume approach. Finally an example of coupling between an earth-to-air heat exchanger and a low-consumption building is presented.

INTRODUCTION

An earth-to-air heat exchanger is a simple system consisting of buried pipes in which outside air circulates before entering a building. Thanks to the ground thermal mass, the air is preheated during the winter and cooled during the summer. After a literature review of the existing models, this paper presents a new model of earth-to-air heat exchanger based on the response factor method that reduces the physical problem. The model is then verified thanks to a comparison with two other models and, finally, the influence of an earth-to-air heat exchanger on the building behaviour is studied.

Many models of earth-to-air heat exchangers developed for buildings or horticultural greenhouses applications can nowadays be found in the literature.

Analytical models

In order to evaluate simply the outlet air temperature, several authors (Tzaferis, Liparakis et al., 1992; Serres, Trombe et al., 1997; De Paepe and Janssens, 2003; Ghosal and Tiwari, 2006; Tiwari, Akhtar et al., 2006) consider that the inside surface temperature T_{sp} does not vary along the pipe. Outlet air temperature can then be evaluated analytically. The surface temperature of the pipe is connected to the ground temperature using the thermal resistance of the pipe. Some authors consider that the ground temperature is constant by blocks (Serres, Trombe et al., 1997). Others (De Paepe and Janssens, 2003; Ghosal and Tiwari, 2006; Tiwari, Akhtar et al., 2006) analytically calculate the response of a semi-infinite wall solicited by a periodic surface temperature:

$$T_{soil}\left(z,t\right)=\overline{T_{sse}}-A_{sse}\cdot e^{-z\cdot\sqrt{\frac{\omega}{2\cdot a}}}\cdot cos\left(\omega\cdot t-z\cdot\sqrt{\frac{\omega}{2\cdot a}}\right) \quad (1)$$

The problem of these basic models is that the influence of the pipe on the ground temperature is not considered. In order to solve this problem, an analytical model was developed by Hollmuller (2003); it considers the complete analytical solution for the heat diffusion of a cylindrical air/soil heat-exchanger with adiabatic or isothermal boundary condition, submitted to constant airflow with harmonic temperature signal at input. The cylindrical volume of the ground considered is given a priori. The analytical solution reveals an influence diameter (formula (2)) which depends on the solicitation period.

$$\delta=\sqrt{\frac{a\cdot P}{\pi}} \quad (2)$$

The real solicitation is decomposed in Fourier series so that the system's response can be calculated by superposition of the analytical response on various sinusoidal components constituting this solicitation. The model thus provides a complete analytical response to the dynamic problem but does not consider the possible influence of exchanges between the ground and the external environment nor does it consider the real geometry.

Numerical models

Among the numerical models of the literature, some consider that only part of the ground is influenced by the exchanger (in the rest of this paper, we will refer to them as "type A models"), while others consider the entire geometry of the problem ("type B models").

Type A models

Several models consider the single-pipe exchanger problem by considering that only a cylinder of ground around the pipe is disturbed by the exchanger (Mihalakakou, Santamouris et al., 1994; Giardina, 1995; Kumar, Ramesh et al., 2003). Ground is divided into concentrical cylinders. Each cylinder can be divided into angular portions. Finite differences or finite elements methodes are then used to solve the problem considering a fixed temperature on the boundary given by formula (1).

The model presented by Thiers and Peuportier (2008) considers the interaction between several parallel pipes. A finite volume formulation with a limited number of meshes is used; this allows very fast calculation. For each pipe, two concentric cylindrical meshes are used. If pipes are distant enough, another cylindrical mesh is considered; if they are too close, the third mesh includes every pipe, so as to take their interactions into account. On the external surface of this third mesh, a temperature is imposed that is equal to the temperature of the undisturbed ground (calculated once again by the formula (1)). This model can take into account the influence of the building on the exchanger.

Type B models

The other models of the literature consider the exchanges more precisely with a 2D or a 3D approach. Badescu (2007) proposes a segmentation in sections that are perpendicular to the pipes (vertical). On each section, the heat equation is solved using the volume control formulation method. The interaction between different sections is made with the energy balance of the pipe (no lateral heat transfer on the ground). Two models of earth-to-air exchangers can consider multiple pipe layers (Boulard, Razafinjohany et al., 1989; Gauthier, Lacroix et al., 1997). Those models are based on a dynamic 3D approach using finite differences on a parallelepipedic control volume with adiabatic boundaries. A model was developed on this basis by Hollmuller (Hollmuller and Lachal, 2001); it can consider more complex geometries, more ground characteristics and more boundary conditions. It uses the finite elements method for the resolution. It can also consider water infiltrations, pressure losses and the control of the direction of air-flow in the pipes.

The problem of this kind of model is that in order to precisely describe exchanger behaviour, calculation time can be considerable due to the mesh required. That is why the model presented in this paper proposes a reduction method for the conductive problem in the ground.

MODEL DEVELOPED

The numerical model developed is based on a 2D approach. Its originality is that it proposes a reduction of the problem thanks to the convolutive response factor method. The system is discretized in n sections that are perpendicular to the pipe (Fig. 1).

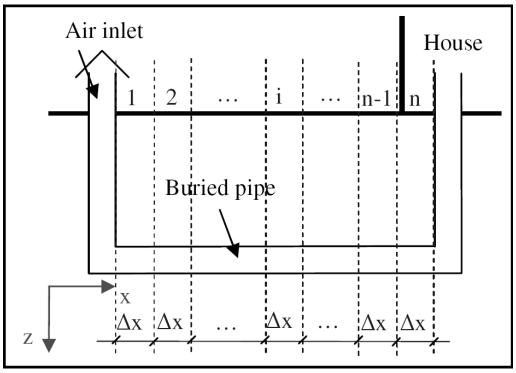

Figure 1: Discretization of the earth-to-air heat exchanger

For each section, the heat flux q'_{sp} that enters the pipe (in W/m) has to be evaluated as a function of the external thermal driving forces and of the air temperature in the pipe T_{ap}.

To evaluate this flux, conductive transfers are treated separately from other heat transfers as a function of the surface temperature of the soil T_{sse} and the surface temperature of the pipe T_{sp}. These temperatures are calculated with surface heat balances.

Heat balance at the surface of the pipe

In view of the hypothesis of surface temperature uniformity in a section, there is considered to be no radiative exchange on the internal surface of the pipe. The heat balance is thus reduced to a conductive flux from the soil and a convective flux between the internal surface of the pipe and the air. To evaluate the convective coefficient it is necessary to know the characteristics of the flow using dimensionless numbers that characterize it (Nusselt, Reynolds and Prandtl number). Many correlations have been used in the literature to link these three numbers. The simplified formulation proposed by Hollmuller (2002) was chosen here:

$$Nu = 0,214 \cdot \left(Re^{0.8} - 100\right) \cdot Pr^{0.4} \qquad (3)$$

Heat balance at the ground surface

Heat balance at the surface of the ground considers convective exchanges, long wave radiation and shortwave radiation:

$$q'_{sse} = \left(q''_{conv} + q''_{swr} + q''_{lwr}\right) \cdot L_{infl} \qquad (4)$$

Evaporation is here neglected. This equation reveals a length of influence because the conductive term is expressed in W/m whereas the convective and radiative terms are flux densities in W/m². The way to evaluate this length is presented later

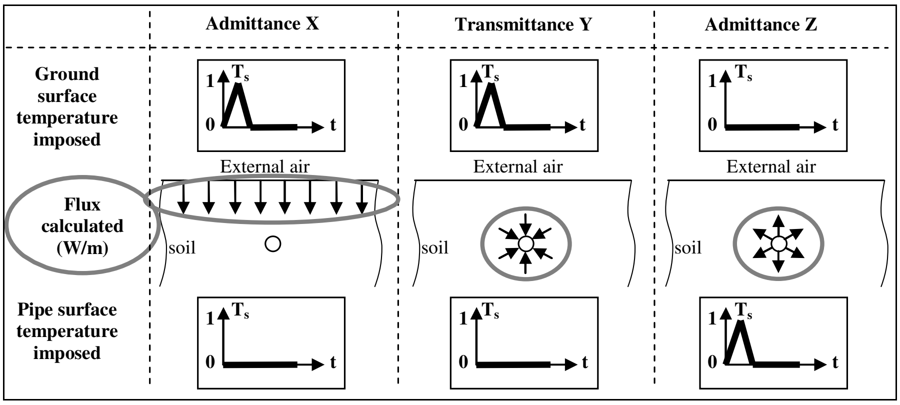

Figure 2: Solicitations and flux considered for calculations of response factors

Evaluation of conductive flow by the response factor method

A response factor represents the flux (here in W/m) resulting from a unitary triangular temperature solicitation on one of the boundaries while leaving the other boundaries at a temperature equal to zero. For the configuration with one buried pipe, three response factors called admittance X, transmittance Y and admittance Z have to be calculated (see Fig. 2). For this calculation, the solicitation time step can be different for admittance X and admittance Z. A computational 2D finite element program is used to find response factors using the real geometry of the ground and the pipe (considering only conduction).

To use the results given by response factors, it is necessary to decompose the solicitations (surface temperature of the pipe and of the ground) into elementary triangular solicitations. Then, output signals can be recomposed by superposition:

$$q'_{sp}(t)=\sum_{i=0}^{\infty} Y[i]\cdot T_{sse}(t-i\cdot\Delta t_y)-\sum_{i=0}^{\infty} Z[i]\cdot T_{sp}(t-i\cdot\Delta t_z) \quad (5)$$

$$q'_{sse}(t)=\sum_{i=0}^{\infty} X[i]\cdot T_{sse}(t-i\cdot\Delta t_x)-\sum_{i=0}^{\infty} Y[i]\cdot T_{sp}(t-i\cdot\Delta t_y) \quad (6)$$

The infinite sums appearing in the former relations are numerically impracticable. To avoid this problem while retaining precision, it is generally considered that response factors have a geometric progression starting from a given row (Peavy, 1978). The common-ratio of this sequence can be calculated with this formula:

$$cr = exp\left(-\frac{\Delta t}{\tau_{max}}\right) \quad (7)$$

τ_{max} is the principal time-constant of the studied system which, unfortunately in our case, is very high because of thermal mass of the ground. That is why the common-ratio has a value very close to 1. It can therefore not be used to construct the series of “conduction transfer functions” (CTF) necessary to use the theory of Peavy (1978). To reduce the infinite sums, a second property of the response factors is used. It results from steady state conduction problem:

$$q'_{sp,SS}=T_{sse}\cdot\sum_{i=0}^{\infty} Y[i]-T_{sp}\cdot\sum_{i=0}^{\infty} Z[i] \quad (8)$$

$$q'_{sse,SS}=T_{sse}\cdot\sum_{i=0}^{\infty} X[i]-T_{sp}\cdot\sum_{i=0}^{\infty} Z[i] \quad (9)$$

In steady state, these two fluxes are equal and can be calculated by:

$$q'_{sse,SS}=q'_{sp,SS}=K\cdot\left(T_{sse}-T_{sp}\right) \quad (10)$$

where K is the steady-state conductance of the system between the surface of the ground and the pipe. By identification, it can be found:

$$\sum_{i=0}^{\infty} X[i]=\sum_{i=0}^{\infty} Y[i]=\sum_{i=0}^{\infty} Z[i]=K \quad (11)$$

This formula allows one to evaluate the sum of the terms for a row higher than n_Z:

$$\sum_{i=n_Z+1}^{\infty} Z[i]=K-\sum_{i=0}^{n_Z} Z[i] \quad (12)$$

Idem for X and Y

This calculation is done only once for the entire simulation. To determine the value of K, the finite elements program is used in steady-state mode with the mesh that previously allowed the calculation of the response factors. The series which occur in the relations (5) and (6) can now be written in the following form:

$$\sum_{i=0}^{\infty} Z[i]\cdot T_{sp}(t-i\cdot\Delta t_z)= \sum_{i=0}^{n_z} Z[i]\cdot T_{sp}(t-i\cdot\Delta t_z)+\sum_{i=n_z+1}^{\infty} Z[i]\cdot T_{sp}(t-i\cdot\Delta t_z) \quad (13)$$

Idem for X and Y

To simplify the second sum of this equation, it is considered that for a row higher than n_Z, the effect of the temperature can be averaged:

$$\sum_{i=n_Z+1}^{\infty} Z[i]\cdot T_{sp}(t-i\cdot\Delta t_1)\#\overline{T_{sp}}\cdot\sum_{i=n_Z+1}^{\infty} Z[i] \quad (14)$$

Idem for X and Y

Equation (5) can then be written:

$$q'_{sp}(t)=\sum_{i=0}^{n_Y} Y[i]\cdot T_{sse}(t-i\cdot\Delta t_y)+\overline{T_{sse}}\cdot\left(K-\sum_{i=0}^{n_Y} Y[i]\right) -\sum_{i=0}^{n_Z} Z[i]\cdot T_{sp}(t-i\cdot\Delta t_z)-\overline{T_{sp}}\cdot\left(K-\sum_{i=0}^{n_Z} Z[i]\right) \quad (15)$$

In the same way, equation (6) gives:

$$q'_{sse}(t)=\sum_{i=0}^{n_X} X[i]\cdot T_{sse}(t-i\cdot\Delta t_x)+\overline{T_{sse}}\cdot\left(K-\sum_{i=0}^{n_X} X[i]\right) -\sum_{i=0}^{n_Y} Y[i]\cdot T_{sp}(t-i\cdot\Delta t_y)-\overline{T_{sp}}\cdot\left(K-\sum_{i=0}^{n_Y} Y[i]\right) \quad (16)$$

Heat balance along the earth-to-air heat exchanger pipe

Thanks to equations presented before, it is possible to give, for each section, a relation between air temperature in the pipe, external solicitations and the flux from the ground to the pipe. It is now necessary to apply a heat balance along the pipe in order to determine how the air temperature changes in the pipe. For each section a mesh of air contained in the pipe is associated. Neglecting energy storage in the air, the heat balance on a mesh can be written as

$$q'_i\cdot\Delta x+\rho_{air}\cdot S\cdot C_{air}\cdot u\cdot\left(T_{i-\frac{1}{2}}-T_{i+\frac{1}{2}}\right)=0 \quad (17)$$

Temperatures used in the formula are average temperatures of the meshes on each side. For the first mesh, T_{i-1} is the outside temperature. For the last mesh, T_{i+1} is the outlet temperature of the pipe.

Choice of adjustment parameters for calculation

The method presented before give us some freedom for the calculation. This paragraph presents the choices made for the adjustment parameters.

Choice of the solicitation time step for the calculation of response factors

Two constraints limit the choice of the solicitation time step (half of the triangle base). It must be higher or equal to the overall simulation time step and it must make it possible to reproduce the solicitation fairly faithfully. As the thermal driving forces are weather data (temperature and solar radiation), a good representation will not be obtained within a time step of more than three hours. The time step for solicitations can be different for the three response factors but in order to make no more than two calculations by the finite element program, it is simpler to choose the same time step for transmittance Y and for one of the two admittances. Therefore, the same time step is taken for admittance X and transmittance Y because these two response factors have very high time constants (the time constant of admittance Z is much lower).

Choice of the parameters n_X, n_Y and n_Z

These parameters represent the number of terms of the series which appear in the calculation of conductive flux (see formulae (15) and (16)). To choose them, the response factors property given by the equation (11) is used. The idea is to consider the much significant terms of the response factor:

$$\sum_{i=0}^{n_Z} Z[i]=K\times 90\% \quad (18)$$

Idem for n_X and n_Y

If this single criterion were used, the numbers could be very high because of the very high time-constants of these two response factors. Therefore, a second criterion is used to limit the temperature history considered to one year:

$$n_z\cdot\Delta t_z\leq 1\,yr \quad (19)$$

Idem for n_X and n_Y

Choice of the mean temperature value to be considered

The choice of the mean temperatures to be considered in the formulae (15) and (16) must also be related to the thermal mass of the phenomenon studied. A criterion similar to that used for the number of terms in the series defined previously is also used by calculating the average surface temperature as follows:

$$\overline{T}_{sp}(t)=\frac{\sum_{i=n_Z+1}^{2\cdot n_Z} T_{sp}\left(t-i\cdot\Delta t_Z\right)}{n_Z} \quad (20)$$

Idem for n_X and n_Y

Mean temperature is evaluated at each time step with n_Z terms that precede the last term used to make the complete calculation of the sum.

Choice of the influence length

The influence length considered in formula (4) is evaluated thanks to steady state calculation carried out to determine conductance of the system. In this calculation, a constant temperature is imposed on the ground surface (1°C) and on the pipe surface (0°C). The heat flux entering the ground surface is then printed. The area under this curve between two limits situated on each side of the pipe's abscises is calculated. This area, representing a flux in W/m, is compared with the conductance of the system. L_{infl} is then defined as follows:

$$\int_{-\frac{L_{infl}}{2}}^{\frac{L_{infl}}{2}} q''_{sse} \cdot dx = K \times 90\% \quad (21)$$

i.e. L_{infl} corresponds to the length through which 90% of the total flux arriving in the pipe in steady state has crossed the surface of the ground.

Initialization of calculation

For the calculation using the response factors, one needs to know the temperature history over a given period; during this same period, the flux arriving in each mesh is regarded as null. The calculation really starts after this initial period. Regarding the criterion (19) that is often reached, the time from which the calculation is carried out is two years.

VERIFICATION OF THE MODEL

The model presented here was implemented on the SIMSPARK simulation platform (Tittelein, 2008), that is, an object-oriented equation-based environment created to study building energy behaviour on the basis of the SPARK environment (Lawrence Berkeley National Laboratory and Ayres Sowell Associates Inc, 2003). For verification, it was compared to two other models developed by Hollmuller. The analytical model (Hollmuller, 2003) is implemented in a program called BURIEDPIPES© and the 3D finite elements program that was experimentally validated (Hollmuller, 2002) is implemented in TRNSYS (Type 460). Four configurations are studied. The characteristics of earth-to-air heat exchanger studied are:

- Dimensions of the pipe: 20 m long, radius: 10 cm
- Soil: conductivity - 1.49W/(m.K), density - 1800 kg/m^3, heat capacity - 1340 J/(kg.K)
- Air flow in the pipe: 250 m^3/h

Two depths are considered for the pipe, 60 cm and 2 m. In order to precisely compare the different results, two sinusoidal solicitations are studied; one with a 1-day period, the other with a 1-year period. The same air temperatures are imposed on the inlet of the pipe and above the ground; no radiation is considered.

Parameterisation of the problem in BURIEDPIPES©

In BURIEDPIPES©, a Fourier decomposition of the inlet air temperature is done. In these cases, solicitations are sinusoidal, so the decomposition uses only the first mode. The penetration depth "δ" (see formula (2)) allows one to know the validity domain of this model. For the soil used and a daily solicitation, the penetration depth is about 15 cm. It means that the amplitude of the 1-day period sinusoidal signal decreases by 63% at a distance of 15 cm from the pipe and by 99% at 75 cm (5•δ). For a 1-year period solicitation, the penetration depth is about 3 m. This means that the analytical model will give a good estimation of the exchanger behaviour for a 1-day periodic simulation even if the pipe is quite close to the surface of the ground, but not for a 1-year periodic solicitation. The radius of the cylinder of soil considered in this analytical method is equal to the depth of the pipe and the boundary considered on the surface of the cylinder is adiabatic.

Parameterisation of the problem in SIMSPARK

The time step chosen for calculation of the three response factors is equal to the global simulation time step (thirty minutes). The influence length found with equation (21) is around 8 meters when the pipe is 60 cm deep and 25 meters for a pipe that is 2 meters deep. In order to calculate the response factor, the width of the soil considered for the mesh must be higher than this influence length (10 m for a depth of 60 cm and 30 m for a 2 m depth were chosen). The depth of the soil considered for the mesh is a function of the penetration depth of the temperature signal. 20 m was chosen because it is more than five times the penetration depth of a 1-year periodic solicitation (15 m) that is considered as the highest solicitation period encountered in real conditions. A very fine triangular mesh is used around the pipe. It can be very thin because this calculation is made only once (about 2000 meshes per section). Ten 2 m thick sections are considered with adiabatic boudaries.

Table 1: Values that reach the number of terms of the sum (solicitation time-step: 1800 s)

Pipe depth	n_X	n_Y	n_Z
60 cm	17520* (1 yr)	6550 (136 days)	490 (10 days)
2 m	17520* (1 yr)	17520* (1 yr)	3590 (75 days)

*: second criterion reached

(.): correspond-ding time

Table 1 shows the number of terms considered here in the series of formulae (15) and (16) and for the calculation of mean temperature. We see that for a fairly shallow pipe (60 cm), the second condition (formula (19)) is reached for n_X, i.e. even at a shallow depth, the time-constant of admittance X is very high. n_X will thus always correspond to a calculation of one year.

Parameterisation of the problem in TRNSYS, Type 460

The dimensions of the ground considered with this model are the same as those considered in SIMSPARK but the mesh can not be as fine because of the simulation time that would be considerable. The mesh is composed of rectangles which are smaller next to the pipe and the surface of the ground than elsewhere (about 600 meshes for each section). Each buried boundary is adiabatic. The initialisation temperature of the soil is the mean temperature of the solicitation (here 10°C).

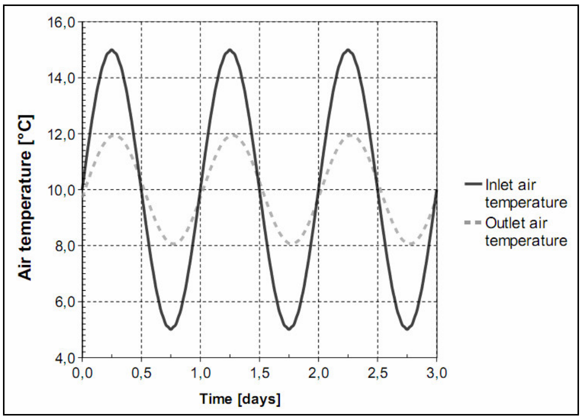

Figure 3: Response of the earth-to-air heat exchanger submitted to daily sinusoidal solicitations

Comparison of the results

For the 1-day period case, the results of the three models are very similar (this is why Fig. 3 presents only one outlet air temperature). For the 1-year period case (Fig. 4), there is a considerable difference between the analytical model and the others. In order to show the variance between the models, phase difference and damping between outlet and inlet air temperatures are shown in table 2.

Table 2: Phase difference and damping between outlet and inlet air temperature of earth-to-air heat exchanger; model comparison

Model used		ANALY – TICAL		NUMERICAL			
		BURIEDPIPES © (Hollmuller, 2003)		SIMSPARK: model of this paper		Type 460 TRNSYS (Hollmuller and Lachal, 2001)	
Solicitation period	Pipe depth	Phase difference	Damping	Phase difference	Damping	Phase difference	Damping
1 day	60 cm	33 min	62.6 %	33 min	61.0 %	37 min	60.2 %
	2 m	33 min	62.6 %	35 min	60.4 %	38 min	60.0 %
1 year	60 cm	7.0 days	1.7 %	5.5 days	10.3 %	5.7 days	11.1 %
	2 m	14.1 days	40.7 %	10.3 days	23.0 %	10.3 days	23.8 %

For the 1-day period case, the most precise model is certainly the analytical one because of the low penetration depth (15 cm). We can see that SIMSPARK's results are very close to those of the analytical model, no doubt because its meshing is thinner than that of Type 460. For the 1-year period case, we explained above that the analytical model was out of its validity domain; this is why the results are so different from those of numerical models. The numerical models show the same phase difference of about 6 days for a 60 cm deep pipe and of about 10 days for a 2 m deep pipe. The results are very similar for SIMSPARK and Type 460.

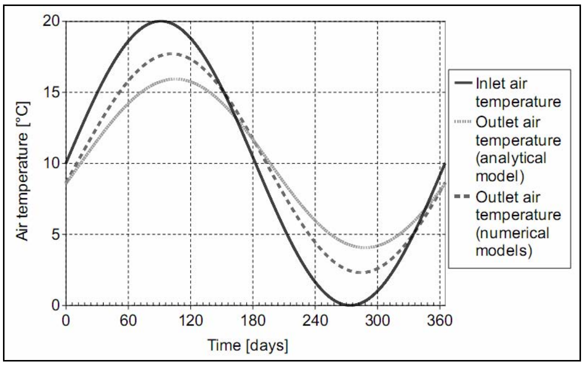

Figure 4: Response of the earth-to-air heat exchanger submitted to yearly sinusoidal solicitations

These observations lead us to conclude that our model makes a good simulation of the response to both 1-day and 1-year period solicitations. It should also be able to represent the response to a realistic solicitation that is not very different from a composition of these two basic solicitations.

INFLUENCE OF AN EARTH-TO-AIR HEAT EXCHANGER ON THE BUILDING BEHAVIOUR

The model of an earth-to-air heat exchanger was coupled to the existing building model implemented in the SIMSPARK platform. The building studied is a two storey low-consumption house that is to be built in the National Institute for Solar Energy (Chambéry, France) in an experimental platform called INCAS. Its net floor area is about 100 m² and its envelope is composed of 20 cm of heavy concrete and 20 cm of insulating material. The outlet air temperature of the earth-to-air heat exchanger is connected to the heat recovery ventilation system via a by-pass that permits the selection of the inlet temperature most suited to the building behaviour. The characteristics of the earth-to-air heat exchanger and the soil studied are the same as those presented for the verification.

Table 3: Heating demand: effect of the earth-to-air heat exchanger

VENTILATION TYPE		HEAT RECOVERY SYSTEM			CLASSICAL SYSTEM		
Earth-to-air heat exchanger		none	Pipe depth: 60 cm	Pipe depth: 2 m	none	Pipe depth: 60 cm	Pipe depth: 2 m
Heating demand	[kW.h/(m².yr)]	18	16	15	36	27	24
	[MJ/(m².yr)]	64.8	57.6	54	130	97.2	86.4

The air flow in the pipe is linked to the building's air change rate of 0.5 volume per hour during normal periods (this value correspond to what is imposed by French legislation) and 4 volumes per hour when over-ventilation is required. The weather data used are those of Chambéry in 2005 (45.6°N, 5.86°E).

In table 3, we can see that the effect of an earth-to-air heat exchanger on the heating demand of the building is very low (2 to 3 kW.h/(m².yr) gain) when a heat recovery ventilation system is used. Gains are about equivalent to the consumption of the fan that is necessary to create the air flow in the pipe. If traditional ventilation is used, the gain is higher (9 to 12 kW.h/(m².yr)). This is because the earth-to-air heat exchanger and the heat recovery ventilation system have the same role of preheating the air entering the building. In any case, 2 m deep pipe seems to be more efficient than 60 cm deep pipe.

To characterise the summer behaviour of the building, the adaptive comfort temperature defined for France in (McCartney and Nicol, 2002) is used. It is considered that the comfort zone is within 2.5°C of this temperature. Table 4 shows that the number of hours out of the comfort zone can be reduced significantly with a 2 m deep pipe but not with a 60 cm deep pipe.

Table 4: Summer comfort: effect of the earth-to-air heat exchanger

EARTH-TO-AIR HEAT EXCHANGER:	NONE	PIPE DEPTH: 60 cm	PIPE DEPTH: 2 m
Number of hours out of comfort zone	188 h	156 h	74 h

This particular example is not presented to make a general conclusion about this kind of system but rather to show that a precise integrated simulation of an earth-to-air heat exchanger coupled with a building will certainly help one to determine when the system can really be useful.

CONCLUSION

This paper proposes a new numerical model to simulate earth-to-air heat exchangers.

Advantages of the model

- Calculation time is reduced by the use of the response factor method while the model remains dynamic.
- It is precise for a short solicitation period (1-day) as well as for a long solicitation period (1-year).
- Every kind of soil characteristic (inhomogeneous, anisotropic etc.) and of geometry can be considered due to the response factor calculation in a 2D finite elements program.
- Multiple pipes exchangers could be considered with their interaction by calculating more response factors.
- By its implementation in the SIMSPARK platform, it is easy to study the coupling with a building.

Drawbacks of the model

- Axial conduction transfers in the ground are not considered. This seems to have little consequence on the final results regarding the verification made with a 3D program.
- It does not consider the presence of a building near the pipe that could influence the ground temperature
- It would be time-consuming to simulate a system with a many pipes (excessive programming and simulation time)

Discussion

With the low-consumption buildings that are now appearing, it is important to know if the earth-to-air heat exchanger is efficient, in which configuration and in what climatic conditions. To answer these questions, it is necessary to simulate precisely, quickly and dynamically their influence on the behaviour of buildings. For this reason, thanks to the reasonable calculation time and the easy coupling with the building model in the SIMSPARK platform, the new model proposed would seems to be very interesting.

However, it is important to put into perspective the results given by every kind of earth-to-air heat exchanger models regarding the insufficient knowledge of ground composition and soil thermal characteristics. The validity domain of the model (like most, perhaps all, other models) is also limited to the case where no moving ground water is situated next to the exchanger pipe .

ACKNOWLEDGEMENTS

The authors gratefully thank Frédéric Kuznik (CETHIL, Lyon, France) and Pierre Hollmuller (Universidade de Lisboa, Portugal) for their precious help in the verification of the model with Type 460 of TRNSYS.

NOMENCLATURE

a	Thermal diffusivity of soil	$[m^2.s^{-1}]$
A_{sse} signal	Semi-amplitude of the surface temperature [K]	
C	Heat capacity	$[J.kg^{-1}.K^{-1}]$
Cr	Common ratio	[-]
D	Diameter of the pipe	[m]
K	Conductance of the problem	$[W.m^{-1}]$
L_{infl}	Length of influence	[m]
L_p	Length of the pipe	[m]
$\dot{m}$	Air flow in the pipe	$[kg.s^{-1}]$
n_X, n_Y, n_z relative to	Number of terms considered in the series response factors X, Y and Z	[-]
Nu	Nusselt number	[-]

P	Period of a signal	[s]
Pr	Prandtl number	[-]
q'_{sp}	Flux entering the pipe at its surface	$[W.m^{-1}]$
q'_{sse}	Flux entering the ground at its external surface	$[W.m^{-1}]$
q''_{conv}	Convective flux	$[W.m^{-2}]$
q''_{lwr}	Long wave radiation flux	$[W.m^{-2}]$
q''_{swr}	Short wave radiation flux	$[W.m^{-2}]$
Re	Reynolds number	[-]
t	Simulation time	[s]
$\overline{T}$	Mean value of the temperature T	[K]
T_{ap}	Air temperature in the pipe	[K]
T_{inlet}	Air temperature at pipe inlet	[K]
T_{outlet}	Air temperature at pipe outlet	[K]
T_{soil}	Soil temperature	[K]
T_{sp}	Inside surface temperature of the pipe	[K]
T_{sse}	External surface temperature of the ground	[K]
u	Air velocity	$[m.s^{-1}]$
X[i]	i° value of admittance X (idem for Y and Z)	$[W.m^{-1}]$
z	Depth in the soil	[m]
Greek		
δ	Depth of penetration	[m]
Δt	Simulation time step	[s]
Δt_X	Solicitation time step to calculate admittance X (idem for Y and Z)	[s]
λ_{air}	Conductivity of air	$[W.m^{-1}.K^{-1}]$
μ_{air}	Dynamic viscosity of air	[Pa.s]
ρ_{air}	Density of air	$[kg.m^{-3}]$
τ_{max}	Maximal time constant of a system	[s]
ω	Pulsation of a signal	$[rad.s^{-1}]$

REFERENCES

Badescu, V. (2007). "Simple and accurate model for the ground heat exchanger of a passive house." Renewable Energy **32**(5): 845-855.

Boulard, T., E. Razafinjohany, et al. (1989). "Heat and water vapour transfer in a greenhouse with an underground heat storage system part II. Model." Agricultural and Forest Meteorology **45**(3-4): 185-194.

De Paepe, M. and A. Janssens (2003). "Thermo-hydraulic design of earth-air heat exchangers." Energy and Buildings **35**(4): 389-397.

Gauthier, C., M. Lacroix, et al. (1997). "Numerical simulation of soil heat exchanger-storage systems for greenhouses." Solar Energy **60**(6): 333-346.

Ghosal, M. K. and G. N. Tiwari (2006). "Modeling and parametric studies for thermal performance of an earth to air heat exchanger integrated with a greenhouse." Energy Conversion and Management **47**(13-14): 1779-1798.

Giardina, J. J. (1995). Evaluation of ground coupled heat pumps for the state of Wisconsin, University of Wisconsin-Madison. **Masters of science**.

Hollmuller, P. (2002). Utilisation des échangeurs air/sol pour le chauffage et le rafraîchissement des bâtiments. Mesures in situ, modélisation analytique, simulation numérique et analyse systémique. Genève, Faculté des Sciences de l'Université de Genève. **Ph. D thesis:** 176 p.

Hollmuller, P. (2003). "Analytical characterisation of amplitude-dampening and phase-shifting in air/soil heat-exchangers." International Journal of Heat and Mass Transfer **46**(22): 4303-4317.

Hollmuller, P. and B. Lachal (2001). "Cooling and preheating with buried pipe systems: monitoring, simulation and economic aspects." Energy and Buildings **33**(5): 509-518.

Kumar, R., S. Ramesh, et al. (2003). "Performance evaluation and energy conservation potential of earth-air-tunnel system coupled with non-air-conditioned building." Building and Environment **38**(6): 807-813.

Lawrence Berkeley National Laboratory and Ayres Sowell Associates Inc (2003). SPARK 2.0 reference manual.

McCartney, K. J. and J. F. Nicol (2002). "Developing an adaptive control algorithm for Europe." Energy and Buildings **34**(6): 623-635.

Mihalakakou, G., M. Santamouris, et al. (1994). "Modelling the thermal performance of earth-to-air heat exchangers." Solar Energy **53**(3): 301-305.

Peavy, B. A. (1978). "A note on response factors and conduction transfer functions." ASHRAE Transactions **84**(Part 1).

Serres, L., A. Trombe, et al. (1997). "Study of coupled energy saving systems sensitivity factor analysis." Building and Environment **32**(2): 137-148.

Thiers, S. and B. Peuportier (2008). "Thermal and environmental assessment of a passive building equipped with an earth-to-air heat exchanger in France." Solar Energy **82**(9): 820-831.

Tittelein, P. (2008). Environnements de simulation adaptés à l'étude du comportement énergétique des bâtiments basse consommation. Chambéry (France), Université de Savoie. **Ph.D Thesis:** 220 p.

Tiwari, G. N., M. A. Akhtar, et al. (2006). "Annual thermal performance of greenhouse with an earth-air heat exchanger: An experimental validation." Renewable Energy **31**(15): 2432-2446.

Tzaferis, A., D. Liparakis, et al. (1992). "Analysis of the accuracy and sensitivity of eight models to predict the performance of earth-to-air heat exchangers." Energy and Buildings **18**(1): 35-43.