ENERGY PERFORMANCE OF EARTH-AIR HEAT EXCHANGER: IMPACT OF VARIOUS INPUT PARAMETERS ON SIMULATION RESULTS

Stephane Ginestet[1], Jerome Lopez[2], and Stephanie Decker[2]
[1]Université de Toulouse, Laboratoire LMDC, EA3027 Université Paul Sabatier Toulouse 3 - INSA de Toulouse, 135 avenue de Rangueil, Toulouse, France.
[2]Nobatek, Esplanade des Arts et Métiers, Talence, France.

ABSTRACT

Earth-air heat exchangers can be considered as one of the current responses to the problem of rational use of energy and comfort in buildings. The aim of the Effipuits project is to validate the thermal performance of this solution experimentally and numerically for an oceanic climate. The modelling of an earth-air heat exchanger is considered through a critical review of the various tools. Then, the paper discusses the energy performance of an installation. Based on experimental site characteristics, two simulation tools were used, DesignBuilder / EnergyPlus and Pleiades + Comfie®. The results enabled the input data used by these tools to be analyzed and a critical analysis of the tools allowed the input data models to be refined.

INTRODUCTION

One of the current responses to the problems of rational use of energy in the housing sector may be provided by the use of earth-air heat exchangers. They are now frequently installed in low-energy HQE ® labelled projects ("haute qualité environnementale" in French, stands for high environmental quality - building label) but little work has been done to validate the energy savings on site, through commissioning procedures for example. The Effipuits project aimed to validate, experimentally and numerically, the thermal performance and the impact on the quality of indoor air of these solutions in an oceanic climate (Aquitaine, France). The project therefore addressed the earth-air heat exchanger in its different phases: design, implementation, use and dismantling. The main objective of the project is to disseminate knowledge so that the technology can be developed with full information on all the difficulties associated with the use and implementation of earth-air heat exchangers.

This paper focuses on the modelling of the earth-air heat exchanger via both thermal dynamic simulation software and feedback from experience in situ. Software packages are often used to carry out the design of earth-air heat exchangers but the main difficulty lies in the precise definition of their input data and the model parameters that enable them to represent reality. The study presented here is similar to a study in the design phase, but also allows some differences in modes of operation to be explained.

The first part of the communication gives a summary of the models used to describe the physical phenomena encountered in earth-air heat exchangers. In a second step, the on-site instrumentation and the input data it collects are presented. Two commonly used software packages are then described and the results of the simulations are given. One of the sites instrumented for the project serves as the basis for comparing the models used in the numerical simulation. Based on a part of the work done during the Effipuits project, the aim of the paper consists here in the search for an explanation of the significant discrepancy in the final result. An input parameter (weather) and a model parameter (soil) will be investigated.

A FEW BIBLIOGRAPHIC ELEMENTS

The whole study of an earth-air heat exchanger can be very consistent if comprehensive, detailed modelling is carried out. The aim of this section is to give an overview of current literature. The studies found mainly compare simulation and experimental surveys to validate the numerical model used. However, these studies are often limited to rather restricted experimental values and tend to make over-restrictive assumptions. They are generally accompanied by a theoretical analysis of heat exchange. Finally, some authors try to adjust the settings for sizing (pipe diameter, length of piping, flow, etc.) to maximize the energy performance of the earth-air heat exchanger.

Modelling the exchanges in the ground

The phenomena involved in an earth-air heat exchanger are complex to model. The first difficulty lies in the representation of heat transfer within the soil to determine the temperature at the level of the tubes of the heat exchanger. Once this has been dealt with, it is possible to calculate the thermal exchanges that take place between the air and the heat exchanger tubes and within the tubes in order to obtain the temperature of the air supplied to the building.

- Simplified modelling

Many studies (De Paepe et al. 2003, Badescu et al. 2003, Ghosal et al. 2006) use a simplified way of modelling the air temperature at the outlet of the earth-air heat exchanger. These models, often confined to a linear configuration with a single tube, take soil temperature as a parameter without considering how it may be influenced by the exchange between the air in the heat exchanger and the ground. Thus the soil temperature is similar to a simplified sine function depending solely on depth and time.

- Hollmuller model

Hollmuller's doctoral thesis is now one of the main references for earth-air heat exchangers (Hollmuller, 2002). Based on theoretical analytical modelling of the depth and also many in-situ measurements, the author establishes basic rules for the design of these exchangers. The dynamics of the heat exchange and the influence of different physical characteristics of the soil are studied in an ideal case (single tube in the ground). After an adimensionalization of the problem, the study describes the complete analytical solutions to simulate the heat exchange occurring between a tube and the surrounding soil. The dynamics of thermal storage is carried for the soil analyzed: the heat exchanger is regarded as a filter acting on the thermal signal, which is the temperature of the incoming air. The author discusses the damping capacity and phase shift of the signal as a function of its frequency of variation.

- Thiers model

More recently, Thiers (Thiers, 2008) considered a model constructed as the superposition of three independent phenomena: conduction in the soil temperature signal from the surface (the effect of weather conditions, including wind), conduction of heat flow from a building near the ground portion considered (influence of the building on the ground temperature) and, finally, conduction flow from the soil (geothermal heat flow).

- Other models

The literature contains few models close to previous. For example, Badescu (Badescu et al., 2007) proposes a model of heat transfer in the ground in two dimensions, based on a heat balance at the surface and a single-pipe heat exchanger model. This model has the advantage of having a reduced mesh (22 cells). However, the system of nonlinear equations must be solved via a tool for solving partial differential equations.
Bojic (Bojić et al. 1997) proposes an even simpler, one-dimensional model with only eight horizontal mesh cells for the ground. The heat exchanger tubes are placed in one of these cells, in parallel, with regular spacing. Neither a variable temperature profile along the tubes nor the influences of the nearby building are taken into account. On the other hand this is the only study that considers the coupling of the heat exchanger with the indoor building environment.
Tzaferis (Tzaferis et al. 1992) conducted a comparative study of several models using a discrete calculation of the length of the tube in each case. He concluded that there was a limit beyond which the configuration changes had no effect on the outlet temperature, with an error of about 3.5% on average compared to the experimental results.
Other authors (Mihalakakou et al. 1994) use an output temperature prediction parameter. Considering the influential parameters as design criteria (length of tube, tube diameter, air velocity and depth of burial), they develop an algorithm based on the use of a nomogram to predict the temperature according to the configuration installed.
Finally, the model implemented in the WKM software (Huber et al. 2006) incorporates a finite difference approach (3 concentric volumes of soil) and considers variable soil temperature. It is quite close to the model developed in Thiers' thesis (Thiers 2008).

Modelling other exchanges

Other parameters are essential to the definition of the thermal dynamics of the system. Among these, it is important to note: the total air flow, the number and diameter of the tubes, the air velocity in the tubes, the tube length, the distance between tubes, the depth of tubes and the nature of the soil and its moisture content.

- Solar radiation

Solar radiation arriving at the ground heats the surface. For models involving a calculation of soil temperature, the heat balance calculation on the surface of the soil should include radiative exchange as it is a major energy contribution, having significant influence on soil temperature, especially at shallow depths. Models that do not take the solar radiation into account provide results in which the error on the evaluation of soil temperature can reach several degrees.

- Building impact

The exchanger is always located close to a building or even in its slab. However, a building can exchange heat with the ground and cause local disturbance of the soil temperature. This interaction has an influence on the overall performance of the heat exchanger. Despite its importance, only Hollmuller (Hollmuller ,

2002) and Thiers (Thiers, 2008) refer to this phenomenon.

- Groundwater table

The exchanger can be located close to or in the middle of a water table, which adds a strong constraint on the sealing of the tubes. It modifies soil properties (moisture) locally and is, when circulating, a source of stable temperature. The soil temperature is then influenced by its presence. Hollmuller (Hollmuller 2002) and Benkert (Benkert and Heidt 2000) are the only authors to include the presence of a water table in their models. Nevertheless, simulations using GAEA software (Benkert and Heidt 2000) indicate a limited influence on the temperature at the exchanger outlet (variation of a few degrees Celsius).

This information is often used as input data in some models. It is therefore essential to ensure its accuracy and consistency.

SITE DATA

Two low-energy, wooden houses (BBC or "bâtiments basse consommation" in French thermal regulations), were delivered to Taillan-Médoc, Gironde (Figure 1) in January 2010. These houses were designed to integrate local wood (maritime pine) in their structure. Their performance was monitored by Nobatek, mandated by the Aquitaine Region, from the time they were delivered. One of them, the 10th "Passive House in Maritime Pine" (MPPMF in the rest of the document), was equipped with an earth-air heat exchanger. The exchanger was coupled to an air handling unit with a bypass on it. This avoided heat recovery from exhaust air from the house in winter, and cooling the supply air in summer. It could be manually controlled from a control panel in the kitchen. A damper installed on the outside air inlet was used to select either exclusive use of the air from the earth-air heat exchanger or use of a mix of such air with the outside air. The geometry of the earth-air heat exchanger used is detailed on figure 3. Operation was automatic and controlled according to the outside temperature. Numerous sensors were installed in order to make a complete study (Figure 2-4) (Gasparin and Lalanne, 2011).

Ground type	sand + gravel
Network type	meander
Supply air number	1
Pipe number	1
Pipe material	PP
Output (m^3/h)	105
Ventilation type	Heat Recovery Ventilation
Model	VMC Deefly 90 Byp.V
Pipe diameter (mm)	200
Supply air diameter (mm)	out 200mm – in 186mm
Distance between pipes (m)	1
Depth (m)	1,5 -2
Slope (%)	1,5
Surface (m²)	37,8
Heat/Cool down surface (m²)	90
Cumulative length (m)	37,8

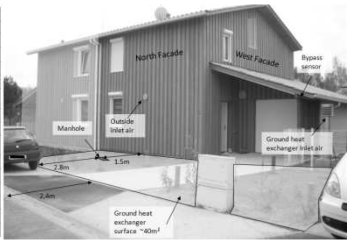

Figure 1. *House and ground heat exchanger data*

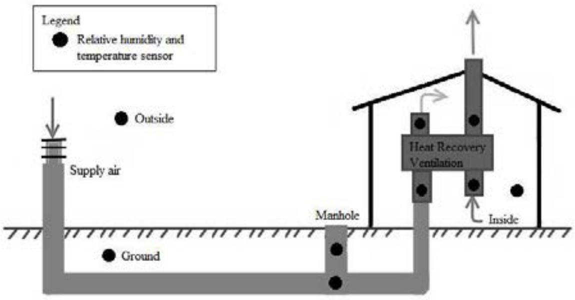

Figure 2. *Deployment of relative humidity and temperature sensors*

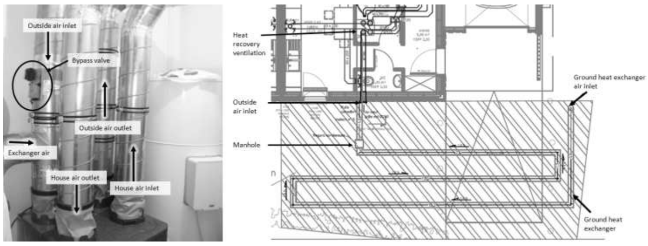

Figure 3. *Details of the exchanger network*

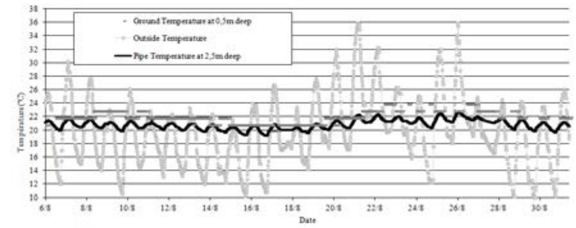

Figure 4. *Temperature measured in August 2010*

Uncertainty on experimental temperatures is about 0.2 K. A study of indoor air quality was also conducted (for example radon measurements were made) but is beyond the scope of this paper.

SIMULATIONS

The present study was based on the software used for the simulation of earth-air heat exchangers in order to explore the consistency of their results. The study (Gasparin 2011, Poupeau 2012) is based on the project MPPMF. Currently, many simulation packages exist, such as Pleiades + Comfie, DesignBuilder, TRNSYS, etc. Based on the publications dealing with the subject as seen in the previous section, the widely used Pleiades + Comfie ® and DesignBuilder software were selected. Comfie Pleiades, which uses the Thiers model, enabled an earth-air heat exchanger to be modelled relatively quickly. On the other hand, the graphic interface did not allow direct modelling using DesignBuilder. Nevertheless, it was possible to enrich this simulation by linking idf format files (file format from EnergyPlus). These were added to the idf generated by DesignBuilder EnergyPlus and processed. To read the results associated with the exchanger (.eso file), it was necessary to use software provided by EnergyPlus: xEsoView. The ZoneEarthtube module proposed by EnergyPlus sets the exchanger and its environment.

Methodology

At first, the work consisted of simulating the well with both programs so as to vary each parameter and study the influence it had on the final result (system outlet temperature). The results expected were the following: the performance of exchangers would increase with the depth and the length of tubes until they reached an optimum, and the building would have no real influence unless the exchanger was under the building. This study also revealed an "offset" difference between the two models for the outlet temperatures of the system.

Input parameters

In order to make a comparison that would be as representative as possible, the input parameters were made as close as possible in both software packages. The choice to study a Maritime Pine House of the Future (MPPMF) having been made, a real house was built to compare the simulation with measurements from the campaign

- Soil properties

The soil model in DB (DesignBuilder) is one of the most basic in the sense that, once the program has provided CalcSoilSurfTemp with the shape of the surface temperature, the temperature wave is transmitted by a simple model of a massive, semi-infinite medium to give the ground temperature and a classic exchange between air and tubes for the output shaft. The program CalcSoilSurfTemp calculates the surface temperature, taking the various conditions into account. An equation of the soil temperature can be found as a function of the depth x and time t as follows:

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

T_m , α_s, A_s are data available from CalcSurfSoilTemp from EnergyPlus.

In P+C (Pleiades + Comfie) software, the soil model developed by S. Thiers [Thiers 2008] is more complete as it takes the influence of the building and the influence of geothermal effects into account and does not simplify the harmonics. The superposition principle is used in this model.

We determined the ground properties experimentally using three different methods as follows:

- Density: weighing

- Thermal Conductivity: hot wire method (Figure 6)

- Specific Heat: flash method (Figure 5)

property	Thermal conductivity (W/m.K)	Density (m3/kg)	Specific heat (Jkg.K)
value	2.6	1900	1330

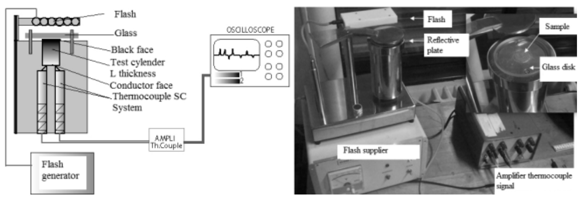

Figure 5 : *Flash method - Assembly procedure*

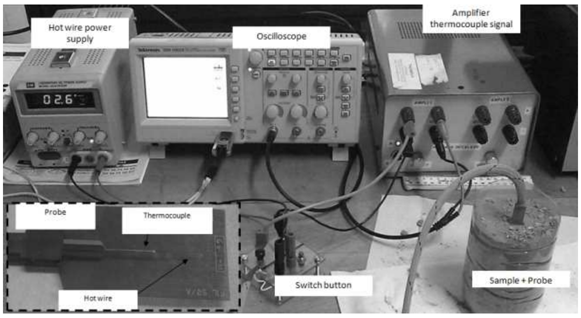

Figure 6 : *Hot wire method - Assembly procedure*

- Weather data

One essential item of data in the simulation is the weather file. It includes all external weather data to make the model as close to reality as possible. As a first step, we simply considered the same file on both weather programs. The weather file was derived from Meteonorm conditions for Bordeaux in 2005. MeteoClac software generated a .EPW weather file (for DB) and a .TRY file (for P + C)

RESULTS AND DISCUSSION

Differences between P+C and DB

The input parameters we chosen to be as close as possible in both software simulations. The simulation was carried out over a full year with no time lag. The final result of the simulation was the annual curve of the output temperature (Figure 7).

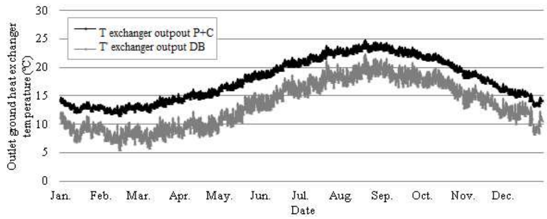

Figure 7. *Comparison between exchanger output temperature in P+C and DB software*

The graph clearly shows the "offset" difference raised by (Gasparin and Lalanne, 2011). Two elements may explain these differences.

Model validation

It was essential to apply model validation software in the comparison with experimental measurements. The majority of publications on earth-air heat exchangers make a comparison but, unfortunately, there are several parameters that are difficult to use. Similarly, there are data (soil conductivity, outdoor air...) that are very specific to each project and require a precise characterization to avoid an accumulation of errors in the final comparison. While authors such as Bansal (Bansal et al. 2009) announce a gap of 2.07% in summer and 11.4% in winter between the model and experimental measurements and Al Ajmi (Al Ajmi et al., 2005) a deviation of ± 0.6°C, the validation of the model is complex. It is necessary to define it as thoroughly as possible to avoid falling into error and these conclusions should be qualified considering the assumptions that have been made (Serres et al. 1997). Thiers (Thiers, 2008) analyzed the parameter sensitivity to limit any possible errors. In his opinion, for an earth-air heat exchanger having high average efficiency, model validation requires correct determination of the temperature of the "undisturbed" soil. Thiers (2008) summarizes the overall results of the sensitivity analysis performed.

Offset explanation

The most influential parameters are those related to heat exchange between the atmosphere and the soil (soil exposure to wind, absorptivity of the surface of the ground, solar radiation data) and those describing the nature of the soil. According to the analysis and comparison of numerical and experimental results conducted in the framework of Effipuits, the difference between the two programs lies in the soil model and the processing by the weather file simulation software.

- Soil models

The geothermal heat flow depends on the site in question (Kunetz et al., 2004). However, due to the shallow depth of an earth-air heat exchanger, the effect of soil heat flow is small compared to other contributions (a few tenths of a degree at most). In our case, at a geothermal depth of 2 m, the effect produced a difference of about 0.4°C on the final result. Finally, after the study of soil models, only one parameter seemed to change the result, and by a rather low value (about 0.4 °C). So another parameter must be the cause of this difference. The study allowed us to identify another phenomenon linked to consideration of the weather.

- Weather effects

The graph shows that the curve shifts vertically according to the choice made for wind exposure in P + C, which applies an "offset" to the final result. With the choice of "normal" exposure, a starting option of "severe" wind seems give a better, or at least closer, fit between the P + C output shaft temperature curve and the DB one (Figure 8).

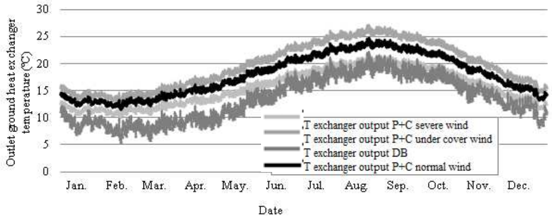

Figure 8. *Comparison of choice of weather effects in P+C with DB*

For P + C, the wind is taken into account through three criteria. We also checked whether, upon conversion via Meteoclac, a loss of wind data could be seen that could be explained by this way of taking the wind into account in P + C. When the automatic conversion of a .Epw file (for DB). Try (for P + C), the wind data seemed to be taken into account more correctly, which offers a serious possible explanation for this discrepancy.

Prospects

Comparison to the real case is an essential phase since it will allow the adequacy of the model to represent reality to be assessed in practice. This phase is currently underway. Work will be necessary to distinguish between direct and diffuse solar radiation (the Taillan Médoc weather station only measures global radiation) and refine the results. However, based on the characteristics of the site, Taillan Médoc weather data and simulated weather data close to the experimental data (including outside temperature, Figure 9), we noted that the output supply temperature oscillated between two output temperatures simulated in P + C and DB (Figure 10). Again, the difference found is largely linked with the data related to the wind parameters.

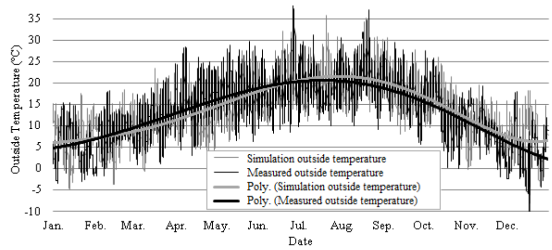

Figure 9. *Comparison between outside temperature measured and given by simulation software (Poly = polynomial interpolation)*

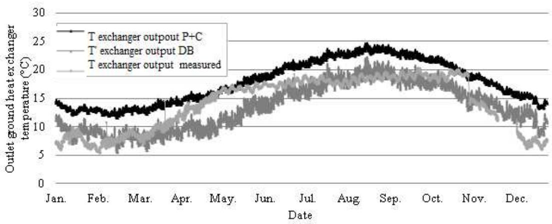

Figure 10. *Comparison between measured exchanger output temperature and exchanger output temperature from P+C and DB software (simulation weather file)*

CONCLUSION

A review of the literature associated with the analysis of the two programs P + C and DB has been used to address a finer modelling/design phase. Many models can be found in the literature, which take more or less input data into account. In this paper, the impact of some input data has been clearly demonstrated, and methods of remediation to reduce offsets have been listed. The impact of geothermal heat flow is negligible. The soil properties must be clearly determined. The influence of wind must be considered with the greatest attention. Direct and diffuse solar radiation measurement will be produced in the further stages of the project and will permit these assertions to be refined.

NOMENCLATURE

T = temperature (°C)

z = depth (m)

T_m = mean temperature (°C)

α_s = soil thermal diffusivity (m^2/s)

A_s = soil thermal amplitude (°C)

HQE ® label = “haute qualité environnementale” stands for high environmental quality (building label)

VMC = controlled “mechanical” ventilation stands for controlled indoor ventilation (using fans)

DB = Design Builder / Energy Plus

P+C = PLEIADES + COMFIE®.

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