Influence of surrounding soil types on the energy efficiency of earth-air heat exchanger

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ABSTRACT

As one of the direct uses of geothermal energy, earth-air heat exchanger (EAHE) systems are now in full development. However, the energy efficiency of these systems depends essentially on thermal proprieties of soil around the buried exchangers as well as the oscillation of the air temperature over ground. In this context, a study is conducted to quantify the impact of surrounding (especially the coating part) soil types on energy efficiency of heat exchangers.

Firstly, the geothermal platform of IUT Robert Schuman University of Strasbourg in France with 3 horizontal ground-coupled heat exchangers is presented. Our study focuses on one of the experimental earth-air heat exchangers, where three types of soils are used around the heat exchanger: fine sand, a mixture of sand and bentonite, and a clay soil. At different vertical EAHE section, soil and flowing air temperatures are measured. Based on the registered data for the year of 2014, a 2D finite elements EAHE modelling is realised and validated for each section. A comparative study is then carried out with different coating soils. Finally, a suitable coating soil type is proposed for optimum energy efficiency of the EAHE system.

1. INTRODUCTION

Earth-air heat exchanger (EAHE) geothermal ventilation system is considered to be an energy efficient means of preheating and cooling of supply air to a building. This system is composed of one or a series of pipe buried below ground at a depth between 1 and 3m for the cost of landfill work. In winter, when the temperature of surrounding soil is higher than the external air, the EAHE system preheats the income air. And in summer, a cooling effect of the EAHE system is applied to the flowing air as the temperature of surrounding soil is lower.

EAHE system can be used either in construction sector for habitation buildings or in agricultural sector for greenhouses. Energy savings of this technology is proven in [Santamouris and Kolokotsa (2012)], which lists 30 pilot projects around the world under different climatic conditions: cold, temperate and warm climate. The types of buildings connected to the air-ground heat exchanger represent a wide range of existing buildings (office, commerce, production, home, university) with an area ranging from 30 to 16,000 m².

Many researcher have investigated the energy efficiency of the EAHE system, and have found different impact factors:

- Configuration of the exchanger pipe: Abbaspour-Fard et al. (2011) tested in Iran the performance of an EAHE system on various parameters: burial depth, length of pipe, air velocity, and pipe material. After 72 experimental trials, it was concluded that all these studied parameters were directly related to performance except pipe material.
- Climatic conditions : Li et al. (2009) constructed an experimental setup at Herbin in China, for a study of a ground sink direct cooling system in cold areas. They concluded that there was substantial scope of energy conservation within a particular region. It was found that geographical and climatic conditions affect the performance level.
- Thermal properties of the soil: Ascion et al. (2011) tested and concluded that best energy performance could be obtained for wet/humid soil by adopting pipe length of more than 50 m, buried and a depth of 3 m. Balghouthi et al. (2014) studied experimentally thermal and moisture behavior of dry and wet soil heated by buried capillary plaits, on a prototype similar to an agricultural tunnel greenhouse. It was concluded that surface temperature amplitude was superior in wet soil as compared to dry soil;

In order to evaluate the impact of these factors, many study have been carried out by using analytical and numerical modeling.

The simplest analytical model is based on the thermos-hydraulic analysis of the EAHE for given soil and air properties [Paepe and Janssens (2003)]. The effect of climate and soil properties can be incorporated into model which take account of the daily and seasonal variations of soil and air temperatures [Thiers (2008) and Hollmuller (2002)]. Analytical models are generally based on simplified solution of one dimensional heat transfer in a circular pipe or the surrounding soil of homogeneous properties.

Numerical models can be classified as one dimensional (1D), two dimensional (2D) and three dimensional (3D). 1D numerical model is used to drive a relation entre pipes inlet and outlet temperatures as Kabashinov et al. (2002). Tittelein et al. (2009) developed a 2D numerical model …Kumar et al. (2003) developed a 2D model using an artificial neural network and examines the effect of soil temperature gradient, the surface conditions and the water content of the soil. Bansal et al. (2013) have studied on the effect of soil thermal conductivity is to the thermal performance of EATHE system with 3D CFD transient. It was concluded that thermal performance of the system Influenced by thermal conductivity of soil, duration of continuous operation and length of pipe. Mathur et al. (2014) have studied effect of thermos-physical properties of soil on year performance of EATE by a transient 3D numerical model for three different kinds of soil.

However, all these analytical and numerical models consider a uniform soil and though same thermal properties around EAHE. In reality, EAHE pipes are generally placed on a thin layer of fine sand to guaranty a constant small slope of the pipe and buried with a coating soil which can be different from the initial soil in place to ensure a good contact between the exchanger pipe and the surrounding soil.

In this paper, a new 2D EAHE numerical model is proposed to determine the temperature field of the surrounding soil especially in the coating part which is disturbed by the use of EAHE and to simulate the evolution of the air temperature along the exchanger pipe. This model takes account of heat transfer between different soils, heat exchanger, supply air and ambient conditions. The proposed model will first be applied to an EAHE experimental site and validated by comparing numerical predictions and measured results. Different coating soil types with different soil moistures will then be simulated by using this model to study the influence of soil type and soil moisture of the coating soil on the thermal efficiency of the EAHE system.

2. PRESENTATION OF GEOTHERMAL EXPEREMENTAL PLATFORM

The numerical modeling investigation of this study is based on the measured results recorded from a geothermal experimental platform constructed in the site of IUT Robert Schuman of University of Strasbourg in France. Three buried geothermal exchangers were installed, as shown in figure 1:

- (a): an EAHE system for "education": Outside air is extracted by the suction mouth and fed into the geothermal space using a polyethylene pipe (PE). A by-pass system allows the outside air to bypass the EAHE pipe when the outside air temperature is close to the soil temperature.

- (b): an earth-to-water heat exchanger (EWHE) for "education": a coolant circulate in a buried network of exchanger pipe to perform the heat exchange. It is then associated with a heat pump (PAC) or a water-air exchange which can be connected to the heating or ventilation system of the building;

- (c): an EAHE system for "research" the working mode is the same as the EAHE for "education» but without the bypass. It is divided into three portions with different types of coating soils: sand (1), a mixture of bentonite and sand (2) and initial ground soil (3);

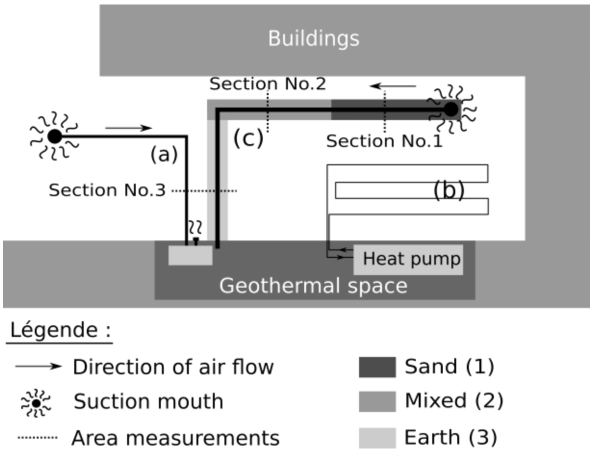

Figure 1: Plan of the geothermal experimental platform

Its total length of 29 m and three different types of soil are spread over almost equal lengths. In the middle of each coating soil type, temperature sensors (PT100) are installed on a vertical section. The measured results of probes are recorded every 20 minutes by a data acquisition system (Keithley 3706A). The instrumentation of a typical section is represented by figure 2;

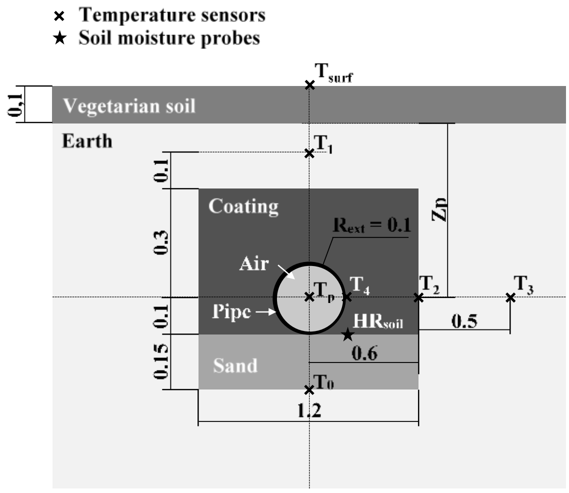

Figure 2: Probe positions of a studied exchanger section

To ensure a good evacuation of condensate water, the installation of this exchanger pipe respects a slope of

2%. Thus, the buried depth of pipe varies according to different locations of 3 coating soil sections:

Table 1: Characteristics of 3 coating soil sections

Vertical section No.	Depth Z_p [m]	Length of exchanger portion[m]
1	0.73	10.4
2	0.92	10.4
3	1.20	8.2

3. MODELING OF THE TEMPERATURE FIELD IN THE SURRONDING SOIL

The modeling of the complete EAHE system is divided into two modeling steps. The first modeling step aims to determine the temperature field in the soil at each instant. The second modeling step simulate the heat exchange between the flowing air and the exchanger pipe over its entire length in order to deduce its outlet air temperature. We present in this section the first modeling step: modeling of the temperature field of surrounding soil.

As a longitudinal soil heat transfer (along the direction of the exchanger pipe) is generally very small compared to vertical and horizontal ones, a 2D model is proposed in our study. Real geometrical forms and different thermal properties of exchanger pipe and different soil layers are taken into account.

3.1 Presentation of the simulation model of soil temperature field

First, the heat exchanger geometry and different soil types are respected in. So there are four types of soil as shown figure 4:

- vegetarian soil : represents the grass covered soil layer at the surface;
- the ground: The initial presented soil on the site;
- coating: the soil surrounding the exchanger along its entire length;
- the stabilizer sand: thin layer of sand to maintain the slope of the tube;

The numerical modeling mesh is designed by a mesh generator software GMSH®. The meshes are triangular shape as shown in figure 3.

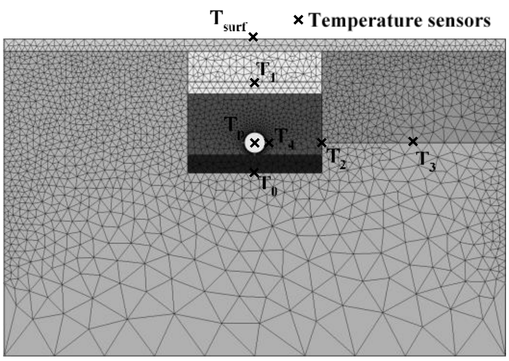

Figure 3: Finite element mesh of the numerical model

The numerical model is solved by a finite element software Code_Aster®. Thermal exchanges by conduction in the soil and by convection between the tube and the air exchanger (h_a) are taken into account. The boundary conditions are:

- T_{surf} : the temperature at the floor surface required by the measurement of T_{surf} probe;
- T_p : the temperature of the air inside of the exchanger imposed by the measuring probe T_p;
- Tgeo: geothermal temperature imposed by a constant value of 16.5°C ;
- φ_l and φ_r : thermal flow from the lateral sides are zero;

Soil thermal properties are considered as constant over time. The initial temperature field is obtained by a prior calculation stationary.

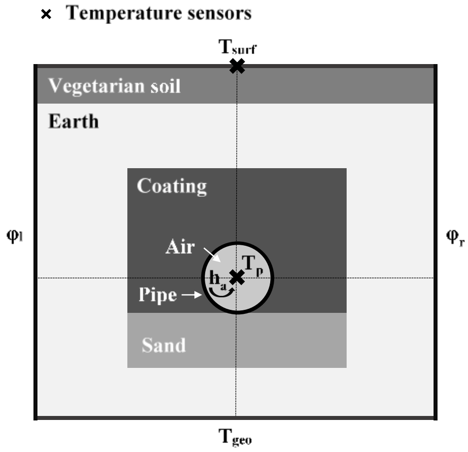

Figure 4: Modeling a vertical air-ground heat exchanger

3.2 Thermal properties of the soil

Aim to simulate the working of EAHE system for a full year of 2014, we need to determine the values of the thermal properties of different materials. Three means are used to obtain these values: the experimental measurement, the bibliographic research and determination by optimization.

Experimental studies [Nowamooz et al. (2014)] have been carried out to evaluate the influence of soil moisture on the thermo-physical properties for the following soil layers: sand, bentonite and sand mixture, clay, and vegetarian soil. From the humidity sensor HS, soil moisture of the coating soil and the sand layer are measured. By linear interpolation of the experimental results, the values of thermo-physical properties of these soils are deducted using the average soil moisture of the studied year.

The thermal properties of the tube are obtained with the technical paper of the tube supplier. For the thermal properties of the ground, they are identified by an optimization procedure by comparing the numerical prediction to the measurements with *PEST*® software, which is an optimization code to estimate model parameters

Table 2: Material thermal diffusivity [mm².s^{-1}] used in numerical model

Cup No.	1	2	3
Vegetarian soil	0.58 ± 0.01		
Coating	0.63 ± 0.04	0.67 ± 0.01	0.71 ± 0.01
Sand	0.63 ± 0.04	0.85 ± 01	0.74 ± 0.02
Ground	0.72 ± 0.01		
Pipe	0.28 ± 0.01		

3.3 Model validation

The modeling of temperature field is performed for the year of 2014. As shown in figures 5, 6 and 7, a good prediction of the numerical model can be observed with standard deviation between the numerical results and the measures vary from 0.5 to 1.5 ° C at different sections. Moreover, for the same probe position, T_1 and T_4 for example, a constant error level is maintained. This signifies a good repeatability of the proposed numerical model.

A good reproduction of fluctuations of numerical model for the temperature sensor T_1, which is positioned nearest to the ground surface, shows that the variations of the air temperature at the surface are taken into account by the model. This remark can be also applied to the T_4 probe. The temperature of the soil near the exchanger pipe (T_4 probe) is disturbed by heat exchanges between the flowing air and the surrounding soil. These disturbances are less pronounced for the external soil layer as shown in T_2 and T_4 probes.

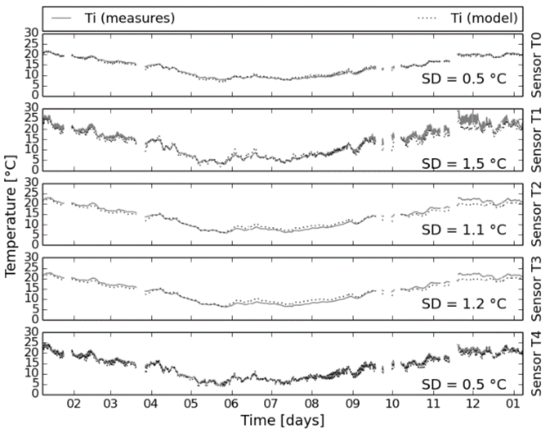

Figure 5: Modeling of the soil temperature field in section No. 1

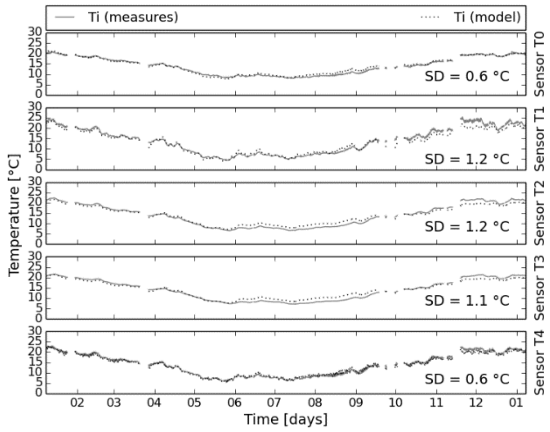

Figure 6: Modeling of the soil temperature field in section No. 2

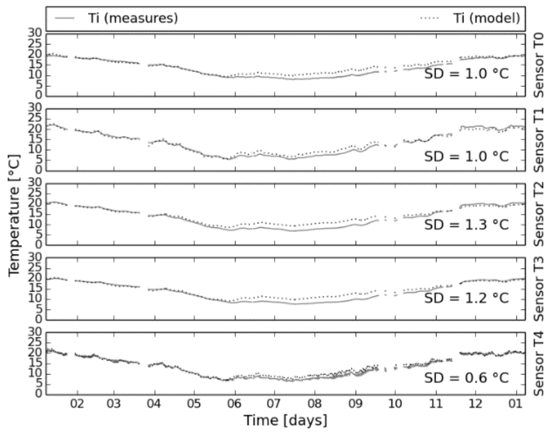

Figure 7: Modeling of the soil temperature field in section No. 3

4. MODELING OF EAHE SYSTEM

In order to simulate the evolution of the flowing air temperature in the EAHE system, once the modeling of soil temperature field is accomplished, these surrounding soil temperature fields can be applied to the second step of the whole modeling: modeling of the EAHE system.

4.1 Presentation of the EAHE model

The knowledge of the evolution of flowing air temperature in EAHE is critical to determine its energy efficiency and thus to propose suitable improvement solutions (for soil types and EAHE configurations) to optimize the obtained energy. However, its modeling is a complex problem which depends on many parameters like: outside air temperature, thermo-physical properties of soil and air, air circulation velocity, geometry of the exchanger pipe [Thiers and Peuportier (2008)]. These parameters can be summarized in two main families: the ground parameters (for different soil layers) and the heat exchanger parameters (for the exchanger pipe and the flowing air).

As we have seen in the last section, for each vertical section, the modeled soil corresponds faithfully with the measures on the site. We therefore have knowledge of soil thermal parameters and these of the exchanger in each vertical section.

Two assumptions are taken for the EAHE model:

- As the flowing air velocity inside of EAHE pipe is only controlled by a fan at its output. To simplify the model, we neglect the pressure loss and consider a constant air flowing speed throughout the whole EAHE pipe. The air velocity of 2.0 m / s, which is measured at the input of the EAHE system, is taken for the modeling.

- For the sake of information between 2 record times (about 20 minutes), no evaluation of the soil temperature field is considered between two measurements.

The principle used in the the EAHE modeling is proposed by Trombe and Bourret (1993). In order to determine the evolution of flowing air temperature in the EAHE, a transient thermal problem in a 2D model is solved over a time corresponding to the distance traveled by the air (see figure 8). For a same portion of pipe, same boundary conditions and pipe buried depth are considered.

We present in figure 9 the whole process diagram of the modeling of the EAHE system.

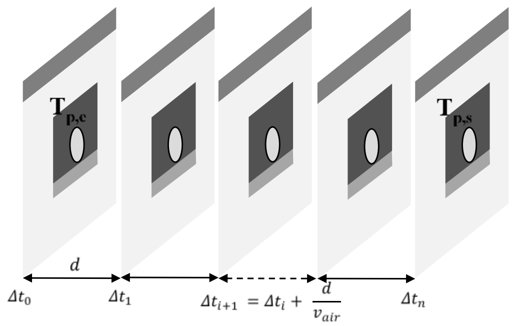

Figure 8: Principle of numerical simulation of the flowing air temperature

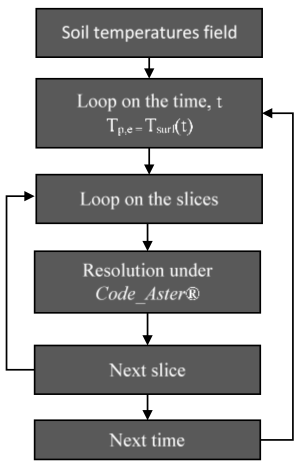

Figure 9: Process diagram of the EAHE modeling

4.2 Model validation

The EAHE in the geothermal platform have records 5 flowing air temperature in different positions: input, section 1, section 2, section 3 and output. In order to compare the numerical results with the measured results of these 5 positions, the EAHE pipe is decomposed to six portions as shown schematically in figure 10. Numerical modeling is carried out for the periods of January and July 2014 by imposing the measured inlet air temperature.

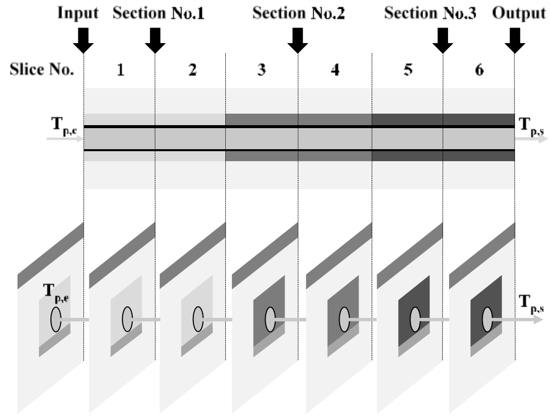

Figure 10: Application of the method for ground-coupled heat exchanger geothermal platform

The model shows a good prediction in figure 11 and 12. The temperature of the predicted output air temperature corresponds well to that measured on site with a maximum standard deviation of 0.6 ° C for the month of January and 0.7 ° C for the month of July. For both periods, an increase of error can be observed along the exchanger pipe. This is due to an accumulation of numerical error throughout the pipe. Generally, a good performance of the proposed numerical model is proven.

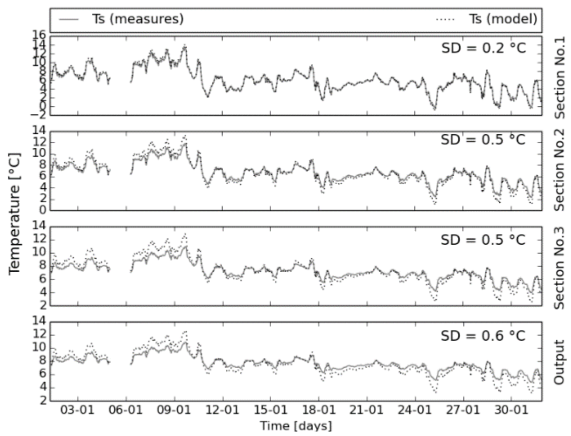

Figure 11: Air temperature inside the heat exchanger at different locations for the month of January 2014

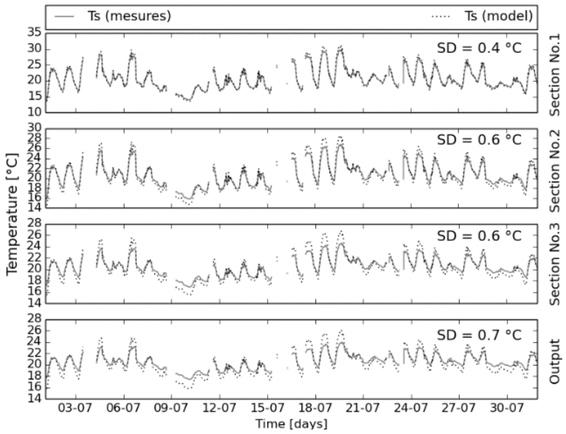

Figure 12: Air temperature inside the heat exchanger at different locations for the month of July 2014

5. STUDY OF THE IMPACT OF DIFFERENT COATING SOIL TYPES

Aim to study the influence of different coating soil type on the energy efficiency of the EAHE system, by using the proposed numerical model, we present in this section simulations of three EAHE systems with three different coating soil type throughout the exchanger pipe.

A comparison is performed to a typical EAHE system for an individual house, with a buried depth of 75 cm and a length of 30 m. An air speed in the heat exchanger of 4.0 m.s^{-1}is considered.

5.1 Overview of the types of studied soils

The studied coating soil types correspond to different types of soil used on our experimental site with their respective extreme moistures measured over the period of 2014. Their thermal properties are presented in table 3. We can observe that the mixture of sand and bentonite is can keep a stable and high water content, which conducts higher density, thermal conductivity and specific heat than the two other coating soil types.

Table 3: Thermal properties of coating soils with maximal and minimal measured soil moisture of 2014

Type of soil	ω		λ	ρ.C$_p$	a
	HR	[%]	[W.m^{-1}.K^{-1}]	[J.K^{-1}.m^{-3}]	[mm².s^{-1}]
Sand	min	5.63	0.80	1.44	0.56
	max	17.0	1.49	1.84	0.81
Mixed	min	18.4	1.38	2.05	0.67
	max	19.5	1.43	2.11	0.68
Ground	min	8.4	0.95	1.36	0.70
	max	16.6	1.45	1.68	0.86

5.2 Comparison of coating soil temperature field

After the first step of the modeling by using 6 different thermal properties of the coating soil (3 soil types and 2 extreme water contents), 6 different series of soil temperature field are obtained. The modeling is carried out for the month of January and July 2014.

To observe the impact of different coating soil type with different soil moisture, we focus on the evolution of soil temperature at the position of T_4 probe, which can represent the temperature of the coating soil. The numerical results are shown in figures 13 and 14.Obvious differences between dry and wet coating soil can be observed for sand and ground, while almost identical soil temperature curves are obtained for sand and bentonite mixture.

Table 4 shows the peak to peak soil temperature amplitude (*A*) with a relative difference between dry and wet coating soil (*R*), which is calculated as:

$$R_{soil} = \left(1 - \frac{A_{HR_{min}}}{A_{HR_{max}}}\right) * 100\ \% \qquad [1]$$

The observation from figure 13 and 14 can be confirmed. The dry/wet relative difference is about only 1% for sand and bentonite mixture, while this value varies from 9% to 14% for sand and ground. However, no season sensitivity is found as similar dry/wet relative difference is obtained for summer (July) and winter (January).

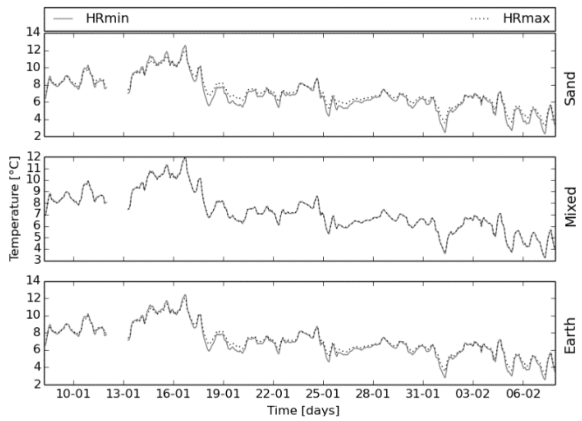

Figure 13: Coating soil temperature for the month of January 2014

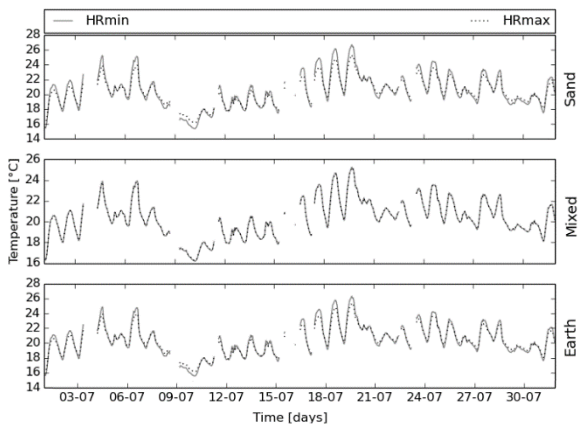

Figure 14: Coating soil temperature for the month of July 2014

Table 4: Coating soil temperature amplitude of the studied periods

Amplitude		July	January
Sand	HR_{min}	11.33 °C	10.2 °C
	HR_{max}	9.18 °C	8.80 °C
	R_{soil}	9.02 %	14.00 %
Mix	HR_{min}	9.08 °C	8.75 °C
	HR_{max}	8.93 °C	8.65 °C
	R_{soil}	1.63 %	1.11 %
Ground	HR_{min}	10.76 °C	9.85 °C
	HR_{max}	9.25 °C	8.85 °C
	R_{soil}	14.00 %	10.17 %

5.3 Comparison of the output air temperature

As shown in the modeling of soil temperature field, a high water sensibility is found for sand coating soil and a stable temperature field is obtained for sand and bentonite mixture. Therefore three coating soil configurations are considered to the EAHE modeling: "dry" sand, "wet" sand and "dry" bentonite / sand mixture.

Our study will focus only on the period of July as similar difference of coating soil temperature is found between July and January.

The simulated air temperature at the outlet of the heat exchanger for the month of July 2014 is presented in figure 15 for the three configurations: "dry" sand, "wet" sand and bentonite / sand mixture.

Between “dry” sand and “wet” sand, a lower variation of outlet air temperature is observed for the “wet” sand. The influence of soil moisture on the thermal performance of the EAHE system is confirmed.

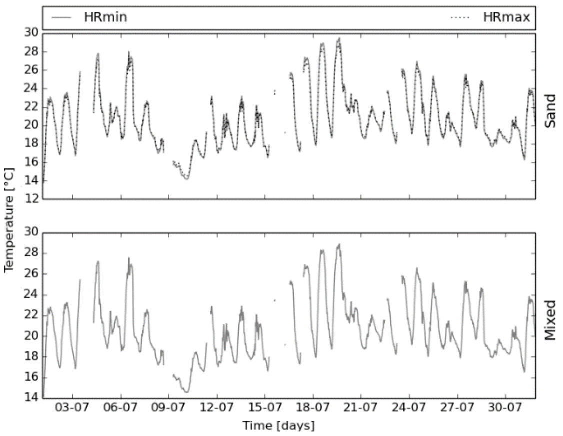

Figure 15: Output air temperature of the EAHE system for the month of July 2014

5.4 Comparison of EAHE’s thermal performance

For a better comparison of EAHE’s performance, an investigation of the exchanged energy between the ground and the flowing air in the EAHE is carried out.

The thermal performance of the exchanger is compared for each configuration by calculating the exchanged energy, which is defined by:

$$E = \int \phi(t).dt \qquad [2]$$

Where $\phi(t)$ is the heat exchange power at each time t. It is obtained by:

$$\phi(t) = v_{air} \times \pi.R_{int}^2 \times C_{p,air} \times [T_{p,e}(t) - T_{p,s}(t)] \qquad [3]$$

Where v_{air} represents the flowing air speed, R_{int} the inner radius of the exchanger pipe, $C_{p,air}$ the heat capacity of air, $T_{p,e}$the inlet air temperature and $T_{p,s}$ the outlet air temperature.

This obtain energy can be differentiated by two parts: cooling energy (E_c) when $T_{p,e} > T_{p,s}$ and heating (E_h) energy when $T_{p,e} < T_{p,s}$. As the EAHE is used only to cool the inlet air in summer, only cooling energy (E_c) is calculated. The results are summarized by the following table 5:

Table 5: Cooling energy of the EAHE system for July 2014

		E_c [kW.h]
Sand	HR_{min}	46.80
	HR_{max}	54.21
Mixed	HR_{min}	54.84

A difference of thermal performance is confirmed between the “dry” and “wet” sand. The cooling energy for the “dry” sand is 15% lower than that of “wet” sand. It can be concluded that soil moisture in the coating soil of the EAHE system is a non-neglected factor to optimize the energy performance of the system.

Moreover, it is shown that the sand and bentonite mixture presents a good energy performance than the sand coating soil, even in “dry” condition. The addition of bentonite in sand plays a dual role: store water and improve the thermal performance of an EAHE.

6. CONCLUSIONS

A finite element numerical model is proposed to simulate the EAHE system. Heterogeneous surrounding soil layers and the thermal impact of the working of EAHE to the coating soil temperature field is taken into account in this model.

The proposed model is validated by comparing its numerical predictions to the measured results of an experimental EAHE in the geothermal platform of university of Strasbourg in France.

Influence of coating soil type to the EAHE’s thermal performance has been investigated by modeling a same EAHE system but considering three different coating soil types. Comparisons have been carried out for the coating soil temperatures field and the energy performance. The impact of soil moisture is non-neglected for the coating soil like sand. However a sand and bentonite mixture can reduce the variation of soil moisture and keep a stable and high energy performance.

By this study, we have shown the importance of choosing the type of soil for the coating part of an EAHE. Especially since both its soil moisture and soil thermal characteristics are important: a high soil moisture and thus good thermal properties can improve significantly the thermal performance of an EAHE. Therefore, using a coating soil with a stable and high water content such as sand and bentonite mixture can be a solution to optimize the thermal performance of an EAHE system.

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