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ABSTRACT

Underground heat exchangers are instrumented by eight multimode optical fiber cables connected to a distributed temperature sensing (DTS) Raman system which provides real time temperature monitoring, versus operational conditions of the installation. A user-friendly Labview® software has been developed, allowing the configuration of the full installation, the signal processing of raw DTS data and storage, as well as the visualization of any temperature profile, on request. Preliminary temperature profiles are very promising. This platform will allow R&D about geothermal exchanges, will provide a full scale bench to characterize new equipments, and will encourage professionals to develop this renewable energy sector.

Keywords: Optical Fiber Sensor, Distributed Temperature Sensing, Geo-exchange system, Renewable energy, Green photonics.

INTRODUCTION

Due to decline of oil (*e.g.* Hubert peak oil) and to ecological consequences linked with the use of fossil fuels (pollution, green house effect, climate change…), renewable (or sustainable, or even green) energy is more and more considered as the provision of energy that meets present needs without compromising future generations to meet their needs. Our main renewable energy source comes from our star, the Sun. The Sun lights and warms our planet and thus provides free energy to Earth. This underground-stored solar energy represents a huge heat tank which can be used to heat or cool buildings. The energy has only to be transferred from ground into houses. This is done either by pumping water from a well (open loop) or by pumping a heat transfer fluid through horizontal or vertical circuit of underground piping (closed loop). This fluid absorbs heat in the ground water or soil and the energy collected is then extracted by a heat pump system, which elevates its temperature. The heat is then distributed at the right temperature level throughout the home (radiator, heating floor…). The chilled fluid is pumped back into the loop and circulates through underground heat exchangers over and over again. So, any Geo-Exchange System (GXS) is made up of three parts: a loop, a heat pump and a distribution system. Ground heat exchange loops are usually made of high-density polyethylene (HDPE) pipes buried in the ground, either in horizontal trenches (horizontal loop), or through drilled boreholes (vertical loop). Today, some GXS solutions are already proposed to customers, but R&D is still needed to improve design rules of under-Ground Heat Exchangers (GHE).

In such a context, the BRGM *(Bureau de Recherches Géologiques et Minières, i.e. French Geological Survey)*, a leading public institution involved in Earth Sciences for the sustainable management of natural resources and (sub)surface risks, is directly involved in the implementation of climate change policies. This activity aims to reach the objective prescribed by the European Union to reduce by a factor of 4 the CO_2 emissions by the year 2050. The BRGM decided to collaborate with the CEA LIST *(Laboratoire d'Intégration des Systèmes et Technologies)*, a well known French high-tech R&D Institute, specialist of applied research, to take benefit of Optical Fiber Sensing in the context of an innovative experimental test facility devoted to the study of GXS. Such a test facility will contribute to the development of this sector on four major points: 1) Supply to professionals design rules for improving efficiency of future installations, 2) Contribute to better inform both professionals and end users on these new technologies, 3) Facilitate the emergence of demonstrations, and finally 4) Disseminate worldwide the experience feedback.

This paper aims to present design, installation, as well as first characterizations of GXS based on distributed temperature optical fiber sensing.

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2. OBJECTIVES AND TECHNICAL ASPECTS

2.1 Technical Objectives

This test facility has been implemented in Orléans (France) to assess the performances of different types of GHE: borehole heat exchangers (BHE), horizontal ground heat exchangers (HGHEs) and innovative types of ground heat exchangers (coil heat exchanger, deviated boreholes,…) [1]. The scientific objectives of this experimental platform are the following: *i)* Evaluate the influence of climatic parameters on the performance of HGHEs (rainfall, sunshine…) and the effect of different types of soil (lawn, park area…), *ii)* Determine the impact of thermal properties of soil along the depth on the efficiency of BHE, and *iii)* Evaluate the performances of new types of GHE.

Technical specifications for temperature sensing are as follows: Temperature resolution of 0.5°C (minimal), spatial resolution of ~ 1 meter. 8 thermal profiles are recorded for both vertical and horizontal pipes, and the temperature ranges from – 10°C to 40°C.

2.2 Temperature sensing solution

Above specifications require a (quasi)distributed sensing over roughly 10 km, the total length of GHE. In such context, it is not conceivable to use thousands of traditional temperature sensors (*e.g.* thermocouples) due to cabling complexity (cost and deployment), enhanced risk due to lightning on the field, plus the huge acquisition data logger required. Raman-based Distributed Temperature Sensing (DTS) is best suited for such application. The DTS is now a well-known instrument which measures temperature profiles along (single or multimode) optical fibers, used as linear sensors. The localization technique, the so-called Optical Time Domain Reflectometry (OTDR) able to provide Rayleigh backscattering measurements, was developed more than two decades ago and has rapidly become a standard tool for telecommunication fiber loss measurements. The principle of OTDR is very similar to time-of-flight measurement used in RADAR. Periodic narrow laser pulses are sent into the fiber core and the backscattered light is analyzed in the time domain. From the time it takes for this light to return to the detection unit it is possible to determine the location of any event. The DTS is basically a twin-OTDR that records both the anti-Stokes and Stokes backscattered Raman lights generated by laser pulses. The principles of DTS are explained in many publications [2, 3], as well as applications [4].

Local fiber temperature is derived from the ratio of the anti-Stokes and Stokes light intensities, while possible variations of source power, fiber attenuation or connectors' losses, etc. are removed from measurement, leading to a very selective temperature measurement. Commercially available Raman-based DTS systems achieve: distributed measurements over typically 20-30 km, spatial resolution of about 1 m and thermal resolution of about 0.1°C on field, temporal resolution ranges from seconds to hours. Classically, these resolutions are mutually dependent, so DTS configuration results from a compromise between them. During the two last decades, DTS Raman were successfully deployed in several sectors, the two main market shares being oil & gas for permanent downhole monitoring [5], and fire detection in tunnels [6]. Other applications deal with storage tanks/vessels, leakage or erosion detection in dams [7], power cable & transmission line monitoring. More recently, DTS devices were applied for ecological monitoring as well: stream temperature measurement, groundwater source detection, temperature profiles in mine shaft and over lakes… but to our knowledge, this is the first time a multichannel DTS is used to fully monitor a so large underground GXS facility.

2.3 Optical measurement system and sensing cables

The selected DTS is able to provide temperature profiles on a single multimode optical fiber, with metrological specifications as follows: 8 km range, 1 m spatial resolution, 1/25°C temperature resolution (in laboratory), and its Q factor, written as Q = (spatial resolution x temperature resolution)$^{-1}$ illustrating the trade-off between spatial and thermal resolutions, is 25. As several fibers are scanned on the geothermal test facility, an 8-channel optical fiber switch is added in front of the DTS. In this experiment, the number of equivalent sensors is therefore 5 000. Considering an integration time of 2 minutes, the data stream reaches 150 000 data per hour, so 25 millions per week and so 1 300 millions collected per year! A dedicated Labview® software was developed to deal with such data stream. It is connected to the DTS through an Ethernet link. It offers several functionalities (modules) able to download raw DTS data, perform dedicated tasks, *i.e.* signal processing, data recording in a database, plus a Man-Machine Interface for users, as well as old data visualisation on request. Main modules are devoted to:

- "Sensing topology": This module fits raw DTS measurements to physical deployment of optical fiber cables on the platform (*i.e.* the fiber topology), and extract useful profiles corresponding geothermal heat exchangers, including an accurate geo-localization of some specific zones (connectors, splices, optical boxes, deeper points on vertical pipes…),

- "Signal processing": This module is devoted to record temperature profiles, including calibration, from selected data files,
- "Real time visualisation": This module proposes 6 windows to display temperature profiles of specific sectors, plus reference outside temperature, date and time of experiment, and several extra useful information, like a flashing alarm in case of damaged or broken fiber, with metric localisation. Such module allows the user to display, on request or in real time, underground phenomena including the influence of warm/cold thermodynamic machinery cycles.

2.4 Sensing underground topology

This unity scale test facility has been implemented in 2008 and integrated within oak trees to show the nice integration of such GXS in the landscape. Both thermodynamic machinery and measurement devices were disposed in three wooden huts. The HGHEs, made out of HDPE pipes, are implemented in a clearing, 1 m below the surface. The area of HGHEs is divided in 4 sectors of 100 m² (each of them being equipped with 2 pipe loops each 100 m long) with different solar expositions and surface linings: a shaded lawn, a sunny lawn, a shaded car-park and a sunny car-park (Fig. 1). During the deployment on field, about 5 km-long optical fiber cables were attached to these HDPE pipes (Fig. 2). Vertical loops are placed into boreholes. Two pipe lengths are fused into a “U-bend” (two 90° elbows) and inserted down at the bottom of the borehole. Once the pipes were set in place, the boreholes were filled with thermally enhanced bentonite grout to prevent potentially polluted surface water infiltration and to improve heat transfers with the ground. The main advantages of a vertical GHE over a horizontal GHE are that it necessitates much smaller are and benefits from the underground temperature stability below ~ 10 m (non-dependent on the seasonal outside air temperature variations).

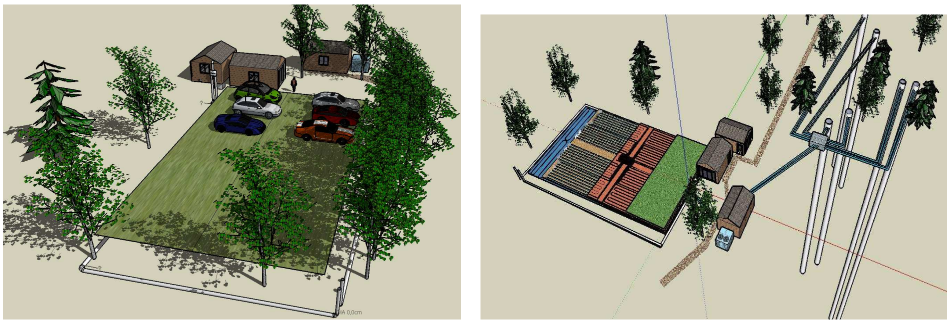

Figure 1. Artist views of the platform, made of horizontal & vertical heat exchangers equipped with optical fiber cables

Figure 2. Deployment of one horizontal heat exchanger sector; HDPE pipe with its fiber along; fiber handling in the hut

2.5 Temperature profiles measurements

To assess the efficiency of the distributed temperature sensing, a first experiment has been carried out on a geothermal borehole equipped with a double U-tube. As explained earlier, the optical fiber sensing cable is attached outside the tube, and the DTS provides an averaged value of temperature every meter, close to the fluid temperature at this location. At first, with an integration time of 2 minutes, a temperature profile is measured without heat injection in the pipe. So, at any depth there is a thermal equilibrium between the fluid, the ground and the optical fiber: the geothermal natural gradient along the vertical pipe is thus obtained (Fig. 3). The slope of this profile gives the natural underground thermal gradient. For instance, if we consider the depth of 10 m below the surface, where the seasonal temperature variations are still visible, the geothermal gradient reaches about 2.5°C/100 m. This value is in a good agreement with traditional measurements performed in France (~ 3.3°C/100 m), depending on location and soil constitution.

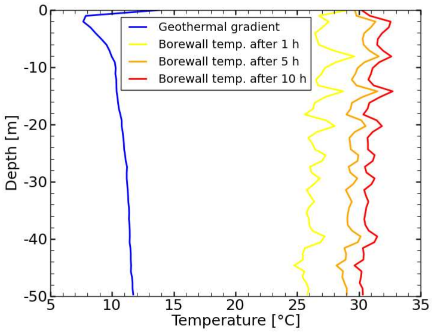

Figure 3. Natural geothermal gradient and temperature curves along the borewall after heat injection at 35°C during 1, 5 and 10 hours

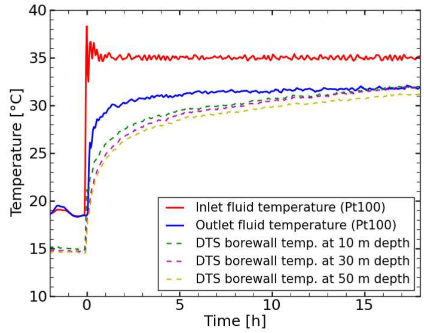

Figure 4. Underground temperature sensing (PT100 & DTS) while hot fluid (35°C) is injected in the GHE

Later on, a second experiment has been carried out while hot water was injected in the underground vertical U-pipe. The experiment started with a 35°C temperature step applied to the fluid at the inlet of the BHE, and then the temperature remained constant during 18 h, the flow rate being maintained to 1.2 m^3/h. The fluid temperature measurements (PT100) at heat exchanger inlet and outlet are reported with continuous lines on Figure 4. After some oscillations, the inlet fluid temperature stabilized at 35°C, while the outlet fluid temperature, roughly 3°C lower, increased slightly with time. The borehole temperatures measured with the DTS are represented with dashed lines for 3 distinct depths (10, 30 and 50 m). These temperature curves are in good agreement with the fluid temperature measured with PT100 probes. The borehole temperature started from 15°C and finally reached 32°C, that is to say 3°C below the inlet fluid temperature, this difference coming from the cooling provided by underground materials surrounding the borehole.

3. CONCLUSION

For the first time in the world a full scale geothermal facility testing both horizontal and vertical heat exchangers has been fully equipped with a 8-channel Raman DTS-based system. Such optical instrumentation provides new functionalities to end users. For horizontal heat exchangers, complete 3D underground temperature cartography is computed thanks to temperature profiles obtained along the pipes and at different depths (above, below and at the pipe level). In case of vertical heat exchangers, the DTS provides thermal gradients along the borehole. This geothermal test facility, now operational, will be very useful to characterize heat exchangers and new geothermal equipments, and will offer the opportunity to both end users and R&D teams to improve their know-how and design rules in this renewable energy sector. Sustainable energy becomes a new application field for optical sensing due to now well known advantages and performances of OFS, and the merging of these two domains constitute the now so-called Green Photonics.

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