Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

An Evaluation of Ground Thermal Properties Measure Accuracy by Thermal Response Test of Horizontal Ground Heat Exchangers

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Keywords: Horizontal ground heat exchanger, ground source heat pump, thermal response test

ABSTRACT

This study aims to compare temperature measurements in horizontal ground heat exchangers to predicted values using thermal response tests. A scale 1 test facility of horizontal ground heat exchangers has been implemented in BRGM (Orleans - France) to test performance in real conditions. The heat exchanger is divided in four parts of 100 m² each with different characteristic locations:

- sunny grass
- shaded grass
- sunny car-park
- shaded car-park

These different configurations have been chosen to compare the performance of ground heat exchangers in different environments (surface state, boundary conditions). Furthermore, the temperature in the soil is measured continuously at 3 different levels (-0.5 m, -1 m, -1.5 m). To map the temperature field at these 3 depths, optical fibers are distributed underground, and the use of a distributed temperature sensor (DTS) allows accurate measurement of the temperature in the soil surrounding the ground heat exchanger.

A thermal response test was carried out on the horizontal ground heat exchanger. A monitored constant heating power was injected at a constant mass flow, and the temperature was measured at the 3 different levels of a three-dimensional numerical model of ground heat exchanger.

In particular, the thermal response test gives the noticeable differences between the 4 different conditions of each part of the ground heat exchanger. The indicated uncertainty with respect to the effects of soil thermal properties on sizing are discussed.

1. INTRODUCTION

With growing international concern related to global warming, it seems necessary to improve the knowledge of renewable energy sources. Geothermal heat pump technology is one way to considerably reduce CO_2 emissions of heating systems. In fact, the relatively stable temperature underground allows heat pumps to operate with very efficient coefficients of performance and to reduce electrical energy consumption. There are different types of underground heat exchangers used in heat pumps, such as horizontal and vertical ground heat exchangers and compact ground heat exchangers. Horizontal ground heat exchangers are less efficient because of the variability of the soil temperature at such depths (generally around 1 m deep), but they are typically much cheaper than boreholes. The performance of such systems, which depend on the soil properties and the climatic conditions at the soil surface, are not yet very well known.

The results of the characterization of horizontal ground heat exchangers by thermal response tests are presented. Thermal response tests are commonly used for vertical ground heat exchangers, generally to size borehole thermal energy storage (BTES). Such tests are then analyzed, and average values of thermal properties of the soil are obtained (Gehlin, 2002). Thermal response test are performed in both the short term and long term (Hellström, 2006).

Thermal response tests have been performed on horizontal ground heat exchangers by Inalli and Esen (Inalli, 2004), and the results of these experiments are used to validate a two dimensional numerical model with the assumption that heat is transferred via conduction only (Esen et al., 2007). In these experiments, the underground temperature was not measured. The underground heat exchangers were linked to a heat pump. The only measured temperatures in the heat exchanger were the fluid temperatures at the inlet and at the outlet (corresponding to the outlet and inlet of the evaporator of the heat pump).

In single buried tube, Piechowski (Piechowski, 1998) also performed some procedures of thermal response tests. The temperature was measured in the soil at different locations around the heat exchanger, allowing Piechowski to precisely validate a two dimensional model of heat and mass transfer in the underground.

A test facility has been implemented at the site of BRGM (French Geological Survey) in Orléans (France) to measure the performances of different types of ground heat exchangers and, in particular, horizontal ground heat exchangers. The scientific objectives of this test facility are as follows.

- Evaluate the influence of climatic parameters (rainfall, sunshine, etc.) and the effects of different types of soil surfaces (lawn, park area, etc.) on the performance of horizontal ground heat exchangers.

- Determine the impact of varying thermal properties of the soil along the depth on the efficiency of borehole heat exchangers.

- Determine the performances of new types of ground heat exchangers.

Figure 1: Overview of the test facility

Figure 2: View of the 4 different sectors of horizontal ground heat exchangers

2. DESCRIPTION OF THE TEST FACILITY

The test facility implemented in Orléans was placed in a grove of oak trees to show the good integration of such systems in the environment (see Figure 1).

The thermodynamic machinery and the metrological devices are located in the three wooden huts. The horizontal ground heat exchangers are implemented in a clearing, 1 m below the ground surface.

2.1 Implementation of the horizontal ground heat exchangers

The area of horizontal ground heat exchangers is divided into 4 distinct sectors of 100 m² each with different expositions and surface linings: a shaded lawn, a sunny lawn, a shaded car-park and a sunny car-park (see Figure 2). The soil is more compact in the car park area, which leads to a reduction of the soil porosity and consequently different potentials of evapotranspiration.

At the time of implementation of these horizontal ground heat exchangers at 1 m depth, the soil was excavated to a 2 m depth. The soil was mixed before filling in order to have the same thermo-physical properties of soil around the heat exchangers.

Each sector of 100 m² is equipped with two 100 m long pipe loops. The loops are then linked in parallel for the regulation of the system, and only one of the two loops can be used for the experiments. The equipment of 1 sector with two loops is presented in Figure 3.

Figure 3: Equipment of one horizontal ground heat exchanger sector with 2 fluid loops at 1 m depth

Figure 4: Thermodynamic machinery implemented in the hut

After soil analysis, it was determined that the soil is argillaceous sand with a few small pieces of flint.

2.2 Thermodynamic machinery and monitoring system

The thermodynamic machinery controls 5 circulation loops. Two of these loops are dedicated to the horizontal ground heat exchangers, and the three others are used to feed the vertical and compact ground heat exchangers. The two circulation loops of the horizontal heat exchangers comprise two sectors in parallel: the first loop for the "lawn" sectors and the second loop for the "car park" sectors.

The different control loops are visible on the monitoring window in Figure 5. All loops are filled with an anti-freeze mixture of water and monopropylene glycol (60 % water).

The thermodynamic machinery can operate in two distinct modes: 1) operation of a ground-source heat pump in winter (withdrawal of heat from the soil); 2) operation of a ground source heat pump in summer (injection of heat in the soil). This machinery is placed in a wooden hut (see in Figure 4).

A 750 L water tank is used to store cold water in winter mode and hot water in summer mode. This tank is linked to a 78 kW chiller for winter mode and a 27 kW electrical heater for summer mode (see at the left of Figure 5). For each control loop, a 3 kW electric heater is used to adjust the fluid temperature before entering into the ground.

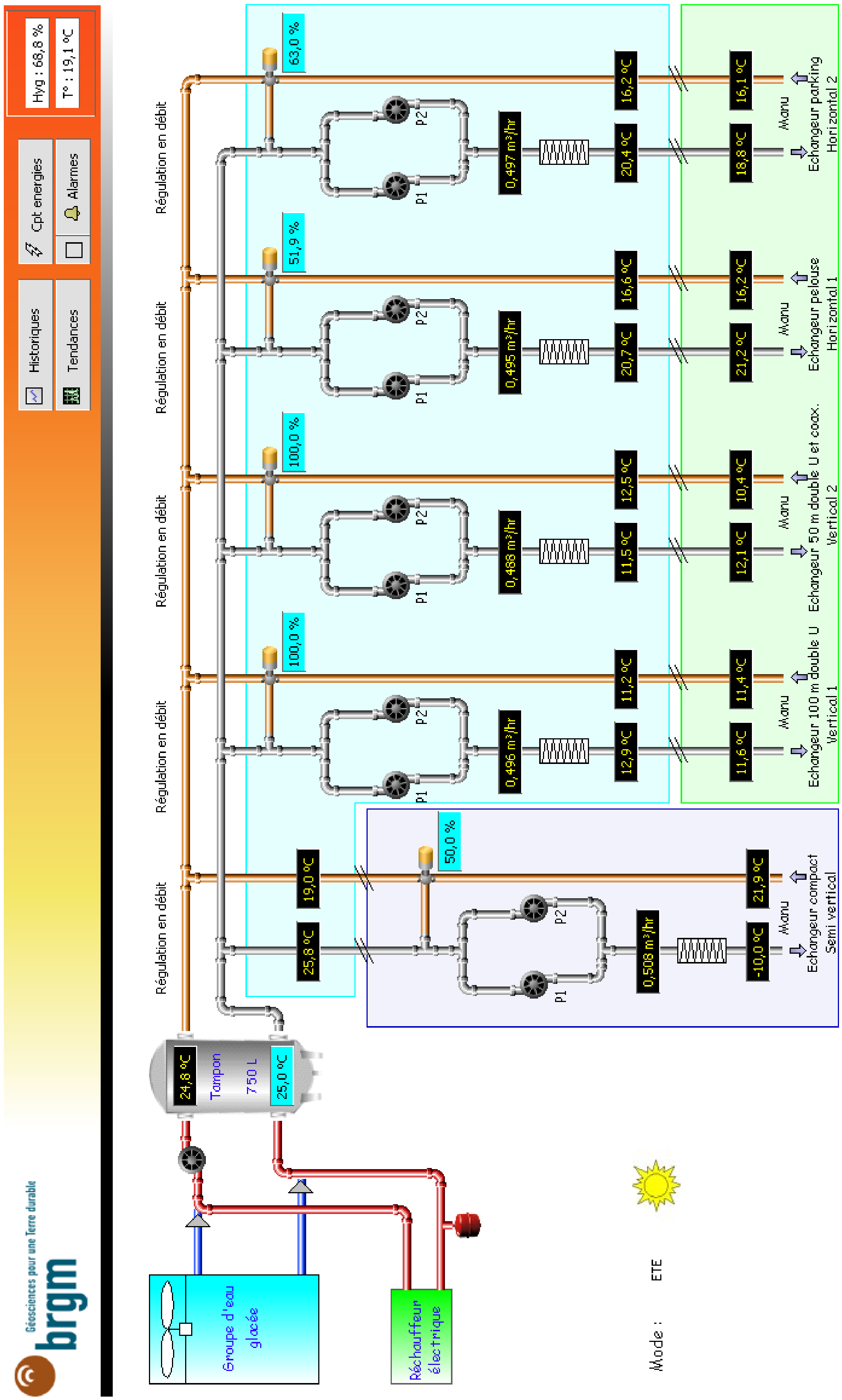

Figure 5: View of the monitoring window of the thermodynamic machinery

Each control loop is equipped with two feed pumps (P1 and P2 in) mounted in parallel (to facilitate maintenance). A three way valve controls the mixed fluid proportions for each loop to reach the set point temperature at the inlet of the ground heat exchanger.

2.3 Temperature measurement in the underground

To obtain the temperature field around the horizontal ground heat exchangers, the principle of distributed temperature measurement was adopted for this test facility. This distributed temperature measurement is carried out using optical fibers. An optical fiber is unrolled in the underground, making it possible to obtain an average temperature value at each meter of optical fiber. This technology of temperature measurement has already been used for geothermal energy studies to measure the temperature evolution around borehole heat exchangers by Fujii (Fujii, 2009).

This measurement technique uses the physical phenomenon of Raman diffusion. After emitting a laser pulse, the distributed temperature sensor analyzes the diffusive signal. The temperature is obtained as a function of the amplitude of the "Raman" satellite lines. The signal analysis that gives the temperature is implemented in a second hut, where all optical fibers exit the soil (see Figure 6)

The measurement optical fibers are spread over three depth levels under the soil surface: -0.5 m, -1 m and -1.5 m. Figure 7 shows the implementation of the optical fibers at -1.5 m after excavation of the soil. The optical fibers are unrolled along the heat exchanger tube for the -1 m level and at the depth of the exchanger tube for the two other levels (0.5 m above and below).

2. A FIRST THERMAL RESPONSE TEST

The first test executed on the test facility is a short term thermal response test. For this test, four ground heat exchanger pipes of 100 m length were activated, one in each sector (shaded lawn, sunny lawn, shaded car-park and sunny car-park). The geometry and the dimensions of these loops, buried at 1 m depth, are specified in Figure 8.

These four underground pipes are linked to two monitored loops (see in Figure 5). The two "car-park" pipes are linked in parallel to the first regulation loop. The two other pipes ("lawn") are linked in parallel to the second regulation loop.

This test was carried out over 6 days in May 2009. The outside air temperature during these 6 days is given in Figure 9. Only one rainfall was registered during the test, occurring on the 3rd day with a level of 5.2 mm water.

The thermodynamic machinery was in summer mode, meaning that hot fluid was injected into the ground. The system was regulated in thermal power and mass flow.

The thermal power exchanged with the surrounding soil is equal to 10 W for each meter of ground heat exchanger pipe. This value corresponds to a value of 20 W/m². It is a typical sizing value according to the German guideline VDI4640 (see the sizing table in Figure 10).

The mass flow imposed in the heat exchanger pipes is equal to 0.25 m^3/h for each, which is a typical value recommended by some heat pump manufacturers for the ground heat exchanger loops linked to their residential ground source heat pumps.

Figure 6: Measurement optical fibers and signal analysis implemented in the second hut

Figure 7: Implementation of the optical fibers at 1.5 m

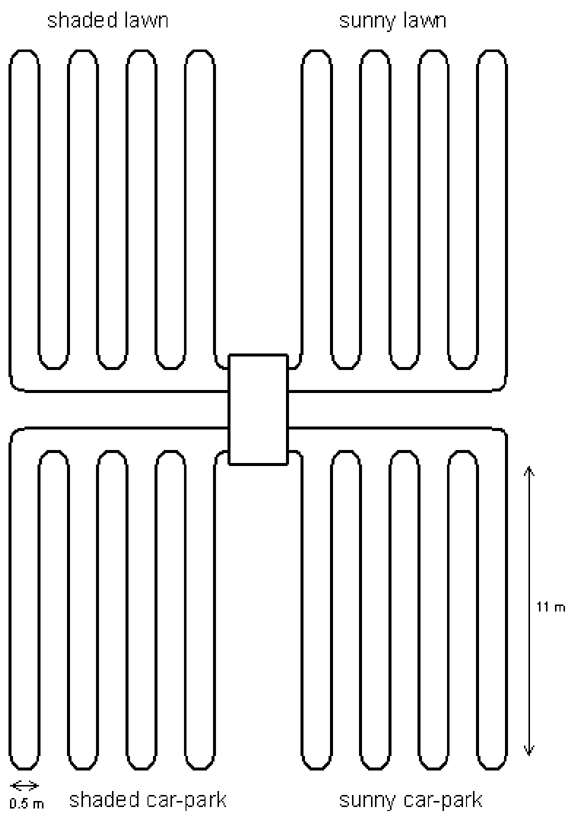

Figure 8: Arrangement of the four ground heat exchanger pipes

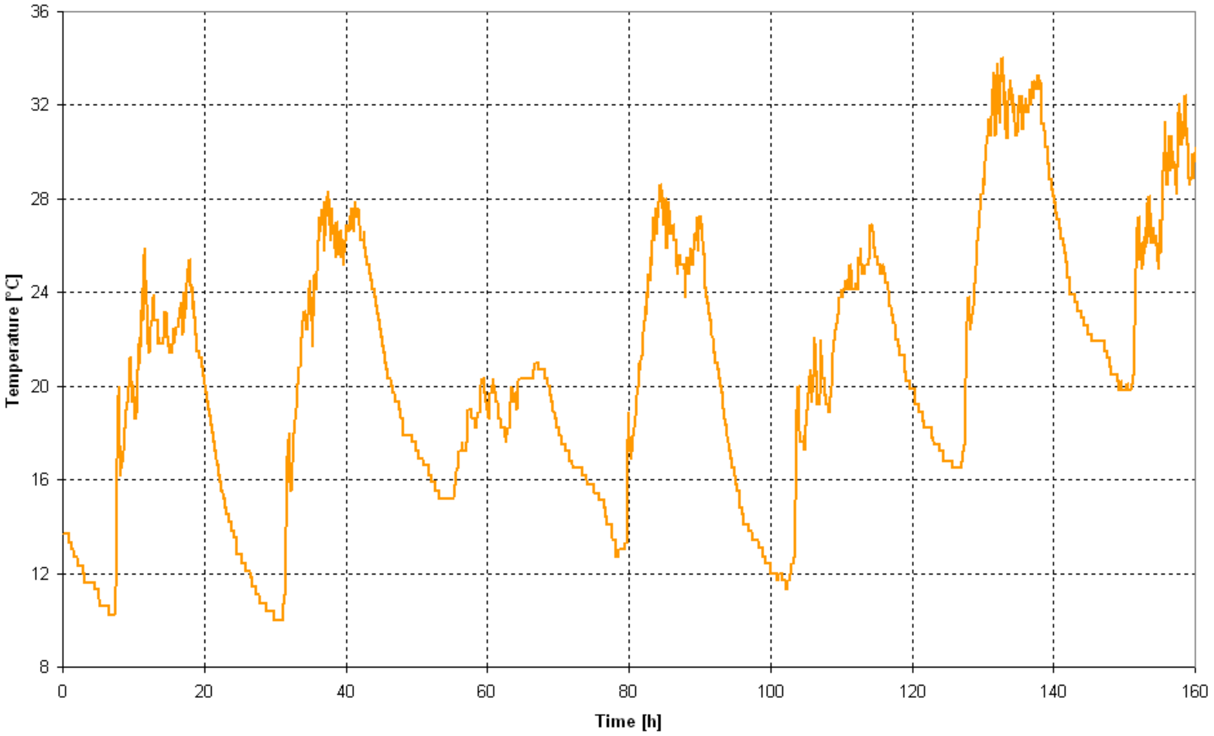

Figure 9: Outside air temperature during the tests

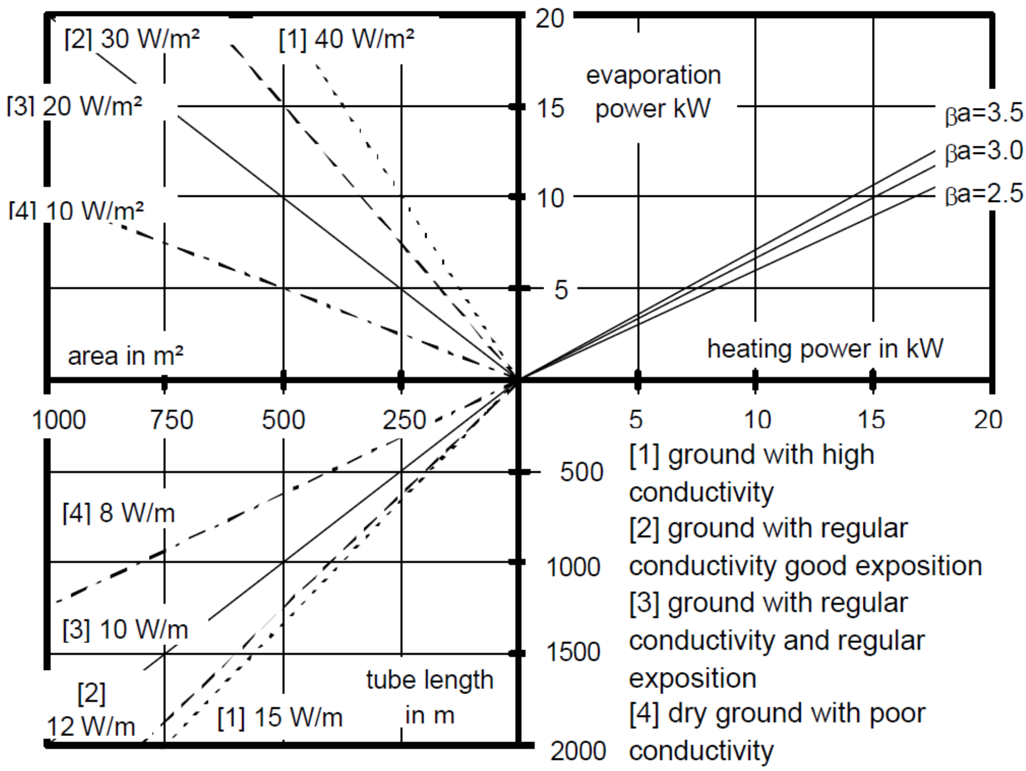

Figure 10: Table of sizing of horizontal ground heat exchangers extracted from the German guideline VDI4640

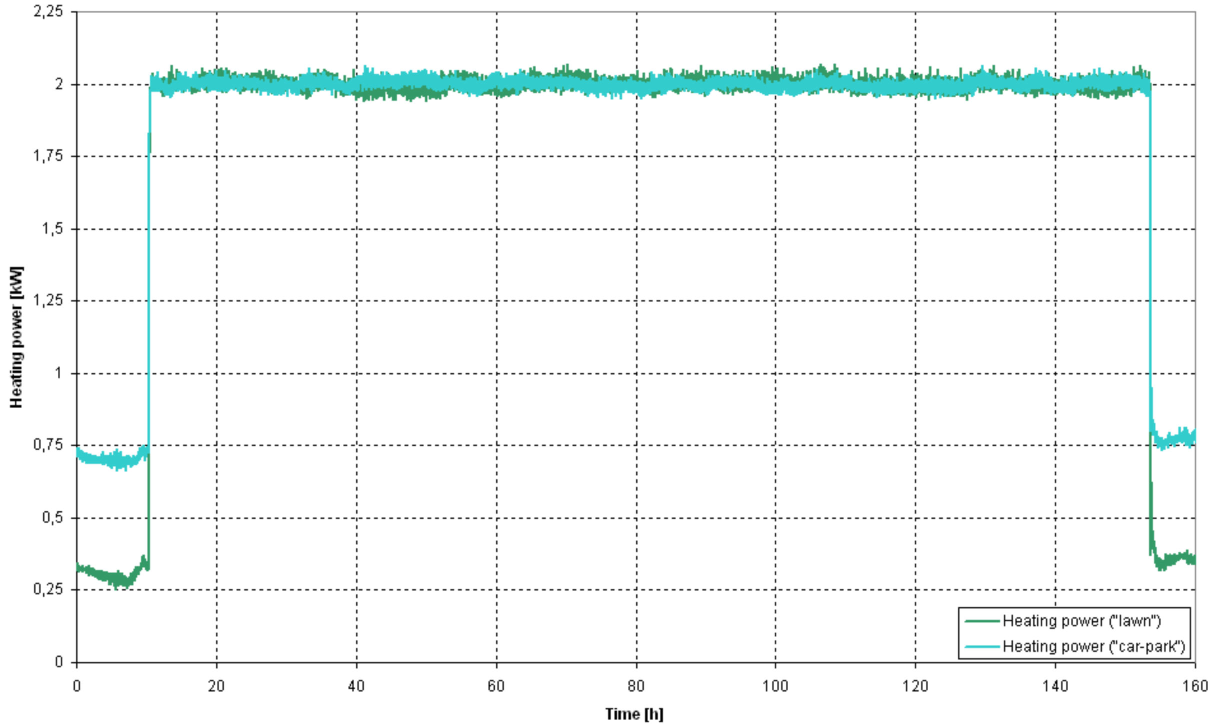

Figure 11: Thermal power injected into the soil by the two control loops during the 6 day thermal response test

Each regulation loop is linked to two ground heat exchanger pipes, meaning that a thermal power of 2 kW is injected into the soil by each regulation loop. Figure 11 shows the evolution of the injected heat load as a function of time. The regulation loop is quite accurate, and a deviation of only 0.1 kW from the set point value was observed.

Figure 12 presents the evolution of the temperatures at the inlets and outlets of the two control loops of the ground heat exchangers. These temperature values are linked to the heat loads in Figure 11 by the following equation:

$$\dot{Q}_{th} = \dot{m} Cp \left(T_{in} - T_{out}\right) \quad (1)$$

where $\dot{Q}_{th}$, $\dot{m}$, Cp, T_{in}, T_{out} are injected thermal power, mass fluid flow rate, mass heat capacity (Cp=3700 J/kg K for the mono-propylene glycol – water mixture), temperature at the inlet of the ground heat exchanger, and temperature at the outlet of the ground heat exchanger, respectively.

According to equation (1), the difference must be constant because the regulation loops fix the values of heating power and mass flow. It is clearly visible in Figure 12 that this difference remains constant.

In Figure 12, the temperature values of the “lawn” area are slightly higher than those of the “car-park” area. This difference is probably due to the fact that the soil is more compact in the car park and consequently, not so well heated by the spring air temperatures. Also, the humidity profiles probably have a non negligible effect on these temperatures. The porosity of the compact soil (“car-park” soil) is different than that of the “lawn” soil. Consequently, the humidity transfer is different and the heat transfer conditions are different. In the future, it is planned to measure the underground humidity field in this test facility to understand this phenomenon more precisely.

It is also interesting that the heating of the soil after 6 days is transient; the slope of the temperature curves remained constant during the tests.

In addition, it is noticeable that the outside air temperature (see Figure 9) has a very slight short term effect on the evolution of the inlet and outlet temperatures for these ground heat exchangers buried at 1 m depth. Only small diurnal temperature waves are discernable.

3. SOIL TEMPERATURE MEASUREMENTS AND INTERPRETATIONS

The temperature in the soil was measured by optical fibers at three levels:

- along the heat exchanger tube at 1 m depth

- 0.5 m above the heat exchanger tube, following the same path as the tube

- 0.5 m below the heat exchanger tube, following the same path as the tube

Figure 13 presents the temperature measurement in the underground at these three levels in the “shaded lawn” sector.

The temperature measurements are represented at different times during the tests. The curves at 1 m depth show the evolution in the soil surrounding the heat exchanger tubes from an undisturbed state to upper decreasing temperature profiles along the path of the fluid in the soil. As the fluid gives heat to the soil, its temperature decreases.

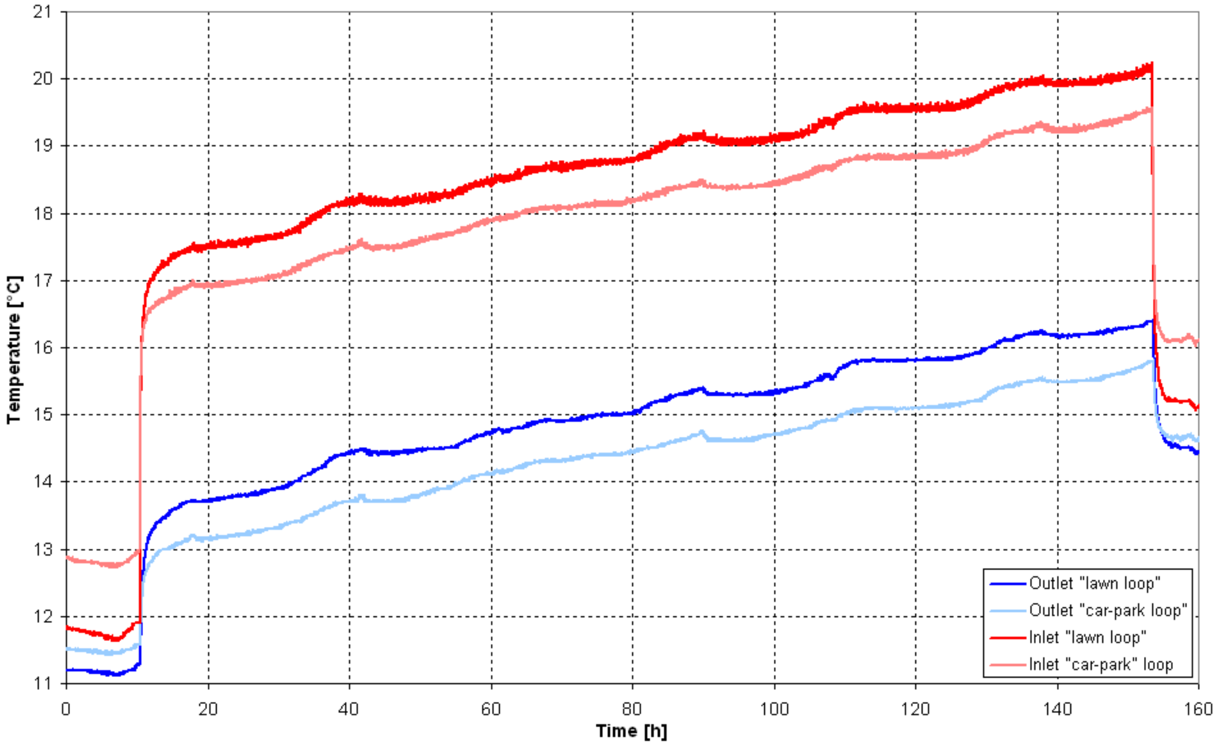

Figure 12: Evolution of the temperatures at the inlets and outlets of ground heat exchangers

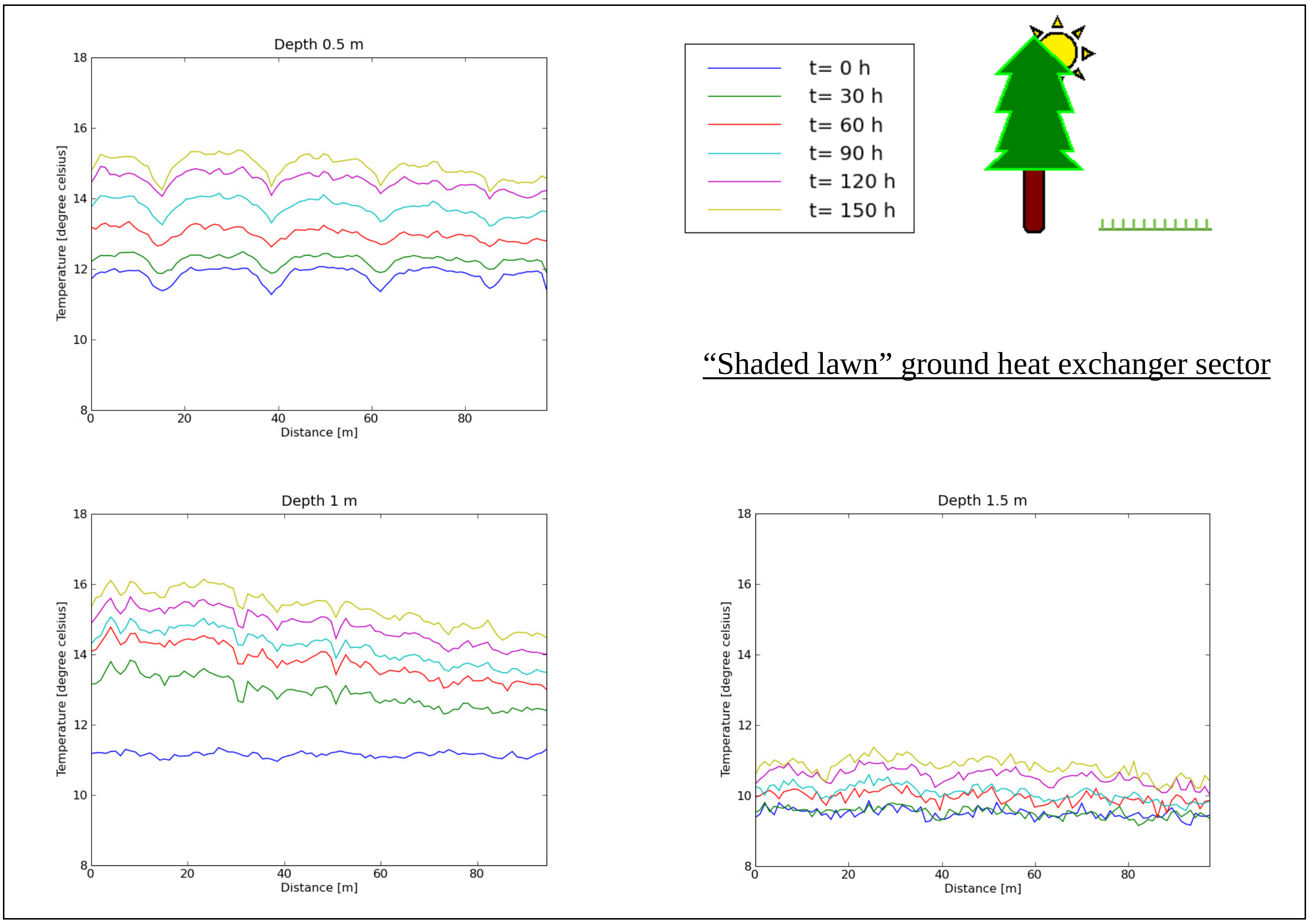

Figure 13: Evolution of the soil temperature at the three depth levels in the "shaded lawn" sector

Further, it is interesting to observe the evolution of the soil temperature above and below the heat exchanger tubes. The "deep" soil (1.5 m deep) acted as a thermal sink, the temperature of which varied slightly, although the upper soil layer (0.5 m deep) experienced a large increase of its temperature because the surface temperature was relatively high (about 20 °C on average, see in Figure 9).

Four small waves are also visible in the curves at 0.5 m depth, corresponding to parts of the four loops that are more in shadow than the rest of the ground heat exchanger surface.

The other soil temperature curves are given in Appendix A.

4. CONCLUSION

In this article, a new test facility of ground heat exchangers implemented in France has been presented. This test facility aims to improve the knowledge of the ground heat exchangers for residential heating applications.

Some innovative features have been installed in this test facility to better know the evolution of the soil properties during an injection of heating and cooling fluid into the soil via different types of ground heat exchangers. The initial results of the tests are presented in this paper and seem to be quite coherent.

The temperature sensors already enable us to see the effect of different surfacing (more or less compact soil) and exposition conditions (shaded or sunny exposition) to the heat exchanges in the underground.

It is also planned to implement in this test facility a system of three dimensional measurement of the humidity level in the underground to better evaluate the effect of penetration of water in the ground on the performances of shallow ground heat exchangers, as the thermal properties of the soil (thermal conductivity and diffusivity) depend strongly on the humidity level of the considered sample.

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APPENDIX A: SOIL TEMPERATURE MEASUREMENTS IN THE TEST FACILITY

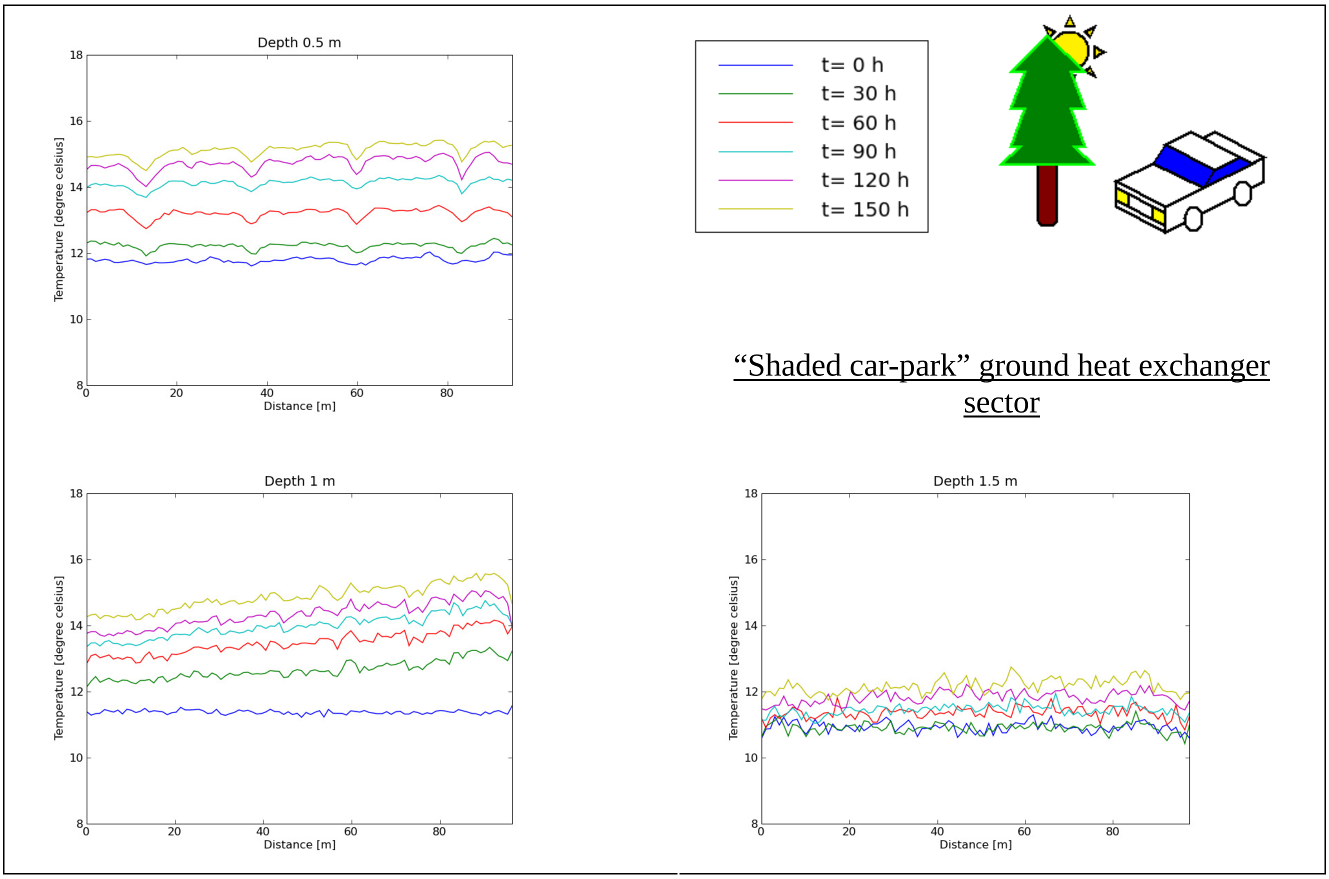

Figure 14: Evolution of the soil temperature at the three depth levels in the “shaded car-park” sector

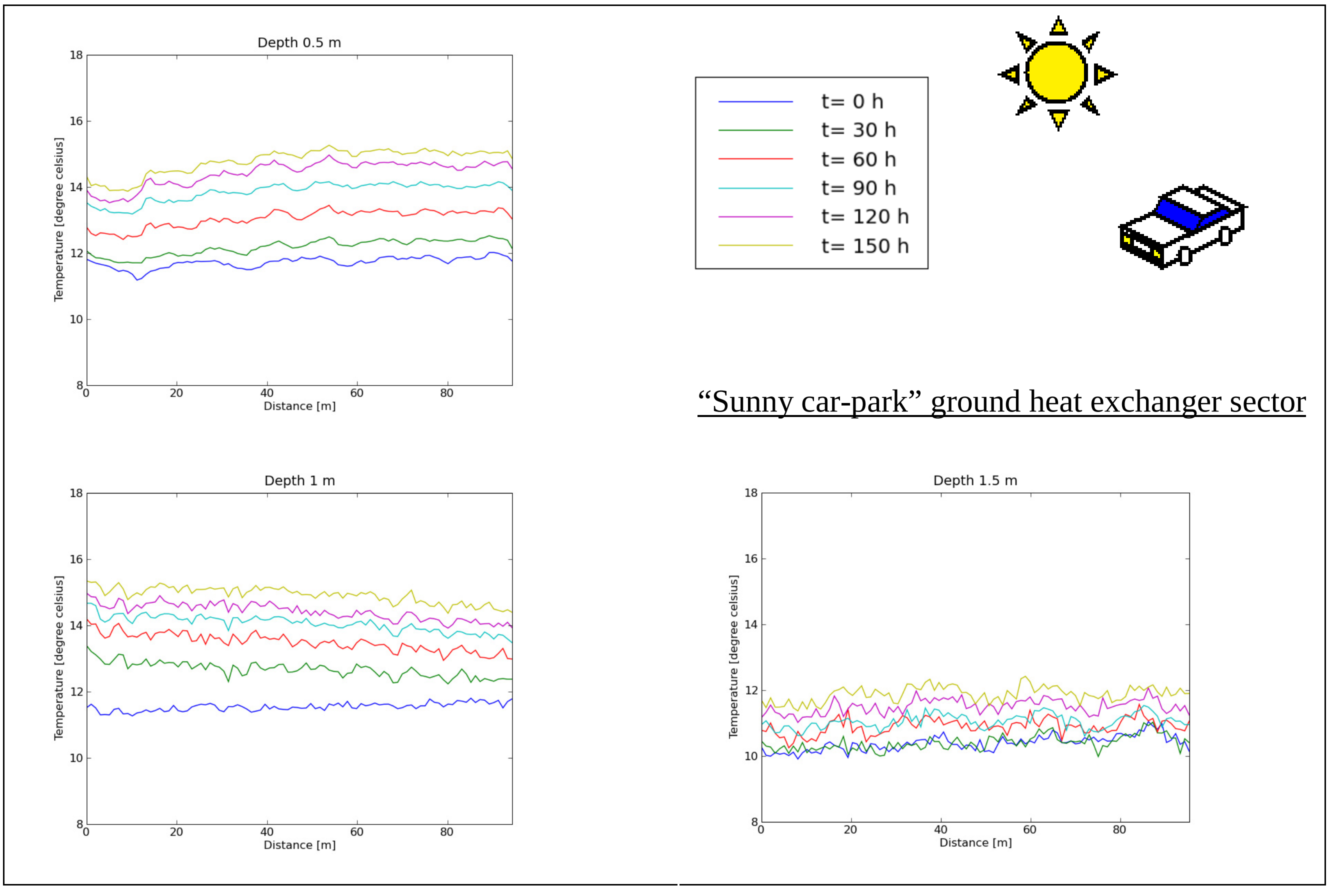

Figure 15: Evolution of the soil temperature at the three depth levels in the “sunny car-park” sector

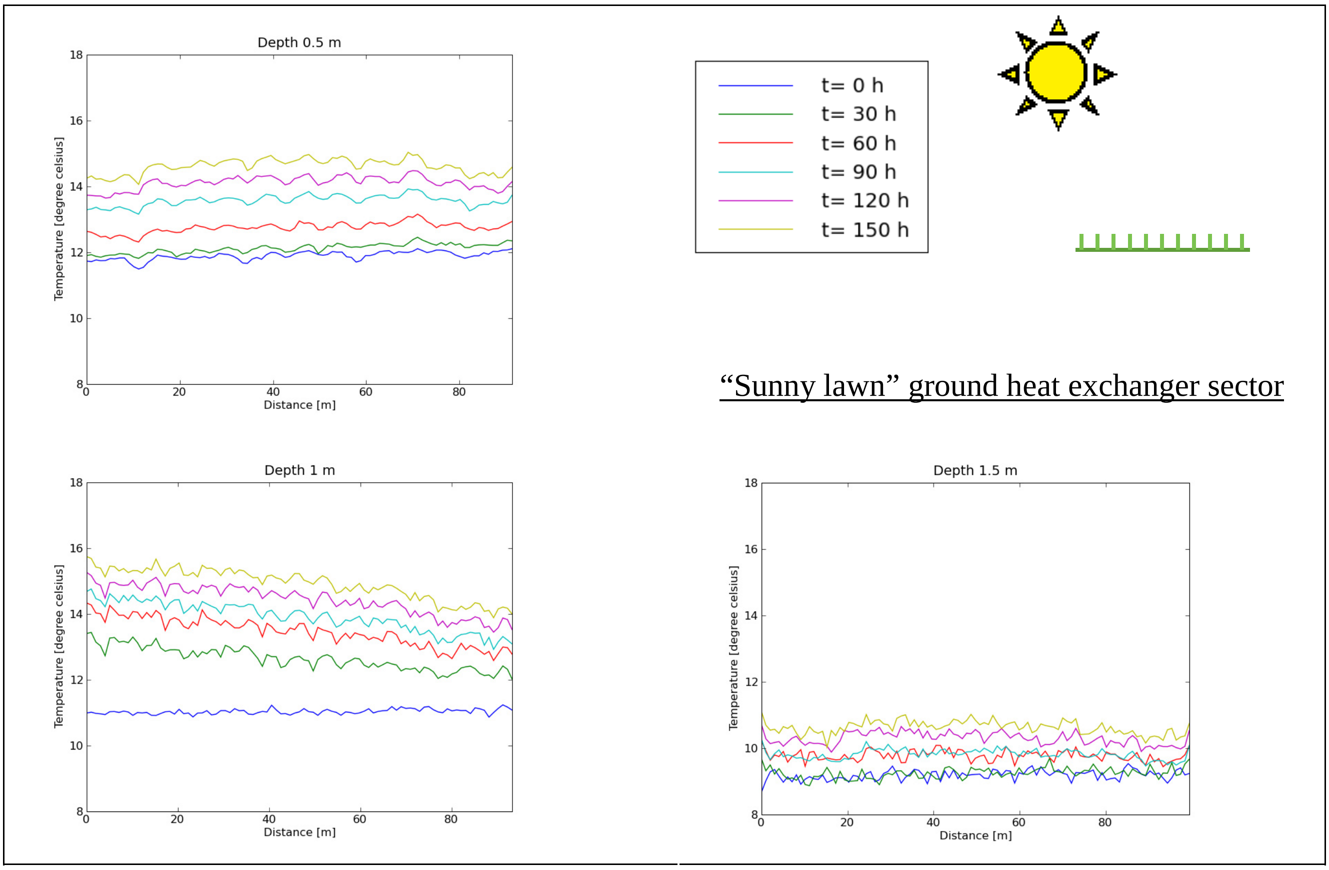

Figure 16: Evolution of the soil temperature at the three depth levels in the "sunny lawn" sector