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Borehole and Aquifer Thermal Energy Storage and Choice of Thermal Response Test Method

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Abstract: - Analysis of a contemporary alternative energy source – the subsoil thermal energy storage – has been presented. Different principles of this storage have been analysed and it was revealed that, from the energy efficiency point of view, it is highly recommendable to use the Borehole and Aquifer TES. Deciding which of the two systems to utilize is dependent upon the hydrogeologic characteristics of soil and thence an analysis of ground in a two milion Balkan city region was made. It has been revealed that in the greater part of that town, as well as in the hilly and mountainous central Balkan, Borehole TES leads to Aquifer. For dimensioning a Borehole TES, it is necessary to know the thermal conductivity (λ) and thermal diffusivity (a) of the ground. An appropriate method for measuring quantites necessary for determining these properties is the Thermal response test. An analysis of the common data reduction methods has been performed, and the Slope determination method is recommended, as simple and accurate. It should be expected that Thermal response test (with mobile set-up for *in situ* measurements) will soon become the standard procedure for determining thermal conductivity and diffusivity of ground in Balkan.

Key-Words: **-** Subsoil Thermal Energy Storage, Aquifer, Borehole Heat Exchanger, Thermal Response Test

1 Introduction

In years that follow southeast Europe will face an ever increasing problem of the lack of energy. Electricity is mostly produced by combusting the non-recoverable fossil fuels. Such an energy policy produces growing problems in the areas of economy and ecology. The countries of the region mostly depend upon the import of expensive fuel and this lays a heavy burden upon the economies of the majority of these countries. Fuel prices are ever increasing as a result of these energy sources being non-renewable. Negative effects on the environment (greenhouse effect, acid rains as well as damage of the ozone layer) induced by the emission of carbon-dioxide, sulphur dioxide and nitrogen oxides during combustion of fossil fuels, endanger the future life on the planet Earth as well.

To eliminate these cited threats, alternative energy sources are to be discovered and utilized. The existing gap between the energy production and consumption in the region is growing ever deeper. The technologies of energy conservation that increase the efficiency of its consumption could surely play an important role in decreasing this difference. The most favorable way of energy conservation is the use of energy qualities that exist in abundance within our surroundings, such as: thermal energy in air, water and ground; solar energy; energy of wind as well as the waste heat produced in various processes. One should note that these energy sources are not exploited to a significant extent.

One of the several realistic ways of utilizing the non-conventional heat sources is surely – the use of the *Underground Thermal Energy Storage* (**UTES)** systems. The advantages of these systems compared to the conventional ones are significant:

- in the nature there are enormous reserves of energy that could be stored in this manner and later used for various purposes,
- low operation costs and high long-term profitability (reduction of electricity costs for operation of cooling machines and plants is

nearly 75%, the period of time during which the additional investment costs become payed off - is shorter than 5 years),

- protection of the environment (there is no pollution of the environment and the sources are recoverable),
- - possible utilization of the abandoned boreholes that were drilled for different purposes.

2 The Subsoil Thermal Energy Storage Systems

The basic concepts of the UTES systems are shown by their schematics in Figure 1; these concepts are:

- **BTES** (*Borehole Thermal Energy Storage)* (Fig.1-a). Boreholes are filled by grout (liquid that is paste-like, less dense than ground, but more dense than water and having high thermal conductivity) that fills the space between the U-pipe heat exchanger and borehole walls and serves for exchanging heat with the ground;

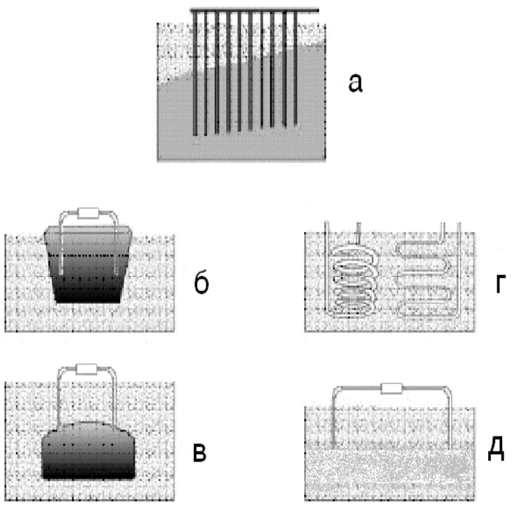

Figure 1: Basic concepts of UTES systems

- Thermal energy storage in water filled pits (Fig.1-б) as well as thermal energy storage in water filled caves (Fig.1-в) – **CTES** (*Cavern Thermal Energy Storage*). These systems – methods are technically feasible, but their practical application is still limited – because of extremely high investment costs;
- **DTES** (*Duct Thermal Energy Storage)* – thermal energy storage using pipe serpents dug in the ground (Fig.1-г). These systems are seldomly used especially with smaller (mostly domestic) installations;
- **ATES** (*Aquifer Thermal Energy Storage*) (Fig.1-д). Aquifer is the ground precipitated with water, mostly beneath rivers (creeks) and lakes (marshes), and lower layers of dried swamp soil, etc. Water is used as the working fluid, sucked from one well and, after passing through heat exchanger, discharged into another well. The distance between the two wells should be large enough so as to eliminate the effect of the return water upon the temperature in the first (charge) well.

Use of thermal energy storage in water filled pits and of CTES is constrained by strictly defined hydro-geologic requests (large pits and caves in the water-non-permeable ground), and DTES is, for its difficult mounting, used only in smaller (home) installations. Liberated from these severe constraints, that is techno-economically the most appropriate types of the UTES systems are – BTES и ATES. Therefore they are most frequently used and – attention will be further focused only onto these two types of UTES systems.

2.1 BTES and ATES – Criteria for Choice

Choicing a thermal energy storage method to be used, linked to a heat pump system, depends primarily upon the hydrogeologic properties of ground (soil type and structure, water-permeability, level and properties of subsoil waters, and mechanic properties of ground). The most often used UTES system is ATES. Though, for its smaller size and its less severe hydrogeologic constraints, a BTES system offers wider scope of use.

BTES is utilized for underground thermal energy storage using vertical U-pipe heat exchangers that are placed in boreholes (50–200 m in depth) and assure heat exchange with ground. Water is utilized as the working fluid in systems operating at temperatures above 0°C, while for winter modes in cold regions, at subzero temperatures, anti-freeze must be added.

ATES is utilized for underground thermal energy storage in aquifers. The system consists of two groups of wells. One group is at the cold side, and the another at the warm side. In the heating mode, water from the warm wells enters the heat exchanger where it is cooled down, and then discharged into the cold wells. In the cooling mode, water from the cold wells enters the heat exchanger where it is warmed up, and then discharged into the warm wells [2].

2.2 Conditions for Use of UTES in Serbia

Ground types satisfying the conditions for the use of BTES are all types of impermeable rocks (crystall-like slates, gneisses, magmatic rocks, etc.) that dominate in central Serbia except for the river valleys.

Use of ATES is favored by some types of highly-permeable (alluvial deposits) and all types of medium-permeable rocks (of sand and clay), i.e. when ground is intergranulary porous. Regions of such a ground are Voivodina, Machva and Morava and Danube valleys .

Conditions for application of BTES are fulfilled, generally, near hill summits, on ridges and plateaux. On the basis of sample analysis given at the example of Belgrade, it is concluded that it is hard to speak of advantages of one of these two systems in a particular hydrogeologically diverse region, but in mountainous and hilly central Serbia one can consider that BTES is more appropriate to be used than ATES.

2.3 Use of Heat Pumps linked with UTES

A UTES system is us in conjunction with a heat pump if soil temperature is lower than heating temperature (e.g. in Fig.2). Efficiency of a heat pump is inversely proportional to heat source and heat sink temperature difference. The higher the difference – the higher the energy consumed by the compressor. Heat pumps that operate linked with an UTES system (ATES or BTES) have lower temperature difference, thus higher value of efficiency, as well as lower electricity consumption, as compared to the heat pumps of other types that utilize ambient air as the heat source (or heat sink).

Beside this, all systems with combustion require appropriate measures to eliminate the threat by fires, explosions and poisoning by combustion products, i.e. the flue gases. These systems exert negative influence upon the environment since these flue gases consist of carbon-dioxide, sulphur-dioxide and nitrogen oxides; and of course, carbon-monoxide is dangerous as well.

3 Borehole Thermal Energy Storage

Boreholes of BTES systems are usually 50 – 200 m in depth, and 150 – 200 mm in diameter. In Switzerland boreholes are often deeper, even over 1000 m (2302 m in Weggis) [3]. Each borehole is equipped with pipes bringing, and removing, the working fluid. There are two basic BTES systems, the open one and the closed.

In an open system, in cooling, the working fluid is introduced at the bottom, and removed from the top of a borehole. In the heating mode, this is vice versa.

In a closed system, the working fluid is introduced into the borehole, and removed from it, by circulation through a U-pipe (*Borehole Heat-Exchanger* – **BHE**). Its use certainly eliminates the problems that possibly occur in open systems, such as leaking of the working fluid through the borehole cracks, need for change of locations for its introduction and removal (during the operation mode switch - heating/cooling), sucking dirt with the working fluid etc. And finally, heat exchange between water in U-pipe and ground is by convection from water to the pipe surface and then by conduction through the pipe wall, grout and ground.

4 Thermal Conductivity of the Soil

Designing BHE requires knowledge on basic thermal properties of the ground, firstly thermal conductivity (λ), which can be determined by utilizing either of the following available methods:

- using properties for classification of soils and rocks,
- experimental testing of samples from drill cuttings,
- by virtue of *Thermal Response Test* (**TRT**).

The thermal response test is a simple experimental method for determining the thermal conductivity. But, the measurements usually last more than 10 days, and require transporting the apparatus far from the lab, and sometimes to hardly accessible locations. Therefore, a mobile test set-up is used. First mobile set-ups for the TRT were constructed and used in Sweden and USA in 1995, and to date this method has been developed in dozen of countries. A mobile TRT set-up (Fig.2) is composed from a BHE conjuncted with a water boiler (+ electrical heater). Heated water from the boiler is introduced into the heat exchanger where it is cooled down, and then flows back to the boiler. The values of quantities needed for the calculation are the flow-rate and the water, inflow and outflow, temperatures that are measured in equal time intervals.

When designing smaller size units, it is feasible to utilize tabulated values, of thermal conductivity λ, for the ground material, or to perform tests in laboratory conditions, but when designing the BTES systems, it is necessary to perform the investigations *in situ*. This does mean that the only method that surely can yield satisfactory results - TRT (thermal response test).

Main methods for determining thermal conductivity of ground from the data mesured during TRT [5] are:

- slope determination technique,
- two-variable parameter fitting method,
- by *Geothermal Properties Measurements* method.- i.e. by utilizing the **GPM** software.

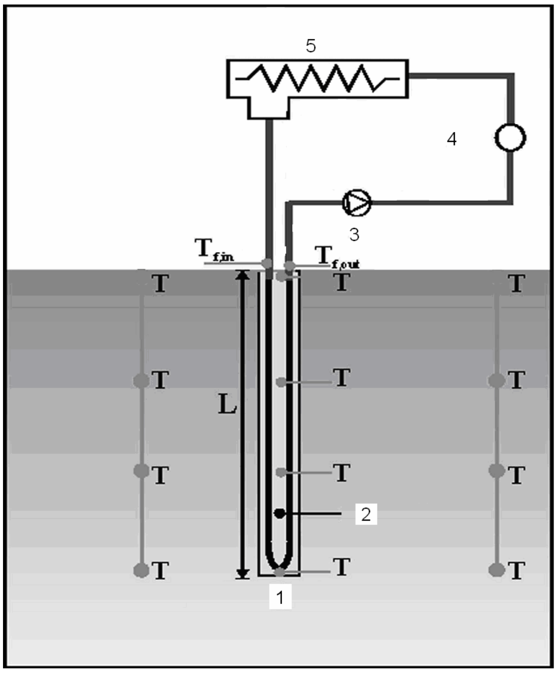

Figure 2: Schematic of the TRT test set-up (T-thermocouples; $T_{f,in}$, $T_{f,out}$-water intake and outflow temperatures; L-borehole depth; 1-borehole, 2-grout, 3-circulation pump, 4-flow meter, 5-electric heater)

4.1 Slope determination technique

This method is simple and accurate. It relies upon the solution of the **LSM** (*Line Source Model*) problem. It is using the expression for the temperature field of the working fluid as the function of time (t) and borehole radius (R) around a line heat source of constant power (P) which can be assumed to = power of the BHE:

$$T_f = \frac{P}{4\pi\lambda L}\left[\ln\frac{4at}{R^2} - \gamma\right] + \frac{P \cdot R_b}{L} + T_0 \qquad (1)$$

Expression (1) is a formula of the form:

$$T_f(t) = k\ln(t) + m, \qquad \text{where:} \qquad k = \ln\frac{P}{4\pi\lambda L} \qquad (2)$$

Therefore, thermal conductivity (λ) is determined based upon slope (k) of linear dependence T_f on $\ln(t)$, therefrom the title of the method. The results that were determined by the virtue of this method are:

λ = 1,8 W/mK	R_b = 0,3 mK/W

4.2 Two-variable parameter fitting method

The need for a more interval-independent evaluation technique led to fit the data using as fitting function an equation (1) with thermal conductivity and borehole thermal resistance left as the two variable parameters. For this analysis, the commercial software "Origin6" was used. This software has a capability of performing nonlinear curve fitting to user input functions using a Levenberg–Marquardt iteration algorithm [4]. Results that were determined by the means of this method are:

λ = 1,749 W/mK	R_b = 0,299 mK/W

4.3 Geothermal properties measurement (GPM)

The GPM is a program developed at the Oak Ridge National Laboratory to determine thermal properties from the short term field test data. The program uses a parameter-estimation-based method - combined with a 1-D numerical model. It relies on the cylinder source model considering two pipes of the U-loop as a single cylinder. Results that were determined by the means of this method are:

λ = 2,35 W/mK	R_b = 0,32 mK/W

Based upon the performed analysis it is concluded that the classic methods (slope determination, as well as the two-variable parameter fitting) - are simple and reliable [1,4]. Accuracy of the results depends only on how precisely the test is led (accuracy of temperature measurements, elimination of meteorologic impacts).

Utilizing the mobile TRT set-up permits an *in situ* measurement, and - the Slope determination technique (the simplest of methods) yields satisfactory results.

5 Conclusions & Recommendations

UTES is a technology which, in conjunction with heat pumps, because of its profitability and positive effect on the environment, can have long-term influence on power industry in Serbia. Energy savings in cooling mode are 40-80%, and in heating mode around 40%. Use of UTES systems also reduces the consumption of fossil fuels for electricity production, and the level of flue gases (CO, CO_2, SO_2 and NO_x) emission.

Of several types of UTES system, only BTES and ATES can be widely used. Other systems are hardly realizable in the practice. Possibility of use of a BTES or ATES system depends solely upon hydrogeologic conditions at a specified location. The ATES systems can be applied in river valleys and in plains rich with water, and the BTES – in regions with impermeable ground. In greater part of Serbia, conditions for use of either of these two modern systems are satisfied.

Designing the BTES systems requires knowledge on thermophysical properties of ground, i.e. thermal conductivity and thermal diffusivity. A reliable method for measuring quantites that are necessary for determining these properties is the Thermal Response Test (TRT). Based upon an analysis of the available data reduction methods, the Slope Determination Method is recommended, as simple and precise. It is to be expected that TRT (using mobile set-up for *in situ* measurements) will become the standard procedure for determining thermal conductivity (λ) and thermal diffusivity (a) of grounds in Serbia.

Nomenclature:

a	thermal diffusivity (m^2/s)
C_v	volumetric specific heat (J/m^{3}K)
L	borehole depth (m)
P	power of the heat exchanger (W)
d	pipe diameter (mm)
R	borehole radius (mm)
R_b	thermal resistance in the borehole (m·K/W)
t	time (s)
m	mass (kg)
T_0	ground temperature (°C)
T_f	working fluid average temperature (°C)
γ	Euler constant (= 0,5772)
λ	thermal conductivity (W/m·K)
ρ	density (kg/m^3)

References:

[1] BUSSO, A.; GEORGIEV, A; ROTH, P.; Underground Thermal Energy Storage – 1st Thermal Response Test in South America, *World Climates and Energy Event*, Instituto de la Copacabana, Rio de Janeiro, Brazil, 2003., pp.189-196

[2] PAKSOY, Haime Ö.; Underground Thermal Energy Storage – A Choice for Sustainable Future, *Report of Çukurova University*, Faculty of Arts and Sciences, Chem. Department, Adana, Turkey

[3] KOHL, Thomas; BRENNI, Renzo; EUGSTER, Walter; System Performance of a Deep Borehole Exchanger, *Report of Institute of Geophysics*, ETH Hőngerberg, Zurich; Polidynamics Engineering Zurich, Zurich, Switzerland, 2002

[4] ROTH, P.; GEORGIEV, A; BUSSO, A.; BARRAZA, E. ; First In Situ Determination of Ground & Borehole Thermal Properties in Latin America, *Report of Department of Mechanical Engineering*, UFSM, Valparaiso, Chile; Department of Physics, FaCENa, UNNE, Corrientes, Argentina, 2004

[5] PAHUD, D.; MATHEY, B.; Comparison of the Thermal Performance of Double U-pipe Borehole Heat Exchanger Measured In Situ, *Energy and Buildings* (33), Switzerland, 2001., pp. 503-507