UNDERGROUND THERMAL ENERGY STORAGE – FIRST THERMAL RESPONSE TEST IN SOUTH AMERICA

A. Busso[*], A. Georgiev[**], P. Roth[***]

[*] Department of Physics, FaCENa, UNNE, 3400 Corrientes, Argentina
[**] Department of Mechanical Engineering, TU Sofia, Branch Plovdiv, Bulgaria
[***] Department of Mechanical Engineering, UTFSM, Valparaiso, Chile

Abstract
The design of a ground heat exchanger for Underground Thermal Energy Storage (UTES) applications requires knowledge of the thermal properties of the soil (thermal conductivity λ and borehole thermal resistance Rb). In-situ determination of these properties can be done by installing a vertical borehole heat exchangers (BHE) and performing the so-called Thermal Response Test (TRT). The so called Borehole Thermal Energy Storage (BTES) can store heat during the summer (used 3 to 6 months later during the winter) and produce cold in the summer. The present paper describes the results of a cooperative work between research groups of Chile and Argentina, which led to the first TRT and natural experiment with solar collectors and BTES performed in South America. A setup for implementing the BTES was prepared at the "Solar Energy Laboratory" of the Technical University Federico Santa Maria, Valparaiso, Chile. The TRT was realized during 9 days (24.06 - 03.07.2003), the charging from solar collectors - during 29 days (18.08 - 16.09.2003) and the discharging with a "water - water" heat exchanger, during 13 days (17.09 - 30.09.03). A comparison between conventional slope determination method, Geothermal Properties Measurement (GPM) data evaluation software based on numerical solutions for the differential equations governing the heat transfer processes and two variable- parameter fitting was performed in order to calculate λ and Rb. The experiments done are a good precondition for future investigation and application of the BTES technology in Latin America (Chile, Argentina and Brazil).

Keywords: Thermal Response Test; Ground Thermal Conductivity; Borehole Thermal Resistance; Charging; Discharging.

* Corresponding author. Tel: +54 (0)3783 473931 ext 129; Fax:+54 (0)3783 473930
E-mail: ajbusso@exa.unne.edu.ar (A. Busso)

1. Introduction

The application of long-term (>3 months) seasonal Underground Thermal Energy Storage (UTES) is uncommon. It can be charged with solar collectors, but first it is very important to investigate the ground thermal properties, normally used as a base for the development of the seasonal BTES.
At first, laboratory methods to study the ground properties (giving bad results) were used. The Thermal Response Test has been used for the determination of the ground thermal conductivity as a very effective method. A defined thermal load is applied to a BHE and water flow and inlet and outlet temperatures are measured at regular intervals. The TRT first was presented by Mogensen [1] (stationary system), later mobile conductivity measurement system appeared in Sweden [2] and USA [3]. Long term storage of huge amounts of thermal

energy for heating and even more important for cooling can give a significant contribution in energy saving and rational use of energy [4].

The theoretical approach commonly used for TRT is based on the Line Source Model (LSM), which depends primarily on the thermal conductivity of the soil and the fluid-to-soil thermal resistance. The theoretical basis of the thermal response test is presented by Gehlin [2] and Kavanaugh & Rafferty [5]. About 10 countries in the world are dealing nowadays with this type of investigation - like Germany, Sweden [2], Canada, USA [3], Norway, Netherlands, England and Turkey [4].

Some months ago (June - July 2003) a Thermal Response Test (TRT) was realized in Valparaiso, Chile. The object of this work is to present in details this important test and the next steps undertaken to develop this successfull laboratory investigation of ground charging and discharging, implemented with the same setup. The installation in Chile is the first one in South America, starting future development in this area - it studies the thermal conductivity, the thermal diffusivity and the temperature of the subsoil [6].

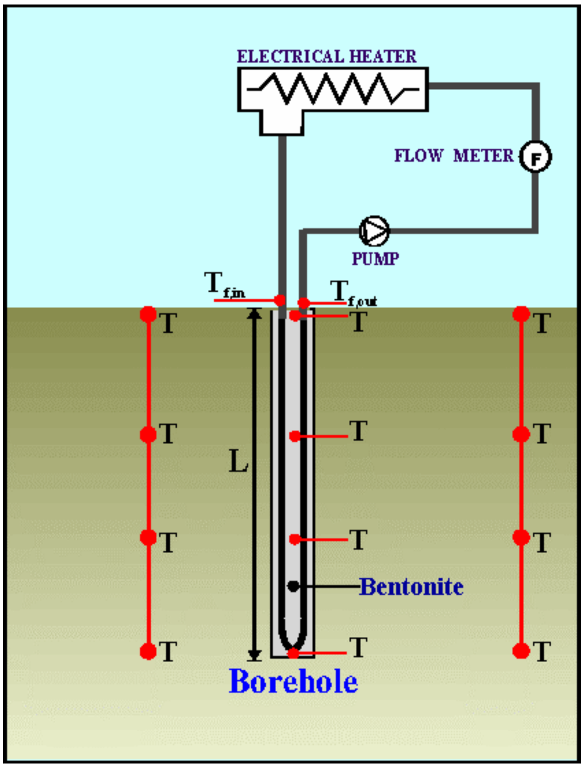

Fig.1.-Installation scheme

Fig.2.-General view of the experimental installation

2. Installation preparation and measuring instruments

The first unsuccessful attempt to create an installation, which will use the subsoil as a storage of heat were done by Prof. Pedro Roth in Chile about 20 years ago. The second attempt, by the same author and his group one year ago, led to the first TRT in Latin America.

Three boreholes were drilled to a depth of 20,5m. A U-loop of HDPE (3/4” SDR 11) was inserted in the central borehole to a depth of 16.5m (Fig.1). The borehole was subsequently grouted with a 12% bentonite mixture. In each of the three boreholes type-K thermocouples were installed at different depths. Thermal energy was supplied by means of a 1000 W electric heater.

Two reconstructions of the installation were done just after the termination of the TRT. First, three solar collectors were connected with the BTES (Fig. 2). It gives the opportunity to charge the BTES by means of solar energy. The new reconstruction led to mounting of heat exchanger "water - water" in the installation. Its object was to discharge the BHE and the surrounding soil using cold water of the net.

A manual rotameter "Blue White industries 9509" with maximal flow rate of 7,5 l/min was used for flow measurement. Two Gemini Data Loggers with sensor of the type Standard Temperature Probe PB-4724 were used for monitoring the temperatures of the boreholes. Ambient temperature was measured with a Gemini Data Logger TGP - 0017 with a case-integrated sensor. The Data loggers were programmed by means of the software GLM v2.8. Measurements were recorded and stored in the memory of the logger and downloaded to the PC on a daily basis using the same software. The global solar radiation was measured during the charging with Gemini Data Logger TGPR - 1001 using Kipp & Zonen SP-LITE Silicon Pyranometer. Additionally, a rotameter (ROTA Apparate- und Maschinenbau, Öfingen, Germany) was installed to measure the flow rate on the other circuit of the heat exchanger during the discharging.
All the equipment was calibrated prior to the test.

3. Tests

The TRT was carried out in June - July 2003. The test was implemented during 9 days (from 24th of June to 3rd of July 2003). Temperatures measured were ambient temperature, inlet and outlet temperature of the borehole. Additionally, although the flow rate was fixed at the constant value of 3,17 l/min it was periodically measured and controlled. The electrical power was regulated and maintained constant at about 1000 W. The electrical power of the circulating pump was about 350 W.

The charging was done by means of solar energy (natural experiment). The test was implemented during 29 days (from 18th of August to 16th of September 2003). Five temperatures measured were - inlet and outlet temperature of the borehole, inlet and outlet collector temperature and ambient temperature. Additionally, the global solar radiation was measured. The Temperature- Difference- Regulator was used to turn on (5°C difference) and off (2°C difference) the pump depending on the temperature difference between the outlet collector and the inlet borehole temperatures.

The discharging followed with the heat exchanger - extraction of heat from the ground. The experiment started on 17th of September and finished on 30 of September 2003. Additionally the flow rate of the cold circuit was measured.

4. Response Analysis

The data gathered was analysed and evaluated using the classical "slope determination technique", "two-variable parameter fitting" and with the aid of the GPM (Geothermal Properties Measurements) software. A brief description of each method is presented.

Line Source Model (LSM) problem - the equation for the temperature field as a function of time (t) and radius (r) around a line source with constant heat injection rate ($\dot{Q}$) may be used as an approximation of the heat injection from a BHE:

$$T_f(t) = \frac{\dot{Q}}{4\pi\lambda H}\left[\ln\left(\frac{4at}{r^2}\right) - \gamma\right] + \frac{\dot{Q}}{H}R_b + T_0 \qquad (1)$$

a - Thermal diffusivity (λ/C), m^2/s;
$\dot{Q}$ - Heat injection rate, W;
r - Borehole radius, m;
C – Volumetric heat capacity, MJ/m^3K.
T_0 - Undisturbed ground temperature, ºC;
R_b - Borehole thermal resistance, m-K/W.
t - Time, s;
T_f - Mean fluid temperature, ºC;
H - Borehole depth, m;
γ = 0.5772 (Euler´s constant);
λ - Thermal conductivity of soil, W/m-K;

Eq. (1) can be re-written in a linear form as:

$$T_f(t) = k\ln(t) + m \qquad \text{with } k = \frac{\dot{Q}}{4\pi\lambda H} \qquad (2)$$

Hence, λ can be determined from the slope of the line resulting when plotting T_f against *ln(t)*, therefore the name and basis of the evaluation method.

The need for a more interval-independent evaluation technique led to fit the data using as fitting function Eq. (1) with λ and R_b left as the two variable parameters. For the analysis the commercial software "Origin6" was used. The used Software has the capability of performing nonlinear curve fitting to user input functions using a Levenberg-Marquardt iteration algorithm. At each iteration, the fitter computes the Variance-Covariance matrix using its value from the previous iteration.

The GPM is a program developed at the Oak Ridge National Laboratory to determine soil formation thermal properties from short term field test data. The program makes use of a parameter-estimation-based method in combination with a 1-D numerical model developed by Shonder and Beck. The numerical model relies on the cylinder source model considering the two pipes of the U-loop as a single cylinder.

As shown by Eq. (2), the thermal conductivity is related to the slope of the resulting line in a logarithmic time plot of the mean fluid temperature T_f in the BHE. Fig.3. show such a graphical representation (excluding the first 15 h) for the entire time span of the test and the slope of the associated regression line. Resulting values for λ and R_b are 1.8 W/mK and 0.3 mK/W respectively.

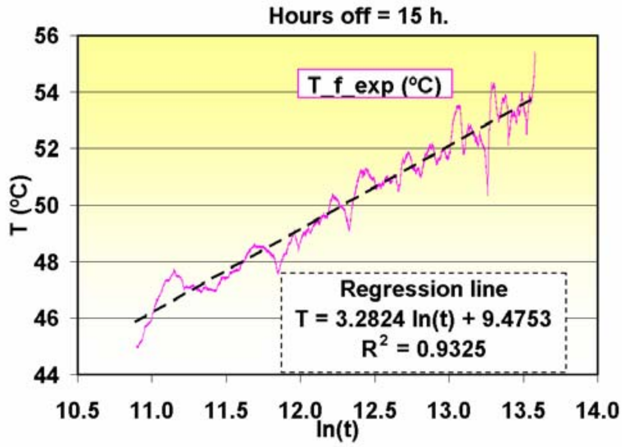

Fig.3.-View of evaluation data interval.

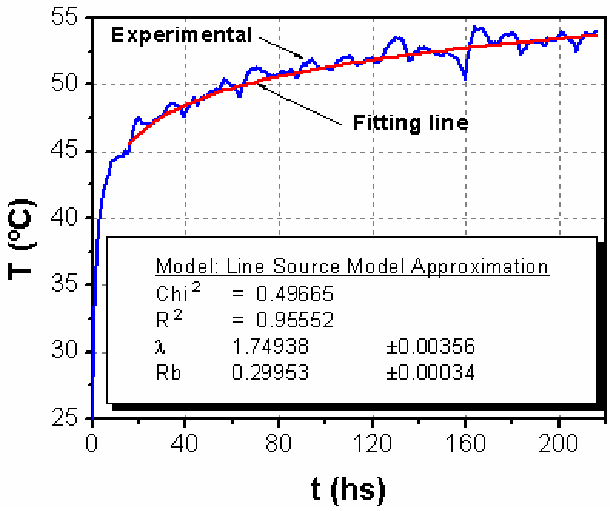

Fig.4.-Response test data and fitted curved.

Fig.4 is a plot of the resulting non-linear fitting curve superimposed to the experimental data. The inset presents the summary of results with the values of the two variable parameters, $\lambda = 1.749$ W/mK and $R_b = 0.299$ mK/W.

The results of the analysis using the GPM software are presented in Fig.5. Superimposed is the mean fluid temperature T_f predicted by LSM, Eq. (2). Because of the transient nature of the model, the entire data set is used in the analysis. The residuals (absolute errors) between predictions and experimental points are shown in the lower part of the graph with GPM values very close to zero. Resulting values for λ and R_b are 2.35 W/mK and 0.32 W/mK respectively.

5. TRNSYS simulation

The response test was further studied using TRNSYS TYPE 141 VERTICAL GROUND HEAT EXCHANGER. This subroutine models a vertical heat exchanger that interacts thermally with the ground.

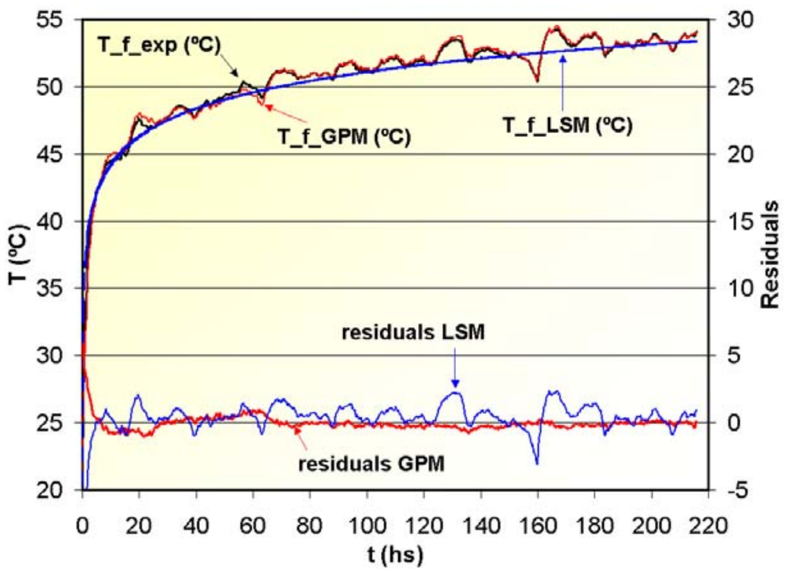

Fig.5.-GPM and slope determination method.

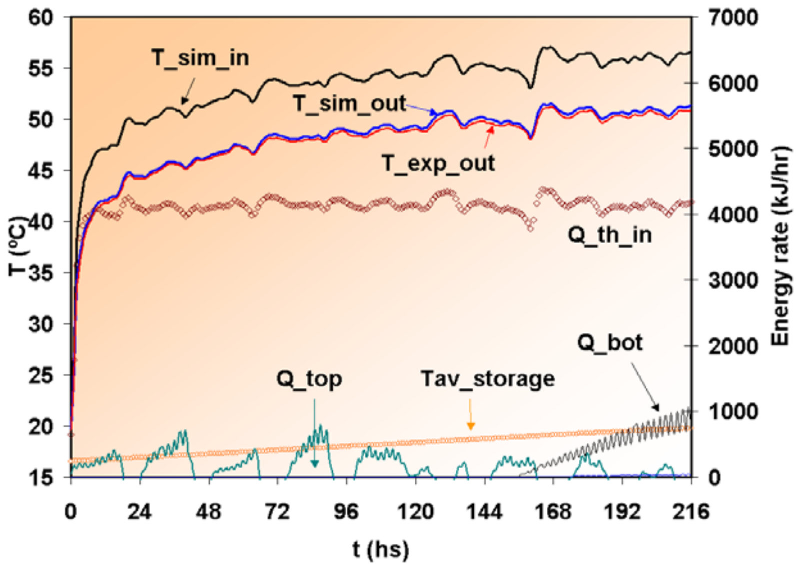

Fig.6.-Simulated by TRNSYS type 141.

The program was fed with measured data on BHE inlet and outlet fluid temperature as well as ambient temperature. Fig.6 presents the results of the TRNSYS simulation. The agreement between experimental and TRNSYS simulated outlet temperature is remarkable. The graph also shows energy rates through the boundaries of the storage region and the evolution of the mean storage temperature.

Given TYPE141 outputs, the temperature profile in the underground at user-specified nodes, 12 h interval mapings were constructed for the entire duration of the test.? Fig.7. depicts four time instances; 12 h., 84 h.,156 h. and 240 h.; of the thermal field so obtained. The observable feature is that top losses prevent the lower part of the storage to increase temperature significantly affecting long-time performance of the storage.

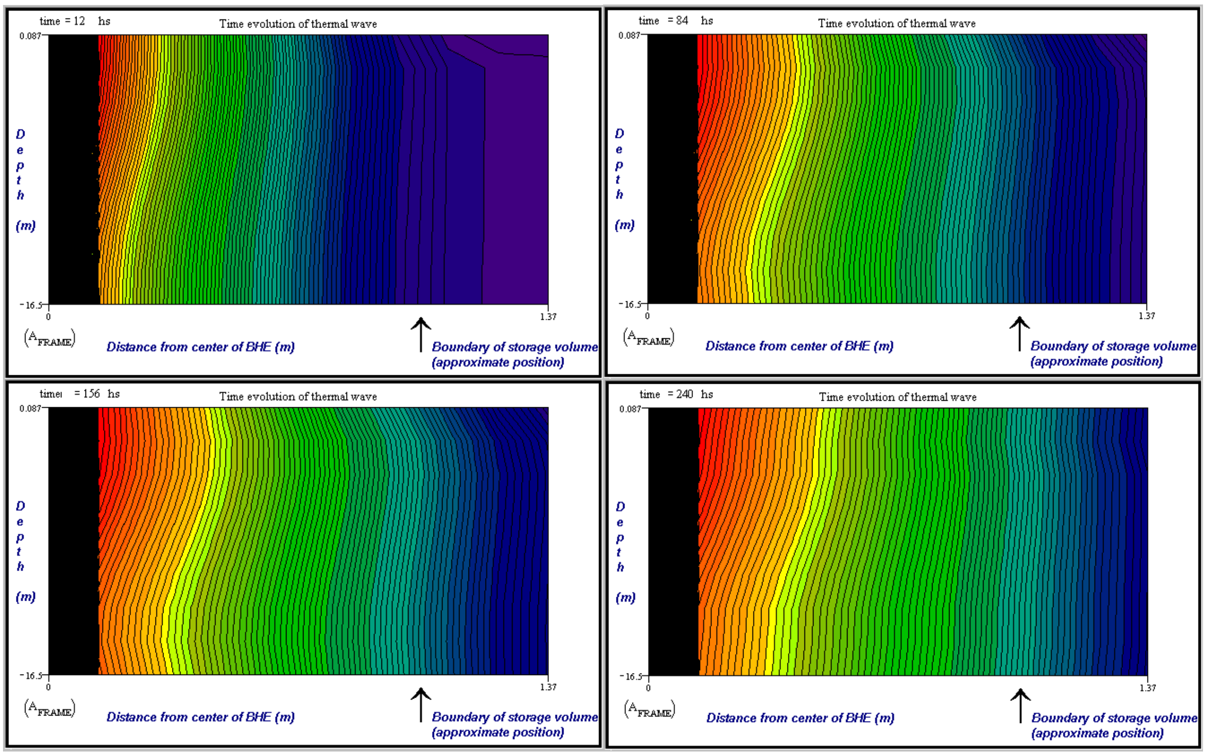

Fig.7. Time evolution of the thermal field in the ground.

After introducing some improvements to the installation, specially regarding the top insulation of the storage, a short term (2 months) charging-discharging test was realized, the results of which are still under analysis. Fig.8 depicts the TRNSYS simulation predictions for the evolution of the energy exchange rates during the first 9 days of charging before and after the improvements. A sensitive reduction of energy losses due to the better thermal insulation used can be observed.

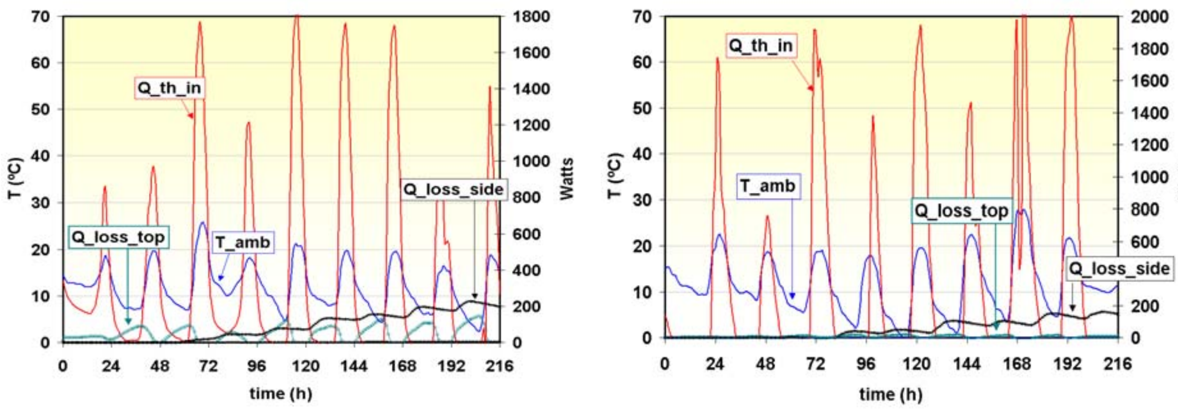

Fig.8.- Evolution of predicted energy exchange rates before and after improvements.

6. Conclusions

From experience and the results obtained we draw the following conclusions:

- The effective values of 1.8 W/mK and 0.3 mK/W were determined for the thermal conductivity λ and borehole thermal resistance R_b respectively;
- Application of the classical slope determination and/or two-variable parameter fitting can be used as a fast and reliable tool for data evaluation;
- Accuracy of the evaluation depends on the care taken when performing the test;
- TRNSYS simulations helped identifying sources of heat losses through the boundaries of the storage.
- This first experience represents a step towards a more detailed study on thermal properties of the soil in different sites in Chile and Argentina with eyes set on possible practical applications of underground thermal energy storage in the region.

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