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Abstract — Response of schist bedrock to a thermal pulse — *The Solargeotherm project is assessing the possibility of using vertical geothermal probes drilled into a schist bedrock for storing the thermal energy produced by solar panels and later releasing it. A thermal pulse was delivered through one of the geothermal probes in order to characterize the stratified thermophysical properties of the schist bedrock (thermal conductivity, volumetric heat capacity). The relaxation phase (cooling) was interpreted by a 1D instantaneous infinite line source type analytical solution. The temperature rise in the borehole (arrival of the thermal pulse) is too complex for an analytical interpretation, because of its highly transient character and the dynamic thermal interactions between the down leg and up leg of the U-shaped probe. A numerical 3D modelling was therefore carried out. Numerical results of the modelling are in good agreement with observations.*

INTRODUCTION

The Solargeotherm project is assessing the possibility of using vertical geothermal probes drilled into a rock mass (bedrock) for storing the thermal energy produced by solar panels and later releasing it. The research project relies on the installation of an experimental system and the use of heat transfer models. The underground device, set up entirely in Paleozoic schist (greenish grey banded sandy pelite of the Aspres Unit of the Jujols Formation) in the Eastern Pyrenees (France), consists of three subvertical boreholes, 180 m deep, equipped with double-U geothermal probes. Geographic coordinates of boreholes are 42°34'28.67"N 2°42'20.76"E.

The probes are instrumented with an optical fibre that enables temperature monitoring inside boreholes via a distributed temperature sensing (DTS) system from Sensornet. Geological characterization and fracturing of the bedrock are determined from borehole cuttings, borehole geophysics (long and short normal resistivity, natural gamma ray), fracture analysis from image logs, and surface geophysical techniques (borehole-surface dipole-dipole and surface Wenner-Schlumberger arrays). The borehole trajectography is precisely known.

A standard thermal response test (TRT) run on one of the three probes over a 10 days period gave an average thermal conductivity of 3.26 W/(m.K) over the entire 180 m of the schist bedrock intersected by the boreholes.

1 DISTRIBUTED THERMAL RESPONSE TEST USING A PULSE AS THERMAL SOURCE

A distributed TRT was performed in order to characterize the stratified thermophysical properties of the rock mass (thermal conductivity, volumetric heat capacity). The thermal pulse was delivered through one of the geothermal probes (1000 litres of water at 70 °C injected over a period of 2940 s). The DTS measured the temperature rise along the entire borehole, followed by the temperature decrease (relaxation) over six consecutive days with no fluid circulation in the probe. The temperatures all along the 180-m-deep probe were measured every two minutes for the first 24 h, and then every 30 minutes (Figure 1).

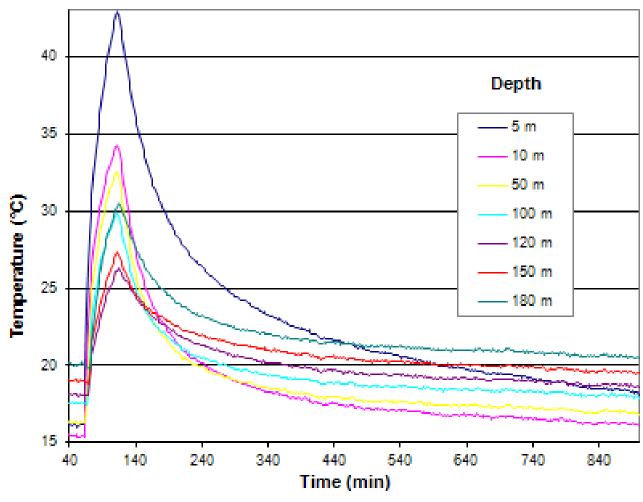

Figure 1: Temperatures during and after thermal pulse

2 ANALYTICAL SOLUTION OF THE HEAT FLOW DURING COOLING (RELAXATION)

The relaxation phase was interpreted by a 1D instantaneous infinite line source type analytical solution adapted to account for depth variations as suggested by Fujii et al. (2009). This analysis made it possible to assess the thermophysical property variations of the bedrock with depth and also to relate them to the geological property variations of the schist bedrock with a resolution of about a decametre.

2.1 Analytical solution

The evolution, with time t, of the temperature T at a distance R from the heat source at a depth z is given by the formula:

$$T(R,z,t)-To=\frac{(\rho C)_{water}.T_{source}(z).V_{inj}}{\lambda_z^*.4\pi.L}.\frac{1}{(t-t_z)}\exp(\frac{-R^2}{4.a_z^*.(t-t_z)})$$

Calculating the wall temperature of the U-shaped probe involves eight parameters: the heat capacity of the water $(\rho C)_{water}$, the thermal diffusivity and thermal conductivity of the rock mass (a_z* and λ_z*), the temperature of the heat source $T_{source}(z)$, the injected volume of water (V_{inj}), the well depth (L), the distance between the probe's vertical axis and the point of measurement R, and the time lag t_z.

2.2 Analytical modelling results

The parameter values were determined for different depths so as to obtain the best match between the analytical solution and the experimental curves (Figure 2). The thermal conductivity of the intersected ground could thus be defined with a resolution of about a decametre through the fit on the decreasing (cooling) part of the experimental temperature curve.

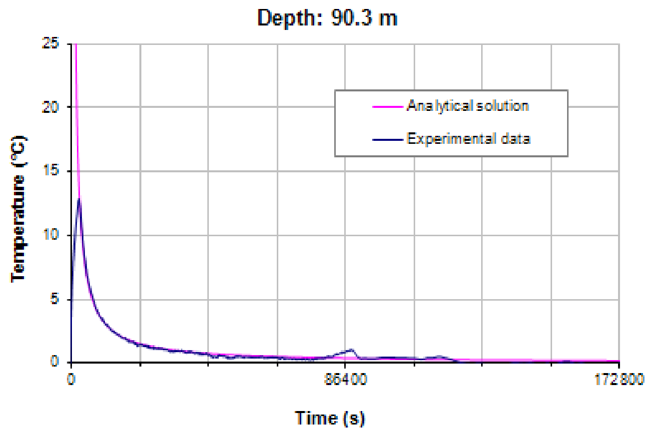

Figure 2: Fit of the measured and calculated data

3 NUMERICAL 3D MODEL OF BEDROCK'S HEAT FLOW RESPONSE TO THE THERMAL PULSE TEST

The temperature rise in the borehole (arrival of the thermal pulse) is too complex for an analytical interpretation, because of its highly transient character and the dynamic thermal interactions between the down leg and up leg of the U-shaped probe. A numerical 3D modelling was therefore carried out with Comsol Multiphysics, taking into account heat flows between the different materials involved (i.e. the bedrock, sealing grout, polyethylene probe tube, heat transfer fluid, surface insulator). The modelling is constrained by the experimental data of the induced thermal pulse.

3.1 Physical model of the system

The elements to be numerically modelled are the 180-m-deep double-U geothermal probe, the polyethylene probe tube, the sealing grout, the surficial polyurethane foam insulation, the heat transfer fluid (water) and the enclosing rock mass. The finite element method used by the modelling software (Comsol Multiphysics) requires the system's geometry to be discretized into tetrahedral or prismatic volume elements.

3.2 Mathematical model of the system

3.2.1 Simplifying assumptions

Due to the large aspect ratio between the length of the modelled tube (180 m) and its diameter (40 mm), assumptions have to be made to simplify the numerical computation without weakening the solution. This is done by combining a 2D model ("shell" modelling), enabling one to calculate the fluid temperature at the inner wall of the polyethylene tube as a function of depth, with a 3D model (solid modelling) for calculating the temperature in the polyethylene tube, the sealing grout and the enclosing rock mass. In addition, the fluid temperature distribution in the tube section is considered to be uniform throughout the section, making it unnecessary to calculate the flow in the tube; the only information required is the flow rate and the flow mode (laminar or turbulent). Finally, it is considered that there is no fluid flow in the rock mass, which is the environment of the implanted experimental device away from any aquifer.

3.2.2 Calculating the temperature of the circulating heat transfer fluid

Calculating the temperature distribution within the heat transfer fluid is done at the surface (shell) on the inner radius of the probe's polyethylene tube. The partial differential equation governing the calculation of the temperature distribution is defined on the surface by the following equation:

$$\rho C_p \frac{\partial T_f}{\partial t} + \nabla_t \cdot (-k\nabla_t T_f) + \nabla_t \cdot (\rho C_p T_f u) = Q$$

d_t: tangential gradient at the shell
T_f: fluid temperature (K)
u: fluid velocity (m/s)
C_p: heat capacity at constant pressure (J/(kg.K))
ρ: mass density (kg/m^3)
Q: heat source (W/m^3)

3.2.3 Calculating the amount of heat

The term "heat source" relates to the heat exchange between the tube and the fluid. It is calculated on the basis of the exchange surface area and the fluid volume by the following equation:

$$Q = \frac{2\pi r dl}{\pi r^2 dl} h(T - T_f) = \frac{2}{r} h(T - T_f)$$

T: temperature of the polyethylene tube
h: exchange coefficient (W/(m².K))

3.2.4 Calculating the heat transfer between fluid and solids

The heat transfer between fluid and solid is defined by the exchange coefficient (h) determined from the Dittus-Boetler correlation. This correlation specifies the value of the exchange coefficient based on the geometric characteristics of the tube, the physical properties of the fluid and the flow mode, which is here turbulent (h = 1893 W/(m².K)).

3.2.5 Calculating the temperature of the solids

The temperatures of the polyethylene tube, polyurethane foam, sealing grout and bedrock are calculated from the three-dimensional heat transfer equation.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = 0$$

3.3 Results of the thermal pulse simulated with the numerical model

The result of the thermal pulse simulated by the three-dimensional numerical model, when compared against the obtained experimental measurements, would appear to be very satisfactory. Figure 3 shows the numerical model simulation of the thermal pulse's temperature changes against the experimental data for two simulated measurement positions, A & B, along the probe. The simulated spatiotemporal evolutions, TA & TB, for different depths are comparable with experimental measurements T_{exp}, on both the injection tube (descending part) and return tube (rising part). The fluid's outlet temperature is also close to the experimental measurements. The developed model, using both the Dittus-Boetler correlation and the shell and solid coupling in modelling, shows its effectiveness for this type of experimental device.

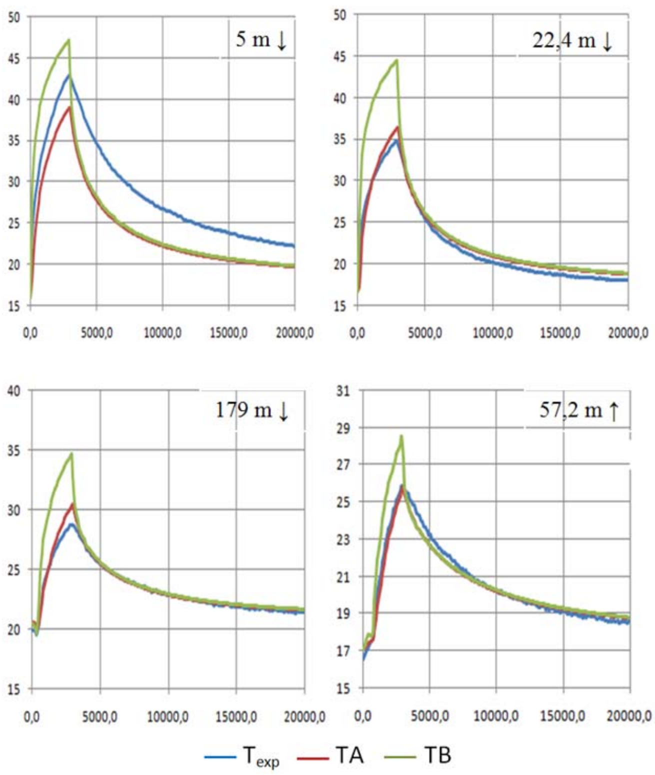

Figure 3: Simulation of the thermal pulse vs. experimental data

3.4 Energy balance

The balance between the amount of energy injected during the injection period and the amount of energy stored (transferred) in the different materials of the system was established as a check on the model. The energy balance appears consistent (Figure 4). One can see that during the injection period (2940 sec) the energy is stored mainly in the grout. This explains why the thermal conductivity of the enclosing rock mass has little influence on the evolution of the temperature during the first part (temperature rise) of the thermal pulse simulation by the numerical model.

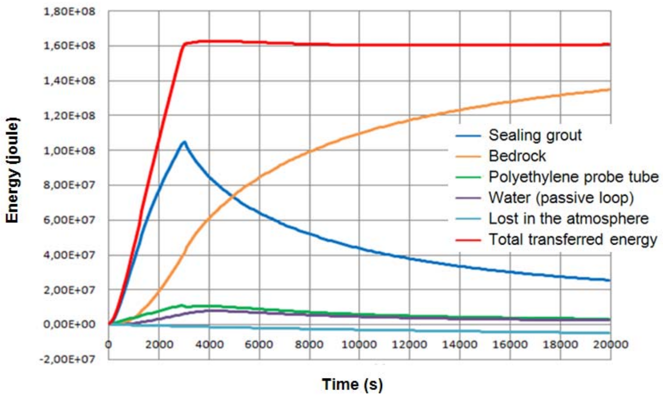

Figure 4: Evolution of the energy flows with time

4 RESULTS

A 3D numerical geothermal probe model has been implemented in order to simulate heat injection in bedrock through vertical geothermal probe in 180 m deep boreholes. This model was applied to simulate a response of schist bedrock to a thermal pulse. Numerical results are in good agreement with observations, which is especially remarkable regarding the particularly transitional nature of the modelled phenomena, and the required spatial and time discretization. A calibrated numerical probe model is now available to simulate a variety of experimental patterns for the injection and withdrawal of heat in a rock mass (Figure 5).

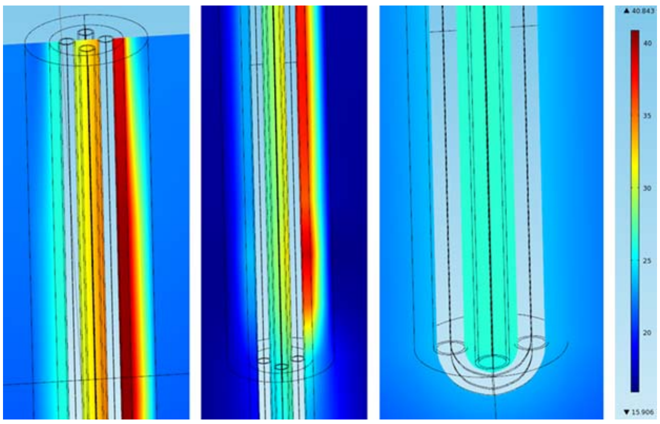

Figure 5: Spatial distribution of the temperatures at t = 6000 s

In a future prospect of managing underground energy storage, this detailed geothermal probe model could be linked to global models of heat transfer in bedrock running multiple probes at larger temporal and spatial scales.

5 DISCUSSION

The DTS system for monitoring the temperatures does not enable one to control the exact position of the measured temperature with respect to the borehole axis because of fibre "fluttering" along the probe. The situation is approximated in the model by the two simulated measurement positions A & B.

The shallow part of the system, between 0 and 10 m depth, could not be properly modelled. The calculations from the simulation differ from the experimental results for this section of the borehole, giving too much "dissipation" compared to observations in the cooling period. The experimental device shows that there are several interfaces in this shallow section: bedrock/atmosphere, presence/absence of insulating polyurethane foam, presence/absence of PVC casing. It is likely that the vertical size of mesh elements, which is of the order of a metre, is not sufficiently precise to correctly model these different shallow-section interfaces.

The fact that the energy injected by the thermal pulse is stored mainly in the sealing grout during the period corresponding to the pulse's arrival limits the possibilities of correlating the thermophysical data against the geological characteristics of the intersected bedrock in this first period of the test, where the temperature measurements are easily interpretable because particularly variable. An higher amount of energy (heat) injected during the thermal pulse should increase the amount of heat rapidly transferred into the rock mass during the temperature rise, and thus improve attempts at correlating the bedrock's thermal behaviour with its geological and geophysical characteristics.

ACKNOWLEDGMENTS

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