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Soil Thermal Response Test of a Horizontal Coil

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ABSTRACT

This work describes results from a Thermal Response Test (TRT), in which the values of the effective thermal conductivity of the subsoil, λeff, and the thermal resistance, Rb, for a particular heat exchanger were determined based on the infinite line kelvin source model (ILS) which is heat transfer by thermal conduction. This purpose was obtained by putting forth the graphical method of the slope. Thereby a heating and cooling system with heat pumps, coupled to the subsoil, producing energy saving and so a diminishing carbon dioxide can be designed.

1. INTRODUCTION

A horizontal system of a particular heat exchanger was analyzed by the standard vertical heat exchanger mathematical model, which gets the effective thermal conductivity of the subsoil λeff and the thermal resistance Rb from the Thermal Response Test (TRT). The objective of this work is to explore and describe the results of the effective thermal conductivity of the subsoil λeff, and the thermal resistance Rb.

The obtained data were loaded in a spreadsheet and plotted with a scattering diagram, then the point cloud was linearized obtaining the straight linear regression line with its equation and the mean squared error. From the straight-line regression, we obtained the value of λefec, and then we proceed to calculate the value of the thermal resistance between the fluid and the well wall called Rb (ºK / (W / m)).

2. METHODOLOGY

The experiment was carried out from the test of an exchanger. For the realization of the experiment, the theoretical contributions were used of Ingersoll, L.R. and Plass, H.J. (1948), Carslaw and Jaeger (1959) and put into Eklöf C, Gehlin S. (1996) thesis were taken as references as well as the UNSL (San Luis National University) testing laboratories.

3. MATERIALS

On a 7.5 cm concrete floor, a swimming pool excavation was already made of 4.5 m long, 2.3 m wide and 1.5 m deep. The water suitable piper coil (PEAD ϕ ¾" K6) was fastened with an iron mesh and then covered with a 7.5 cm thickness concrete layer. The exchanger was in the middle of a 15 cm concrete layer without any type of additive, such as bentonite. Then, an expansion tank was built and thermally insulated. A circulation pump was placed, and subsequently the measuring instruments were installed, which consisted on thermometers, hygrometers and mechanical flow meter. The thermal disturbance was carried out with an electrical resistance placed in the tank water with its respective connection, likewise the electrical power was determined by means of current and voltage measurements. The collected data were uploaded in a spreadsheet where they were processed, determining the straight-line regression which led us to the coefficient of subsoil thermal conductivity.

4. DEVELOPMENT

The conventional thermal response tests were performed for vertical exchangers buried in an individual well, through which a heat transfer fluid was circulated and disturbed with a constant heat injection rate. In the theoretical model, the involvement of nearby wells was not considered, and the injection rate was assumed to be constant.

Geothermal gradient is referred to the increase of subsoil temperature with increasing depth. If the geothermal gradient does not change, then the subsurface conditions are considered stationary.

If heat is injected into a borehole, the temperature field will start to vary and the more heat is injected, the warmer the soil becomes, so the undisturbed subsoil temperature will be at a greater distance from the well. If the injected heat is constant, the temperature field will be stationary again, and it will take at least from 20 to 25 years to get it. In this situation, a thermal process is generated to be analyzed in three stages:

First: transitory process when there is an increase in the temperature of the subsoil;

Second: stationary process when the increase in temperature is no longer recorded and the heat transfer speed from the subsoil to the environment equals the heat injection speed to it.

Third: a pulse when occurring a variation of the injection heat and overlaps the stationary process.

The pulse does not lead to a steady state since it is limited in time and is overlapped. The average stationary temperature is described as Tr. In an increasing temperature transitory process is overlapped on the undisturbed subsoil temperature Tsur. This differentiates the pulse of the transitory process.

The fundamental heat conduction equation shows us that the variation of the temperature depends on the diffusivity 'α'.

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\cdot\frac{\partial T}{\partial t} \qquad (1)$$

Then the temperature T, at a coordinate point (X, Y, Z), is determined by the time 't', and the diffusivity 'α'.

This diffusivity 'α' given in [m2 / sec] depends on the properties of the material and shows whether the material is good or bad thermal conductor. The higher the value of the 'α' parameter the material is the better conductor of heat.

In stationary conditions, the heat capacity loses importance, as well as the temporary derivative, so that the heat conduction equation can be represented by the Laplace equation.

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0 \qquad (2)$$

During the transitory process we get:

$$T_r(t)=T_{sur}+T_{rq}(t) \qquad (3)$$

During the process of a pulse:

$$T_r(t)=T_r+T_{rq}(t) \qquad (4)$$

For the mathematical model of the thermal response test, only the transitory process will be considered, since the superposition of the pulse is not important.

The relationship between the undisturbed subsoil temperature, Tsur, and the temperature of the heat transfer fluid Tf., Is given by a thermal resistance Rb [ºK (W / m)], and it turns out to be the resistance between the heat transfer fluid and the well wall, and it is defined like this:

$$T_r - T_{sur} = R_b \cdot q \qquad (5)$$

When heat is injected into the subsoil, a transitory process begins, thereby a relationship is established between the undisturbed soil temperature Tsur and the temperature of the heat carrier fluid Tf. given by Ingersoll, L.R. and Plass, H.J. (1948) and Carslaw and Jaeger (1959):

$$T_f=\frac{Q}{4\pi\lambda H}\left(ln\left(\frac{4at}{r_0^2}\right)-\gamma\right)+\frac{QR_b}{H}+T_{sur} \qquad (6)$$

The above equation (6) is worth from the determined time:

$$t\geq\frac{5r_0^2}{\alpha} \qquad (7)$$

The transitory process culminates and begins a stationary one, after decades "tb":

$$t_b=\frac{\gamma H^2}{16\alpha}\left[seg\right] \qquad (8)$$

described by the following equation:

$$T_f - T_{sur}=\frac{Q}{H}\left[\frac{1}{2\pi\lambda}ln\left(\frac{H}{2r_0}\right)+R_b\right] \qquad (9)$$

4.1 Test performance:

In the expansion tank, a solution of 100 liters of water with 2 liters of glycol was placed. The thermal disturbance was carried out with an electrical resistance. The test began on 04/19/2013 "without thermal disturbance", to determine the temperature of undisturbed soil. The average of the exchanger outlet temperature, which was Tsur = 21.65 ºC. was obtained and ended on 04/20/2013, with the data collection performed in isolation. TRT started "with thermal disturbance" on 04/20/2013 and ended on 04/23/2013 lasting 72 hours. The data collection was done manually every 10 minutes, with an injection of 818.9 watts of average power and with a water flow of 0.00042 (m3/sec).

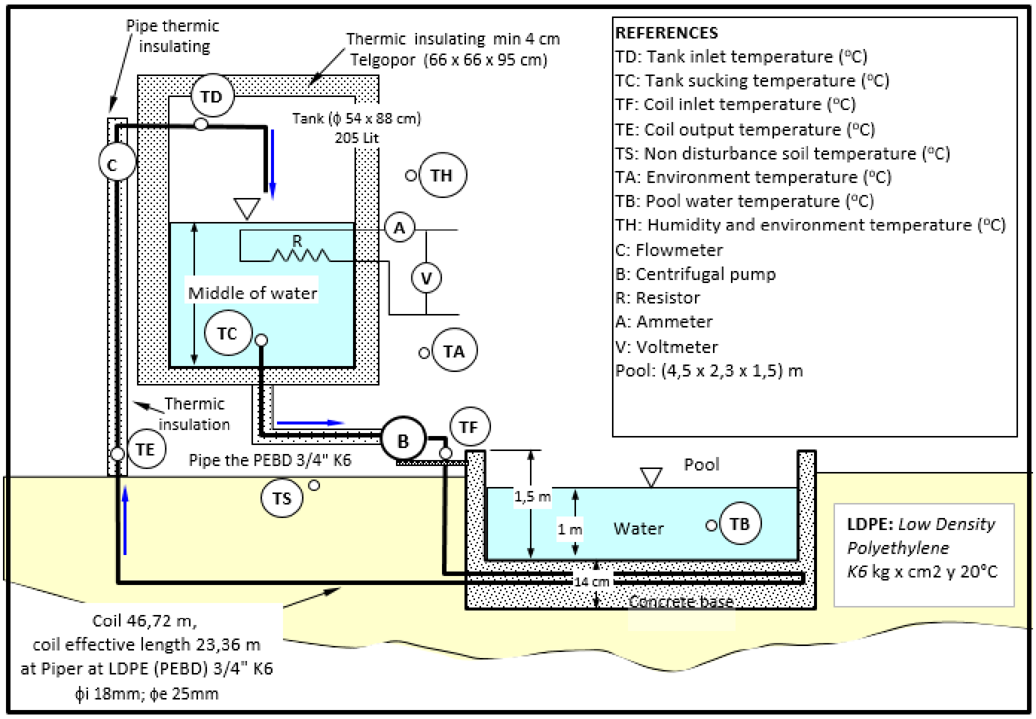

Figure 1: Measurement device scheme which was set in San Luis - Argentina.

Figure 2 shows the evolution of the average temperature of the heat carrier fluid "Tf", as a function of the "ln (t)" in hours, from the moment in which it starts to inject heat up to the test completion. Likewise, the straight-line regression with its equation and the mean square error is observed.

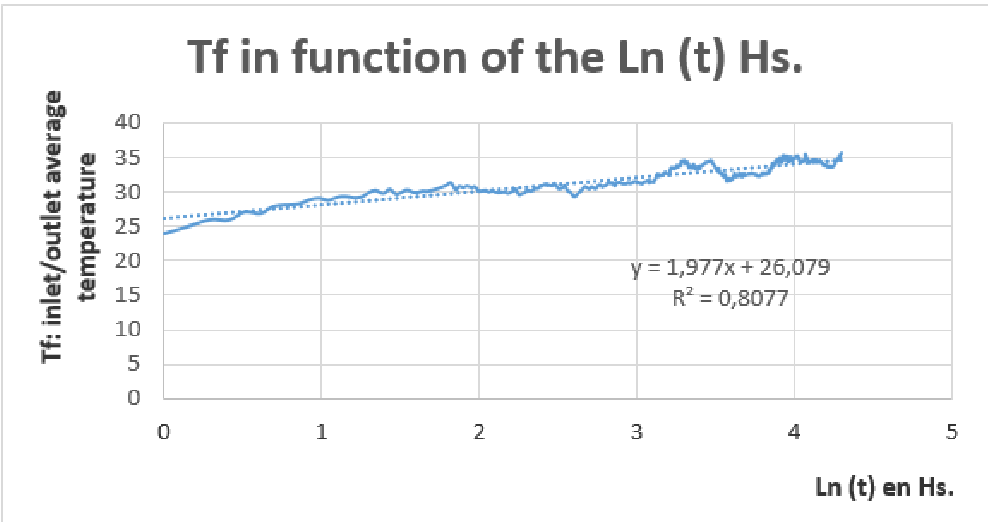

Figure 2: Average input / output temperatures as a function of "ln (t)".

4.2 Time criterion

This type of tests has been established with a time criterion. The data obtained below are not considered. This test resulted of 9 hours, as of this time the evolution of the average temperature of the fluid is evaluated in function of the time natural logarithm, shown in Figure 3.

$$t \geq \frac{5r_0^2}{a} \tag{10}$$

$$t = \frac{5 \cdot 0{,}075^2}{0{,}91 \times 10^{-6}} = 30907\,seg \tag{11}$$

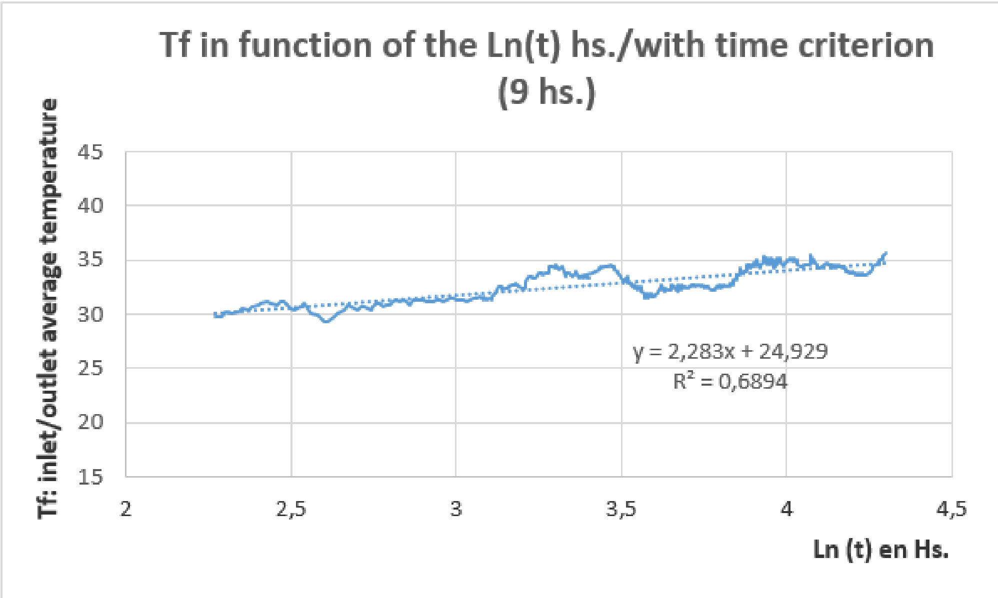

Figure 3: Evolution of the input / output average temperature as a function of ln (t) in hs, with time criterion.

To determine the effective thermal conductivity coefficient by means of the slope method, the starting point is the equation of the straight-line regression, approximating it by the following equation:

$$T_f = k\,ln(t) + m \tag{11}$$

$$k = \frac{Q}{4\pi\lambda H}\,ln(t) \tag{12}$$

$$\lambda = \frac{Q}{4\pi k H}\,ln(t) \tag{13}$$

λ_{eff}:: was of the order of: 1,42 W/m*ºK, for the total trial with a K= 1,97slope

λ_{eff}:: resulted 1,23 W/m*ºK applying the time criterion, for K= 2,28 slope

4.3 Thermal resistance determination

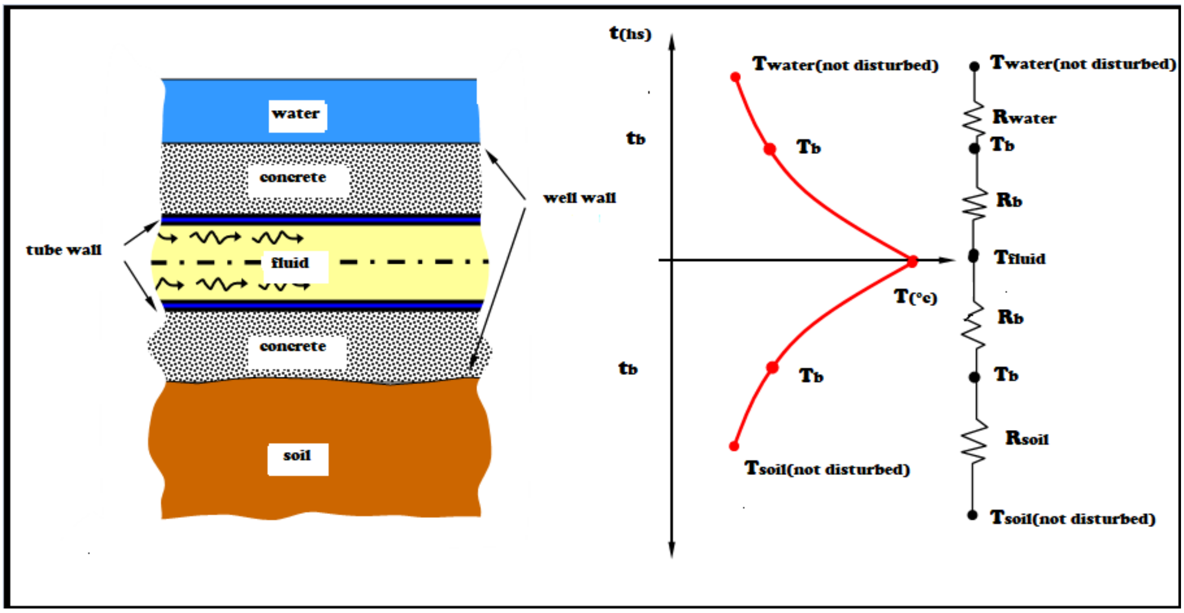

Figure 4: Thermal resistance scheme between the fluid and the well wall Rb (ºK/(W/m)).

$$T_f = \frac{Q}{4\pi\lambda H}\left[ln\left(\frac{4\alpha t}{r_0^2}\right) - \gamma\right] + \frac{QR_b}{H} + T_{sur} \;\; para\; t \geq \frac{5r_0^2}{\alpha} \tag{14}$$

$$R_b = \left(T_f - T_{sur}\right)\frac{Q}{H} - \frac{1}{4\pi\lambda}\left[ln\left(\frac{4\alpha t}{r_0^2}\right) - \gamma\right] \tag{15}$$

The average value for Rb for the total duration of the trial was 0.117 [ºK / (W / m)]. The average value for Rb applying the time criterion was: 0.087 [ºK / (W / m)].

Table 1: San Luis thermal response test results – Argentina.

α: concrete thermal Diffusibility (m2/seg)	Time criterion	Slope: K	λeff (W/m*ºK)	Rb: (K / (W/m)	Effective length (m)
0,91x10-6	Total	1,97	1,42	0,117	23,36
0,91x10-6	9 hs	2,28	1,23	0,087	23,36

5. EXPERIMENTAL DATA PARAMETRIC ADJUSTMENT

The solution to the mathematical model representing the heat transfer process has been used as an adjustment function, with λeff and Rb obtained experimentally as adjustment variables, as shown in Figure 7. It is possible to determine the evolution of Tf (t) in function of Ln (t) in hours, as plotted as the blue curve. The experimental data parametric adjustment curve is overlapped on it, as plotted as the red curve, where the good adjustment is observed and a low accumulated quadratic error.

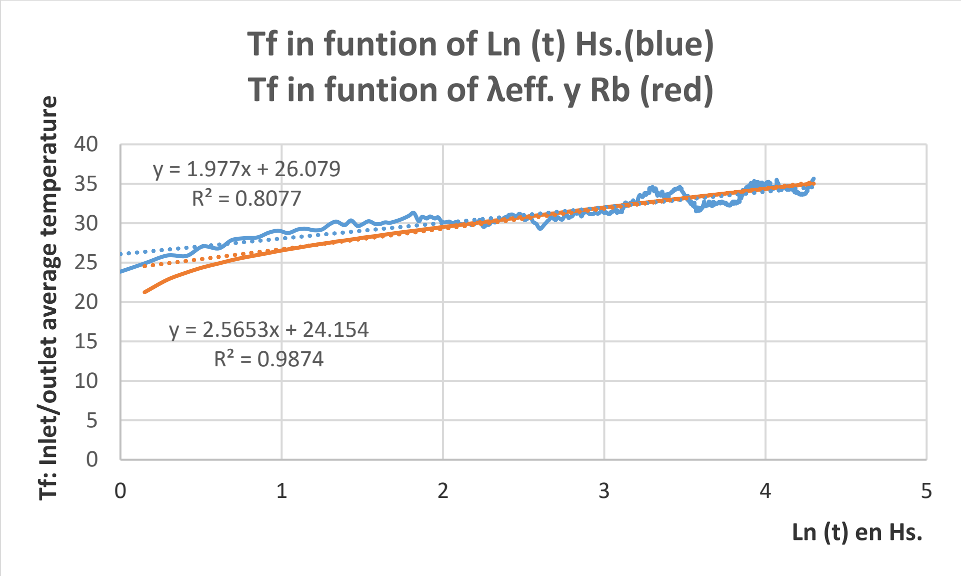

Figure 6: The fluid average temperature evolution (blue curve) and parametric adjustment overlapped curve (red curve).

6. WORLD TRT COMPILATION

Table2: Results of multiple TRT in situ (Mol TRT workshop in Germany 2000).

Borehole / TRT-unit		1 (NL)	2 (DE, UBeG)	3 (DE)
1, backfilled with Mol-sand		λ = 2.47 W/(m·K)	-	λ = 2.47 W/(m·K)
2, backfilled with graded sand		λ = 2.40 W/(m·K)	-	λ = 2.51 W/(m·K)
3, backfilled with bentonite		*test disturbed*	λ = 2.49 W/(m·K)	-
Location in Langen, Germany, tests by UBeG in 1999 (Langen 1) and 2000 (Langen 2 and 3)				
Borehole	Depth	Grout	thermal conductivity	borehole therm. res.
Langen 1	99 m	standard bentonite	λ = 2.8 W/(m·K)	r_b = 0.11 K/(W·m)
Langen 2	70 m	therm. enhanced	λ = 2.3 W/(m·K)	r_b = 0.08 K/(W·m)
Langen 3	70 m	therm. enhanced	λ = 2.2 W/(m·K)	r_b = 0.07 K/(W·m)
Location in Mainz, Germany, tests by UBeG in summer 2003				
Mainz 1	30 m	standard	λ = 1.43 W/(m·K)	r_b = 0.16 K/(W·m)
Mainz 2	30 m	standard	λ = 1.41 W/(m·K)	r_b = 0.20 K/(W·m)

CONCLUSIONS

The main idea of this work is to be able to determine both the effective thermal conductivity λeff (W / m * ºK) and the soil thermal resistance of the Rb (K / (W / m) for an adapted exchanger to preexisting conditions, located in the province of San Luis, Argentina. The VDI 4640 directive "Thermal use of the underground", for installations with a thermal power of up to 30 kW, indicates sizing rules, with values of λeff and Rb. given by this directrix while for higher thermal powers requires the realization of the TRT. In this way, the geothermal collector correct sizing is achieved by being able to obtain in situ the real values of λ and Rb. which constitute with the key element for this type of geothermal installations, because it is expressed into costs.

As it is shown in this work, the effective thermal conductivity, λeff, is given by the slope of the curve determined by the point cloud of the inlet/outlet average temperature measurements with respect to the natural logarithm of time. The value of this slope is determined by the time criterion used and in turn this value is related to the concrete thermal diffusivity, which is adopted by means of tables. In this particular case, we obtain a λeff, which would be the reflection of the adapted geothermal collector, while there was a soil without rocks and on the other one, such as water.

Comparing data between the test conducted in San Luis, with other tests tabulated above (Table 2), it is possible to affirm that the slope graphical method, used in this case to obtain the values of λeff. and Rb, is approximate enough. The observations were carried out. Data acquisition method was manual without any tools, the injection power supply was quite variable during the test and the undisturbed soil temperature was a little higher.

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NOMENCLATURE

Tr(t): temperature in time "t".

Tr: stationary temperature caused by the average temperature of the injected fluid.

Tsur: undisturbed soil temperature.

Trq(t): change in temperature due to the deviation of the average temperature of the fluid.

Tf: Temperature of the heat carrier fluid [ºC]

Q: Injected power [W]

H: Effective well depth [m]

q=Q/H: Power injected per meter of tube [W/m]

λ_{eff}: Collector thermal conductivity (W/m ºK)

γ: 0,5772 (Euler constant)

r0: Well radius (m)

α: Thermal diffusivity (m2/seg)

Rb: Thermal resistance between the heat carrier fluid and the well wall [ºK (W / m)]

t: Time [seg]

tb: Time interval [seg]

k: Straight-line regression line Slope