Bulgarian Chemical Communications, Volume 48, Special Issue E (pp. 19 - 26) 2016

In-situ measurements of ground thermal properties around borehole heat exchangers in Plovdiv, Bulgaria

A. G. Georgiev[1,3], R. K. Popov[2*], E. T. Toshkov[1]

[1]*Technical University of Sofia, Plovdiv Branch, Dept. of Mechanics,25 Tsanko Diustabanov Str, 4000 Plovdiv, Bulgaria*
[2]*Plovdiv University "Paisii Hilendarski", Department of Electronics, Telecommunications and Information Technologies (ETIT), 24 Tsar Assen Str, 4000 Plovdiv, Bulgaria*
[3]*European Polytechnic University, Dept. of "Green Energy", 23 Kiril and Metodiy str., 2300 Pernik, Bulgaria*

The knowledge of the geodata (subsurface characteristics) is important for the design and construction of the Underground Thermal Energy Storage (UTES) and to design an installation using Borehole Thermal Energy Storage (BTES) - it is a big advantage during the project calculations and the construction of the geothermal systems. In situ determination of ground thermal conductivity, borehole thermal resistance and undisturbed soil temperature can be done by installing a vertical borehole heat exchanger (BHE) and performing the so-called Thermal Response Test (TRT). This paper describes the determination of ground thermal properties by a research group of the Technical University of Sofia, Plovdiv Branch. A mobile system for conducting Thermal Response Test has been created recently in Plovdiv, Bulgaria. The first Bulgarian TRT was carried out in January 2009 using a 41 m deep BHE, constructed in November 2008. Later tests are carried out on other two constructed BHEs in Plovdiv (single and double, 50 m depth and 32 mm diameters of the U-tubes). The tests were realized while the ambient temperature, the inlet and outlet fluid borehole temperatures and the temperatures of the BHEs at different depths were measured every minute. A large quantity of experimental data was gathered and analyzed by two parameters curve fitting based on the analytical formula of the Line Source Model for temperature distribution in the borehole (determining the ground thermal conductivity and the borehole thermal resistance). The detailed study of ground properties in different regions of Bulgaria is a good precondition for future application of the geothermal technology in the region.

Keywords: Thermal Response Test, ground thermal properties, borehole heat exchangers

INTRODUCTION

The Underground Thermal Energy Storage (UTES) is a good solution for saving energy. Laboratory methods have been used to study the ground properties - unfortunately their results are usually not precise. A very effective method used for the determination of the ground thermal conductivity is the Thermal Response Test (TRT). It is an internationally approved technique to identify geothermal underground parameters like effective ground thermal conductivity and borehole thermal resistance R_b. It has been in use since 1995 in International Energy Agency: Energy Conservation through Energy Storage (IEA ECES) countries but the method, equipment and evaluation procedure are still under development. Generally, these tests are performed with heat injection, using the same assumed power level as the one planned by the BHE system.

The TRT was first presented in 1983 [1] - the installation is designed as a stationary system. After that, a mobile conductivity measurement system appeared. In principle two different methods have been developed: one using electrical heater elements [2-4] and another one using a reversible heat pump in Netherlands [5]. With the latter heat can be injected and extracted from the ground. The theoretical basis of the thermal response test is presented in [6-8]. Today about 10 countries in the world undertake this type of research - e.g. in Germany [9], Sweden [2], Canada, USA [4], Norway, Netherlands [5], England, Turkey [10], Chile [11, 12] and Cyprus [13].

Several TRTs are done in Bulgaria, too. Some activities in Bulgaria have preceded the first official TRT [14]. Several Thermal Response Tests had already been employed in Bulgaria [15-17]. This paper describes the results of three TRT tests, conducted by the mobile unit constructed at the Technical University of Sofia, Plovdiv Branch. One test was performed in the campus 3, and the other two tests in the campus 2.

MOBILE SYSTEM FOR EXAMINING GROUND THERMAL PROPERTIES

The basic quality requirements for the experimental apparatus are an uninterruptible supply of constant heat power to the borehole and the capability to take highly accurate temperature and flow rate measurements. Fig.1 shows the unit design.

---

[*] To whom all correspondence should be sent:
rum_pop@yahoo.com

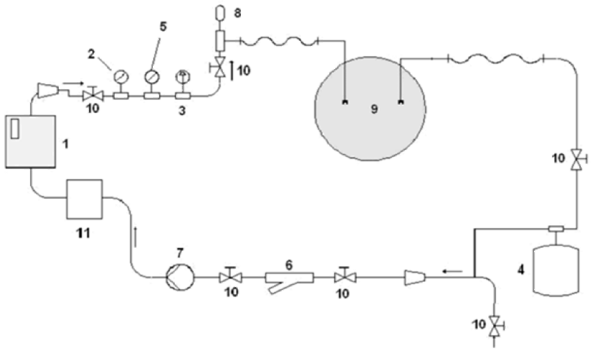


Fig.1. System set-up

The following elements are presented here: electrical boiler 1, calorimeter 2, pressure relief valve 3, expansion tank 4, thermomanometer 5, filter 6, circulation pump 7, de-aeration pipe 8, quick couplings 9, valves 10 and electrical unit 11. The laboratory is installed on a mobile trailer, which contains the equipment for conducting the TRT (Fig.2). The constructed trailer combines the characteristics of both an experimental unit and a place for temporary lodging. The lodging part is foreseen as a complete outfit delivering the corresponding comfortable living conditions to the researchers during the tests (the tests are normally carried out on locations outside populated areas). The experimental unit has two different parts - a mechanical one and a measuring and control part (Fig.3).

Fig.2. Test mobile system with the borehole (top end)

The Electrical boiler 1 consists of a body and a control unit. Three tubular electrical heaters are situated in the well-insulated steel body of the boiler. The heaters are capable of producing different heating temperatures. A three phase circulation pump 7 ensures the movement of the heating medium through the boiler. This pump possesses the function of flow rate regulation on frequency.

The calorimeter MEGATRON2 2 produced by SIEMENS is built in the system. It is an independent electronic apparatus for tracking and reporting the consumed heat in automatic heating and cooling installations. The calorimeter has a memory and a display which reports the measured values of energy consumed on a chosen day.

Fig.3. Measuring device

"AEROFLEX" insulation is used in the mobile unit to avoid errors heat losses during the measurement.

A pressure relief valve 3 protects the pump and the unit from high pressure or from overheating of the fluid in the boiler. The protection is fulfilled through the automatic current switching of the pump motor and the boiler heaters. The used pressure watch is produced by the "WATTS", Italy - PM/5 model.

The expansion tank 4 of the system is needed to balance the small variations of the heating medium. The used expansion tank is of the membrane type and has a capacity of 8 litres.

A thermo-manometer 5 is needed in the setup to monitor the pressure and the temperature of the heating medium after it leaves the electrical boiler and before it enters the borehole.

A system filter 6 is used to eliminate all impurities which enter the system while the heating medium fills it up. The filter is of the net type and allows movement only in the direction of the working fluid flow.

The pipes used in the unit are produced by the German company "AQUATHERM". The main advantages of the pipes are the following: absolute corrosion stability, chemical stability, high impact stability, low tube roughness, very good welding characteristics and high thermal stability.

Some measuring elements and sensors are mounted on the mobile station. The flow rate through the borehole is measured on the basis of the calorimeter sensor and on the basis of the electronic transformer of frequency to voltage. An inductive sensor with a code disc is used for measuring the rotation frequency of the electricity generator. The data-logging system (SIGMATECH) is used for measuring and archiving the installation parameter values. A computer (supplied with processing software) analyzes the collected information. There are 8 temperature elements with PT100 which are used to measure the fluid temperature difference of the borehole (input and output), the temperature in the borehole at different depth and the ambient temperature. All elements have an accuracy of about ±0.15K in the temperature range 0°C - 120°C (Class A PT100). An additional calibration was done of the temperature elements on the borehole input and output (they have an accuracy of ±0.05K).

A fully automated system for data archiving of the company "SIGMATECH" LTD (logger for collecting of the temperature data) Plovdiv has been selected. The multiprocessor system SH700 automates the measurement process of the ground thermal conductivity and analyses the obtained data. It collects the data of the measured inlet and outlet borehole temperatures, the five temperatures in the borehole depth and the ambient temperature. The maximum number of measured temperatures is 20. The controller has a memory, where the measuring data are recorded. If a computer is used, it is possible to show the measurement in real time and to analyse the collected data.

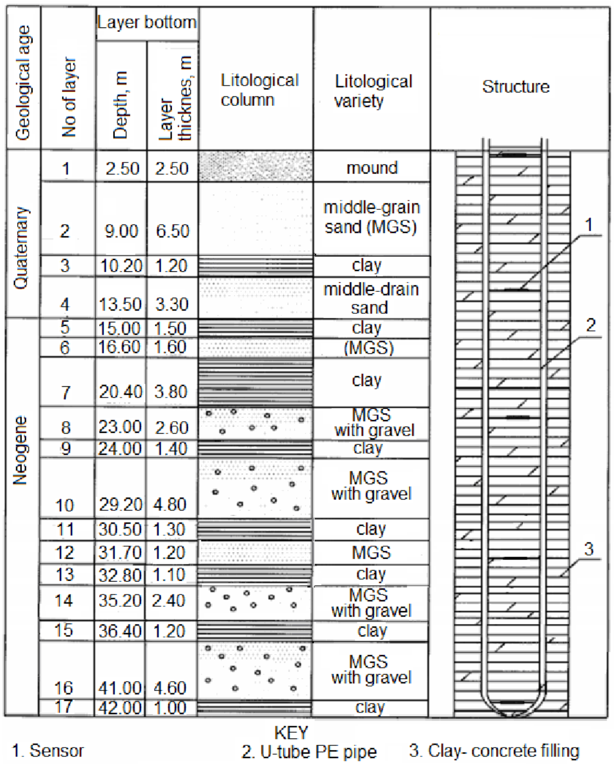
A power regulator is situated in the electrical unit 11. It is used to control the power of the electrical heater. Thus a precise regulation of the measurement process is ensured.

The induction motor of the circulation pump is regulated with the help of a frequency regulator (MOELLER" DF51-322 company production), which is built in the electrical unit. The frequency regulator can be used to manage the speed, torque, direction, start and stop of the pump motor.

Later some improvements have been made - a mains voltage stabilizer SVC-5000WS was added to the installation with the aim to keep constant the heat transfer rate to borehole despite diurnal variations of the power line voltage.

PREPARATION OF THE BOREHOLE HEAT EXCHANGERS (BHES)

A number of different BHEs were constructed in the territory of TU – Sofia, Plovdiv Branch. Electrocarotage measurements were made with the carotage station KFE-2-12 on the campus 3 of the Technical University – Sofia, Plovdiv branch. They were compared to the lithological data of the soil. The station consists of three electrodes, which are directed down into the drilling hole and a fourth one is grounded. A 40 Hz electricity current is fed in and the potential difference between the electrodes in the hole is measured. The data received are recorded by means of the electrocarotage equipment. A general lithological structure is worked out on its base (Fig.4).



Geological age	No of layer	Layer bottom		Litological column	Litological variety
		Depth, m	Layer thicknes, m		
Quaternary	1	2.50	2.50		mound
	2	9.00	6.50		middle-grain sand (MGS)
	3	10.20	1.20		clay
	4	13.50	3.30		middle-drain sand
Neogene	5	15.00	1.50		clay
	6	16.60	1.60		(MGS)
	7	20.40	3.80		clay
	8	23.00	2.60		MGS with gravel
	9	24.00	1.40		clay
	10	29.20	4.80		MGS with gravel
	11	30.50	1.30		clay
	12	31.70	1.20		MGS
	13	32.80	1.10		clay
	14	35.20	2.40		MGS with gravel
	15	36.40	1.20		clay
	16	41.00	4.60		MGS with gravel
	17	42.00	1.00		clay

Fig.4. Geological section

The lithological structure of the ground at campus 2 is very similar. It consists mainly of clay, sands with different size of grains and some gravel (the distance between the both campuses is about 2 km).

A single U-tube heat exchanger of PN10 HDPE pipe, 25 mm diameter, was installed in the borehole with a depth of 41 m at the campus 3. The borehole has a diameter of 0,18 m and was backfilled with 11% bentonite and 2% cement mixture. Cement was added because of the specific soil type: sand soil with high water content. The U-shape was inserted in hole by connecting two separate pipes

(42m long each) - a welding process and two joints were used (Fig.5).

Fig.5. Mounted temperature sensor in the lower part of the U-tube

Polyethylene (PE) pipes are used in the geothermal drills. The chosen polyethylene pipes are of the PE 100 type and their technical specifications are given in Table 1.

Table 1. Specifications of PE 100 pipes

Marking	PE 100
Material	Polyethylene
Pipe roughness	0.04 mm
Mean thermal coefficient of linear extension	0.20 mm/mk
Minimal temperature of laying	-10° C
Flow limit	26 MPa
Strength	>10 MPa
Melting index	0.2 – 0.5 g/10 min

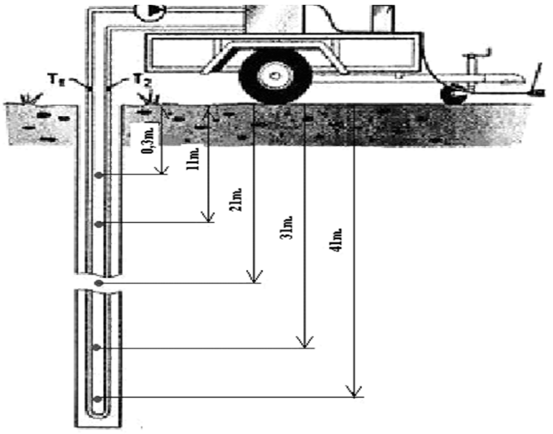


Fig.6. Placement of temperature sensors in the borehole

Five detectors RD Pt100 type are attached between the two pipes at regular intervals (Fig.6). They are used to collect data from the temperature field inside the BHE. Cement mixtures with low permeability rate are used to fill the hole after the pipes have been mounted.

The pipes stand out about 0,5m above the ground level and are insulated with porous insulation of the Aeroflex type to minimize thermal losses. The BHE has to be insulated from the surrounding environment with any available type of insulation material. We covered an area of 4 m² over the borehole pipes with insulation of the type XPS (extruded polyester) known under its commercial name “fibran” - two layers of 0.05m thickness each (Fig.2).

Fig.7. Drilling of boreholes with MDT Mc 200 B

Two vertical perforations were drilled in the laboratory vicinity of campus 2 with depth of 50 m, diameter of 165 mm and distance of 13 m between the holes. It was done by the help of a modern Italian hydraulic drilling machine MDT Mc 200 B (Fig.7).

Fig.8. Inserting the HDPE tubes in the perforations

Two different loop types were inserted in the boreholes (single and double loop of high density polythene, HDPE PE 100) with external diameter 32 mm. They have been backfilled with cement-bentonite grout (mixture of cement and bentonite with factor 0.5) to enhance thermal transfer between tubes and ground (Fig.8). Before backfilling in the two boreholes were inserted 6 three-wire thermoresistors Pt100 along the tubes on every 10 meters to measure the temperature distribution underground. So two different types of BHEs were designed. Fig.9 shows the upper part of the double U-tube borehole.

Fig.9. Upper part of the double U-tube borehole

THERMAL RESPONSE TESTS

First Thermal response test in campus 3

The first TRT, 10 days long, was carried out from the 11th to the 21st of January. The measured parameters were the ambient temperature, the inlet and outlet fluid temperatures of the borehole and the temperatures of the BHE at different depths. The flow rate was measured and controlled at the constant value of 6.45 l/min. The electrical power was regulated and maintained constant at about 1500 W. The electrical power of the circulating pump was about 100 W. The water pressure in the installation was maintained at about $2.2.10^5$ Pa. The measuring time step was 60 s. The mean undisturbed ground temperature $T_{0,m}$ was determined by pumping the heat carrier fluid out of the borehole pipes and measuring its outlet temperature over a time of 10s [18]. $T_{0,m}$ is then calculated as the mean of the measurement data. In the presented experiments $T_{0,m}$ has been established to be 16.3°C.

All data are automatically controlled by a specially designed system for the laboratory trailer that is installed on the control board. The system is fully automatic and stores all measured data in text files. In the experiments the aim of a constant heat flow was realized by a constant frequency control of the circulation pump and boiler.

Thermal response tests in campus 2

Tests with duration about 7 days were implemented to evaluate soil thermal conductivity around the two boreholes and temperature distribution in depth. The experiments were carried out in December 2011 (with double loop) and in August 2012 (with single loop).

The test conditions were as follows:

- Test from 3rd till 10th December 2011: pump flow rate of 550 l/h, electric heater power - 2820W, electric power of circulating pump - 100W, measured intervals – 10s for the undisturbed temperature and 60s for the rest parameters; the mean undisturbed ground temperature $T_{0,m}$ was 16,5°C;
- Test from 7th till 14th August 2012: pump flow rate of 540l/h, electric heater power - 2630W, electric power of circulating pump - 100W, measured intervals – 10s for the undisturbed temperature and 60s for the rest parameters; the mean undisturbed ground temperature $T_{0,m}$ was respectively 16.7°C.

A turbulent regime for circulating water like heat carrier with Reynolds number more than 8000 was available during the two tests.

RESPONSE ANALYSIS

Basic equation

The Kelvin's line source theory [19] is normally used as a base for mathematical evaluation of the Thermal Response Test. The temperature of the surrounding ground is raised as a result of the circulating heating fluid through the borehole heat exchanger. The following formula gives the distribution of the temperature field as a function of the borehole radius and time:

$$\Delta T(r_b,t) = \frac{q}{4\pi\lambda}\int_{r/2\sqrt{at}}^{\infty}\frac{e^{-\beta^2}}{\beta}d\beta \qquad (1)$$

where:

$\Delta T(r_b,t)$ - temperature rise, K;

q - heat injection power per unit borehole length, W/m;

λ - ground thermal conductivity, W/mK;

t – time, s;

a - thermal diffusivity, m²/s;

r - radius from the borehole, m;

β - integration variable, -;

r_b - radius of the borehole, m.

Slope determination technique

With this approximation, the delivered heat is considered as coming from a line source, the borehole [2]. The heating process is presented by the equation:

$$T_{f,m} = \frac{Q}{4\pi\lambda H}\ln(t) + \left[\frac{Q}{H}\left(\frac{1}{4\pi\lambda}\left(\ln\left(\frac{4a}{r_b^2}\right)-\gamma\right)+R_b\right)+T_o\right]$$

for $t \geq \frac{5r_b^2}{a}$. (2)

where:

$T_{f,m} = (T_{f,in} + T_{f,out})/2$ - mean fluid temperature, K;

Q - delivered heat power, W;

λ - ground thermal conductivity, W/mK;

H - borehole depth, m;

t - time from start, s;

a - thermal diffusivity, m²/s;

r_b - radius of the borehole, m;

γ = 0,5772 – Euler's constant;

R_b – borehole thermal resistance, mK/W;

T_0 – undisturbed ground temperature, K.

Equation (2) is simplified with

$$T_{f,m} = c.\ln(t) + d \qquad (3)$$

where c and d are constants.

The value of c is to be determined from the inclination of the line in the plot of the mean fluid temperature versus ln(t). The conductivity λ is computed then from the graph slope:

$$\lambda = \frac{Q}{4\pi c H} \qquad (4)$$

Respectively to calculate R_b we are applying the following formula:

$$R_b = \frac{H}{Q}(T_{f,m} - T_o) - \frac{1}{4\pi\lambda}\left(\ln(t) + \ln\left(\frac{4a}{r_b^2}\right) - \gamma\right) \qquad (5)$$

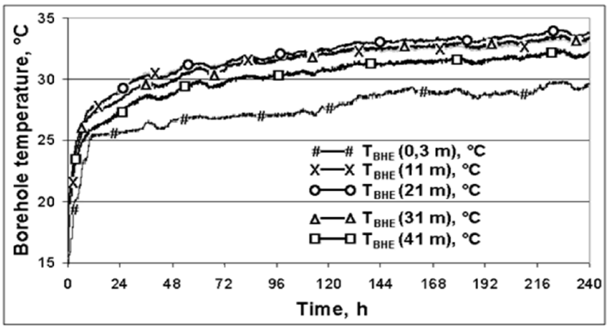


Fig.10. Temperature profile in the borehole heat exchanger (January 2009).

Experimental data

The measured temperatures in the borehole heat exchanger are presented in Fig.10 (campus 3). They show the temperature field inside the BHE at depth of 0.3m, 11m, 21 m, 31 m and 41 m. The ambient temperatures and the mean inlet and outlet fluid borehole temperatures for the month of January are also indicated in Fig.11 (campus 3).

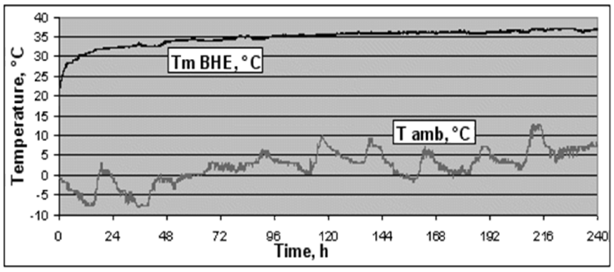


Fig.11. Test temperature profile (mean fluid borehole and ambient temperatures) in January 2009

Fig.12 and Fig.13 show the temperature profiles of mean fluid borehole and ambient temperatures concerning experiments in campus 2.

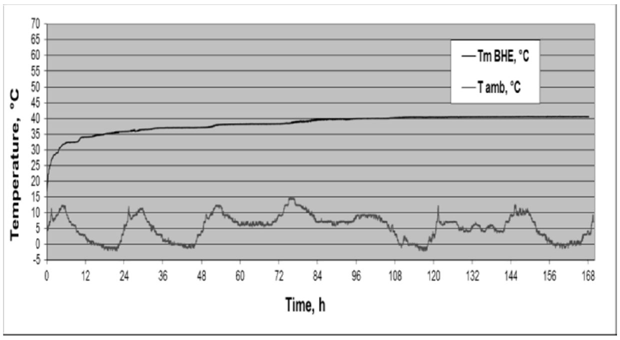


Fig.12. Test temperature profile (mean fluid borehole and ambient temperatures) in December 2011

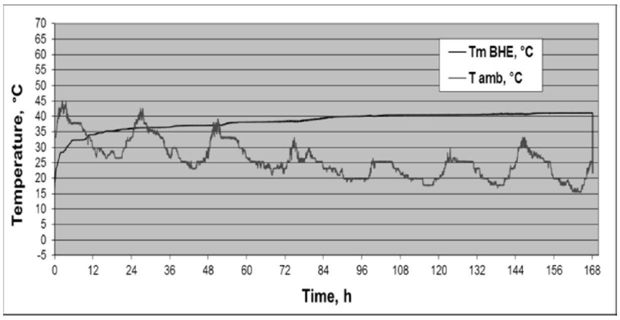


Fig.13. Test temperature profile (mean fluid borehole and ambient temperatures) in August 2012

Hours-off and duration of the test analysis

The Line Source Model was used for determination of the ground thermal conductivity and the borehole thermal resistance. Normally, the data corresponding to the first 7 to 24 hours of experiment are not taken into account in the analysis. The reason for discarding initial data points from the original set is based on the fact that the solution used for data evaluation is an approximation applicable for times satisfying the criterion $t \ge \frac{5r_b^2}{a}$.

To assess how the starting point (hours-off) of the evaluation data interval affects the values of the thermal conductivity and the borehole thermal resistance, a series of evaluations were performed on intervals with the same end point but different hours-off at the beginning. Table 2 shows that the dispersion from the average value is no more than 1.4 % for the thermal conductivity and 0.57 % for the borehole thermal resistance (campus 3).

Table 2. Results of the hours-off analysis for sets of data intervals beginning at the hour-off point (January 2009)

Hours-off, h	Slope	λ, W/m K	R_b, m K/W
7	2.0515	1.37	0.310
10	2.0437	1.38	0.312
15	2.0465	1.38	0.314
20	2.0682	1.36	0.312
24	2.0831	1.35	0.311
Average		1.37	0.312

Fig.14 (campus 3) shows the logarithmic time dependence of the temperature and the slope of the associated regression line (the accepted hours-off period is 15 hours).

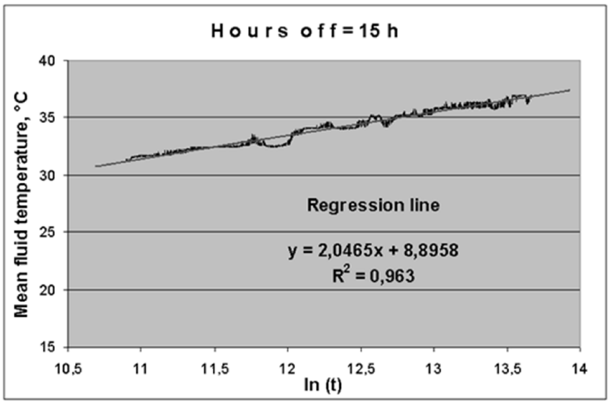


Fig.14. Logarithmic time plot of the mean temperature for the entire test length in January 2009 (excluding the first 15 hours)

The thermal conductivity λ is related to the slope of the resulting line, given by Eq. (2). The resulting values received during the tests for λ vary between 1.35 and 1.38 W/mK and for R_b vary between 0.310 and 0.314 mK/W (campus 3).

The results of the experiments done in campus 2 are presented in Fig.15 and Fig.16. They are as follows - thermal conductivity λ is 1.58 W/mK and thermal resistance is R_b – 0.187mK/W (December 2011, Fig.15). Respectively for August 2012 - thermal conductivity λ is 1.65 W/mK and for thermal resistance R_b – 0.179mK/W (Fig.16). Both results are closed to those for campus 3 in 2009.

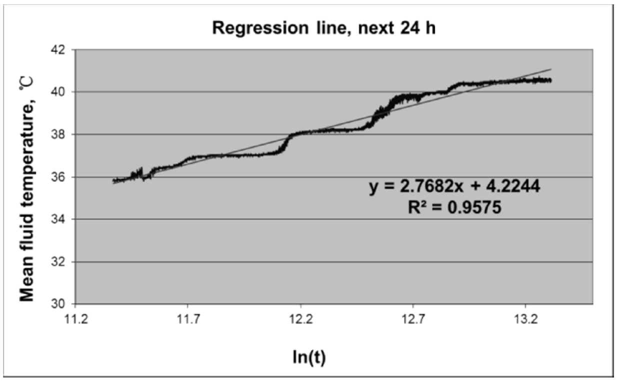


Fig.15. Logarithmic time plot of the mean temperature for the entire test length in December 2011 (excluding the first 24 hours)

A comparison with the results of different experiments [9, 11, 20] performed elsewhere in the world was done. It shows that the values of thermal conductivity and thermal resistance of the borehole obtained by our tests (in Plovdiv) are comparable with the values obtained by other tests.

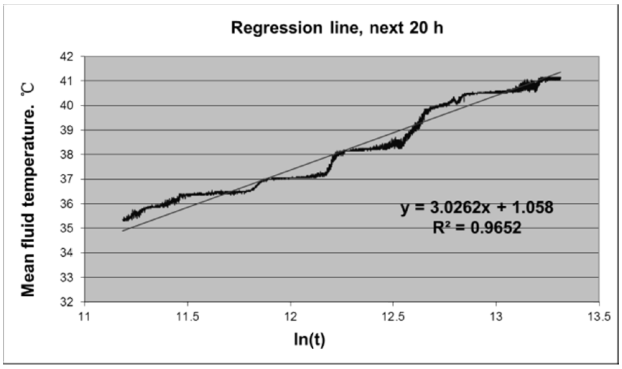


Fig.16. Logarithmic time plot of the mean temperature for the entire test length in August 2012 (excluding the first 20 hours)

CONCLUSIONS

Some TRTs have been conducted in 2009, 2011 and 2012 at the Technical University of Sofia, Plovdiv Branch, with the created mobile installation. Here are the main conclusions:

- The working installation, which is incorporated in the mobile laboratory, works fully automatically;
- The Line Source Model is used as a method for estimation of the experimental results. Several additional estimation methods have to be used in the future with the purpose to determine more

exactly the values of the thermal conductivity and the borehole thermal resistance;

- The resulting values received during the tests in campus 3 for λ were between 1.35 and 1.38 W/mK and for R_b - between 0.310 and 0.314 mK/W;

- The obtained results for campus 2 are as follows: thermal conductivity λ=1,58 W/mK, thermal resistance R_b=0.187 mK/W (December 2011); λ=1.65 W/mK and thermal resistance R_b=0.179 mK/W (August 2012) respectively;

- The values of thermal conductivity and borehole resistance are similar in both campuses (2 and 3) of the University situated in a distance of only 2 km, but the differences are explained by differences on the soil characteristics (density water content) and on the geological structure;

- The values of the conductivity λ and of the borehole thermal resistance R_b for the experiment values are comparable with the values obtained by other tests in the world [9,11,20].

REFERENCES

1 P. Mogensen, P., 1983. Fluid to duct wall heat transfer in duct system heat storages. *Proc. of the int. conf. on subsurface heat storage in theory and practice, Stockholm, Sweden*, pp. 652–657 (1983).

2 C. Eklöf, S. Gehlin. TED - a mobile equipment for thermal response test. *Master’s Thesis 1996:198E. Sweden: Luleå University of Technology* (1996).

3 S. Gehlin, B. Nordell. Thermal response test - a mobile equipment for determining thermal resistance of borehole. *Proc. of Megastock 1997, 7th int. conf. on thermal energy storage, Sapporo,* pp. 103–108 (1997).

4 W.A. Austin. Development of an in-situ system for measuring ground thermal properties. *Master’s Thesis. Oklahoma State University, Stillwater, Oklahoma* (1998).

5 H. Witte, S. Kalma, A.J. van Gelder. In-situ thermal conductivity testing: The Dutch perspective (part 1 and 2). The Source 13 (3) and The Source 13 (4), (2000).

6 G. Hellström. Ground heat storage. Thermal analysis of duct storage systems. *Part I theory. Lund, Sweden: Department of Mathematical Physics, University of Lund*, pp. 148–154 (1991).

7 S. Gehlin. Thermal Response Test. Method Development and Evaluation. *Ph.D. Dissertation. Luleå University of Technology,* 2002:39, Sweden (2002).

8 S. P. Kavanaugh, R. Rafferty. Ground-source heat pumps: design of geothermal systems for commercial and institutional buildings. *Atlanta: ASHRAE, Inc;* pp. 22–31 (1997).

9 B. Sanner, M. Reuss, E. Mands, J. Müller. Thermal response test - experiences in Germany. *Proc. of Terrastock 2000, 8th Int. conf. on thermal energy storage, Stuttgart, Germany*, pp. 177-182 (2000).

10 H. Paksoy, Z. Gurbuz, B. Turgut, D. Dikici, H. Evliya. Aquifer thermal storage (ATES) for air-conditioning of a supermarket in Turkey. *Proc. of world renewable energy congress-VII 2002, Cologne, Germany,* 10_n66.pdf (2002).

11 P. Roth, A. Georgiev, A. Busso, E. Barraza. First In-situ Determination of Ground and Borehole Thermal Properties in Latin America. *Renewable Energy 29,* pp. 1947-1963 (2004).

12 A. Georgiev, A. Busso, P. Roth. Shallow Borehole Heat Exchanger: Response test and Charging - Discharging test with solar collectors. *Renewable Energy 31*, pp. 971-985 (2006).

13 G. Florides, S. Kalogirou. First in situ determination of the thermal performance of a U-pipe borehole heat exchanger, in Cyprus. *Applied Thermal Engineering 28*, 157-163 (2008).

14 A. Georgiev, O. Pekov, A. Angelov, R. Popov, J. Urchueguia, H. Witte. First steps of the ground accumulation in Bulgaria. *Proc. of the World Renewable Energy Congress-IX, Italy, Florence, Italy,* Bulgaria.pdf (2006).

15 A. Georgiev, S. Tabakova, R. Popov, Y. Todorov. Bulgarian Variant of a Mobile Installation for Ground Thermal Properties Determination. *Yang SS, Sayigh AAM, Lai CM, Chen S. Progress in Development and Applications of Renewable Energy, National Taiwan University, Taipei, Taiwan, first Edition,* pp. 197-208 (2009).

16 A. Georgiev, R. Popov, S. Tabakova. First Thermal Response Test in Bulgaria. *Proc. of Effstock 2009, 11th int. conf. on thermal energy storage, Stockholm*, 24.pdf (2009).

17 A. Georgiev, R. Popov, S. Tabakova. Computer Simulation of Ground Thermal Properties. In: *Proc. of the 11th nat. congress on theoretical and applied mechanics, Borovets, Bulgaria*, Georgiev_128.pdf (2009).

18 I. Zervantonakis, M. Reuss. Quality requirements of a Thermal Response Test. Proc. of Ecostock 2006, 10th Int. conf. on thermal energy storage, Stockton, USA, pp. 435-441 (2006).

19 S. Gehlin. Thermal response test—in-situ measurements of thermal properties in hard rock. Licentiate Thesis. Luleå University of Technology, Department of Environmental Engineering, Division of Water Resources Engineering, 1998:37, Sweden (1998).

20 G. Hellström. Duct ground heat storage model, Manual for Computer Code. Sweden: Department of Mathematical Physics, University of Lund (1989).