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Preliminary Design of Experimental Set-Up for Conducting the Thermal Response Test

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Abstract: - Difficulties being faced when dimensioning a heat pump system using subsoil thermal energy storage have been considered. For making proper design of such a system, it is necessary to know exact values of thermal conductivity (λ) and thermal diffusivity (a) of the soil. Some of the past investigations in the world have been reviewed as well as the most frequently used experimental procedures. 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. A new testing procedure (with mobile set-up for *in situ* tests) was defined – for determining the thermal conductivity and thermal diffusivity of grounds in Balkan area. This method is based on conducting the Thermal response test and reducing data by the Slope determination method. An idea project is proposed of a new test set-up, for conducting the Thermal response test that has been suited to the material and other relevant conditions in Balkan area.

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

1 Introduction

Heat pumps using subsoil thermal energy storage show better performance compared to systems using other alternative energy sources. This is primarily reflected in their energy efficiency and low maintenance cost.

The aim of this research is to define the procedure for determination of soil thermal properties (thermal conductivity - λ, and thermal diffusivity - a) that conforms to the conditions in our country. That means a comparison of TRT with the other available methods. Within TRT, a comparison has been made of the: slope determination, two-parameter and GPM, methods. At the very end a preliminary design is proposed of the experimental test set-up for TRT as conforming to the financial and other conditions in Balkan area.

2 Thermal Properties of Soil

Past investigations have revealed the great importance of determining the number and schedule of boreholes. In order to determine the distribution of boreholes, the design engineers first determine the thermal properties of ground. Number and size of a borehole depends on thermal conductivity and diffusivity. The initial price of a heat pump system using the underground thermal energy storage depends on location and drilling price.

There are several methods for determining thermal properties of ground: a) soil and rock identificaiton; b) experimental testing of drill cuttings; c) in situ probes; and - d) thermal response test (TRT).

2.1 Use of Ground / Stones Classification

This method for determining λ is described in the EPRI handbook for ground and stones classification [4]. The procedure starts with classification of soil based on the visual observation. Each type of the soil is followed by thermal conductivity so it is possible to read this value directly. The lower thermal conductivity does yield a greater borehole depth and, vice versa, high value of ground thermal conductivity yields the lesser value of borehole depth, i.e. shallower borehole.

If the investigated soil consists of different types of rocks - they should be classified into categories. Although the utilized procedures for soil and rock identification are tedious, the *λ* determination method is easier for its simple use. Picking a lower value from the proposed conductivity range is recommended.

2.2 Laboratory Experiments on Cuttings

The 2nd method for determining thermal conductivity of the ground is based on the drill cuttings. The plastic cell (a short plastic tube of approximate wall thickness 0.16 cm), filled with the sample that consists of water and soil is - covered on top and bottom by copper lids. Constant temperature drop through sample is observed and, for a known thermal flux, approximate value of mixtre thermal conductivity has been determined. The results of this - thermal conductivity yielding - method are not fully reliable because they are based upon the vague and arbitrary assumption of soil homogeneity.

2.3 Laboratory Tests with *In Situ* Probes

According to Choudhary [3], the extraction of ground samples reduces the error in determining the thermal conductivity of ground. The probe incorporates an interior heater and thermal sensors mounted in ceramic isolation or epoxy tar. The probes are usually inserted in the samples of ground obtained by drilling, that are located in tubs and kept in laboratory. These results -obtained on the basis of temperature measurements amidst the probe, as well as of the heat flux, are used in expressions for thermal conductivity of soil.

2.4 Borehole Thermal Response Testing

As example of experimental determination of ground thermal properties by using the TRT, cited are the results of a research group working in Argentina [2]. Thermal conductivity and the borehole heat resistance, have been computed by using the: slope determination; two parameter; and - GPM, methods i.e. procedures.

At the Faculty of Mechanical Engineering in Belgrade, a demonstration project is going on, with drilling the borehole 60 m in depth, and with inserting a BHE in the form of U-pipe and eleven sensors (thermocouples) for measuring the temperature at different depth level. This all is placed in the borehole that is subsequently filled with bentonite grout. Making, and later usage of the BHE, give the opportunity to use it for conducting the TRT and determining the λ of ground. Thence, in the paper a procedure of experimental determination of λ of ground, and borehole thermal resistance, is being defined and a preliminary design of TRT set-up given.

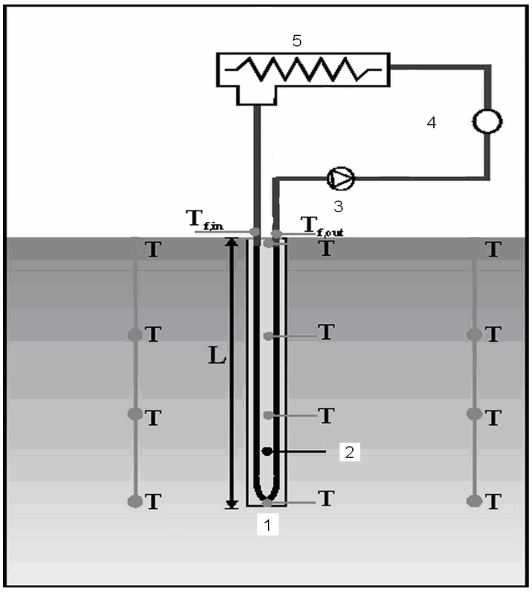

Figure 1: Schematic of the TRT test set-up (T-thermocouples; $T_{f,in}$, $T_{f,out}$-water intake and outflow temperatures; L-borehole depth; 1-borehole, 2-grout, 3-circulation pump, 4-flow meter, 5-electric heater)

3 Theory on Thermal Response Test

Analysis of data gathered during the TRT is based on the Line source model (LSM), that depends on thermal conductivity of ground and thermal resistance of the borehole [1]. During the investigations that can last up to several days, the ambient temperature is measured, as well as temperature of water at the BHE intake and outlet. Water flowrate and heater power are measured and maintained constant. Different BHE types were tested for determining the borehole thermal resistance.

3.1 Line Source Approximation

The model is based on the approximation of borehole by a linear heat source. The fundamentals of the model were set by Lord Kelvin, expressed by the virtue of the so-called Kelvin's or - line source equation. In this equation, it is apt to introduce resistance to heat flow between water in the U-pipe and the borehole wall - m_{TR}. By taking it into account, it is obtained that:

$$\Delta T_{(R,t)} = \dot{Q}\, m_{TR} + \frac{\dot{Q}}{4\pi\lambda}\left[\ln\left(\frac{4at}{R^2}\right) - C\right] \qquad (1)$$

Equation (1) is reduced onto the simple shape by compressing into the linear form: $y = mx + b$, this is the equation of straight line of slope „*m*“, based upon which λ is determined. Thermal conductivity and the slope of straight line, in the plot with abscissa ln(*t*), are related via the average temperature of water in BHE. This model is easily used with experimental data.

3.2 Two Parameters Simulation

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 [2].

3.3 Cylindrical Source Approximation

This model is based upon approximation of the U-pipe by a cylinder, shown in Fig.2. It uses the GPM code [2] i.e. the geothermal properties method linked with the 1-D numerical simulation. To make this model be radial, two (or four) tubes of a (or two) U-pipe(s), are approximated by one cylinder of equivalent diameter ($D_{ekv} = \sqrt{2}\cdot D_0$). The BHE may, if necessary, contain 2 U-pipes. This model, in the majority of cases, does not account for the thermal conductivity of bentonite, but it can be included too - for higher accuracy.

Methods for experimental determination of ground thermal properties by means of TRT are world widely accepted for simplicity and accuracy. Past experience yields a conclusion those methods: slope determination; two parameter; as well as GPM-method are the most appropriate. Comparison of results of all three methods (λ = 1.8; 1.749; 2.35 and R_o = 0.3; 0.299; 0.32) show small differences in the determined values of thermal conductivity and thermal resistance of the borehole, and, for its simple usage and satisfactory accuracy, the „slope determination“ method is proposed.

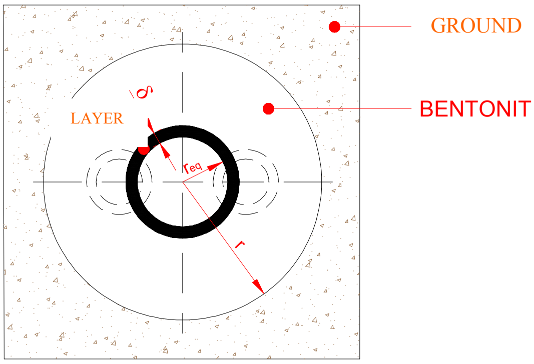

Figure 2: Approximation of U-pipe by cylinder

4 Mobile TRT Experimental Set-Up

For conducting the previously defined methodology, a mobile experimental test set-up is designed, suited for determining ground thermal properties via TRT, of a sensible price, to conform to conditions in our country.

The preliminary design is shown of a mobile set-up for determination of ground thermal properties via TRT, of sensible price, bearing in mind all constraints. It is situated in a small car trailer and - contains the following three components, i.e. subsystems:

- water supply with flowrate control,
- water heat-up with temperature control,
- electric power supply with voltage control.

In practice, mobile test set-up must be designed so that it can operate independently of water and electric network availability, considering that the test locations are often of under-developed infrastructure. The trailer must be designed so that it can contain almost all the components of the mobile set-up. Precisely, the trailer is used for placing the water tank, 120 l in volume, a small crossflow electric boiler with heaters of 12 kW in total power, and the other necessary equipment.

4.1 Water Supply System

This system must be designed to completely enable the water supply regardless of water network availability. An alternative is – a supply of the system with water from the wells if they exist at the test site.

This water supply system consists of the following components: a water tank, two booster pumps, a flow meter and a filter. This system is schematically shown in Fig.3. The first component of this system is a water tank, i.e. a vessel of cylindrical shape, 120 l in volume. This volume has been determined from the volume of water that fits into the U-pipe of outer diameter 1“, wall thickness 3 mm and 60 m long.

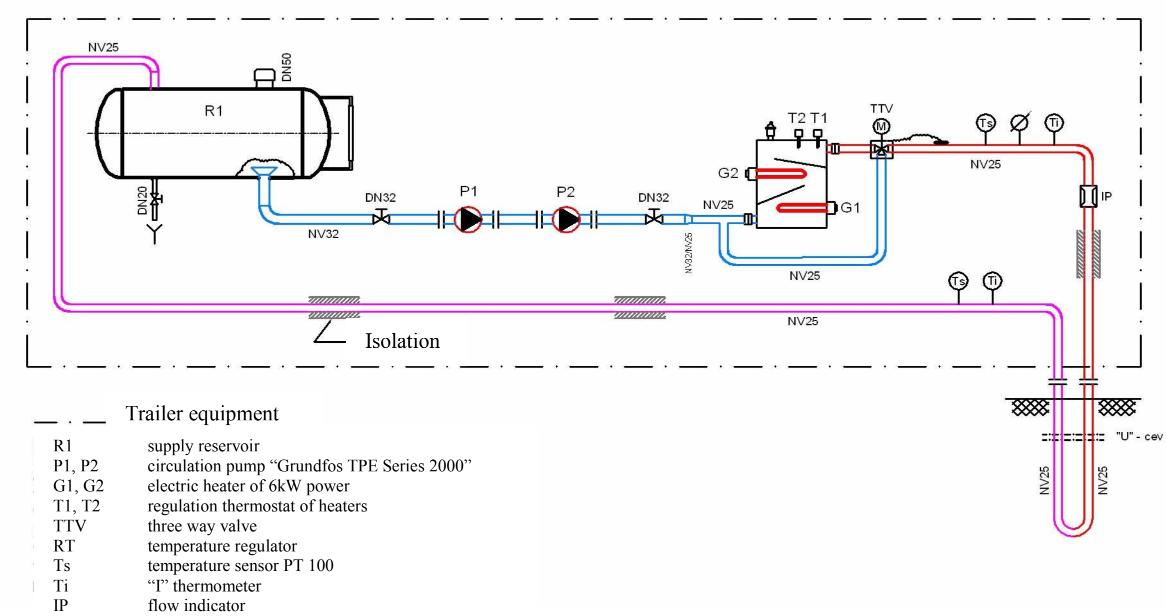

Figure 3: Schematic of the experimental apparatus for TRT (preliminary design)

The 2nd component of the water supply system are the pumps. They serve for maintaining the water circulation during the test as well as setting the system under pressure. The third component of the system is a flowmeter for measuring the flow rate of water from the borehole or from the interior pipeline (that is the installation in the trailer). It is mounted downstream from the pump and serves to check if the flow rate is high enough to ensure the planned value of heat flux. Water flow rate is controlled by a control valve.

The fourth component of the water supply system is a filter. It consists of a standard filter insertion that is used also in home water systems for eliminating rust and mineral depositions, and larger particles.

4.2 Water Heat-up System

Water that circulates through the system is heated up by means of an electric crossflow boiler that contains two electric heaters. Each heater is 6 kW in power and the boiler as whole is 12 kW in electric power. Water heat up *in situ* may be attained by operation of one or two heaters, as needed. The boiler contains automatic control that enables switching on both sections of the heaters or operation of only one section, as attained by the two control thermostats, one per heater. Inside the boiler, between the two heaters, mounted at different heights, there are two separating tins for redirection of water, aiming to increase the heat up effect (Fig.5).

4.3 Electric Power Supply System

Supply of electricity is attained by connection to the electric network. If it is not available, an alternative solution is diesel aggregate generator, able to supply about 20 kW power and produce voltage 240 V. Line connects the generator and the external control box. It satisfies the needs of water heaters in the crossflow boiler, of 2 pumps and other parts of the installation. Knowing the generator cost about 8.000$, makes this alternative power supply financially non-appropriate.

5 Conclusions & Recommendations

Heat pump systems with underground thermal energy storage, for their profitability and pleasant influence upon the environment, may have long-term effect on power production in Balkan area. Their use reduce the consumption of fossil fuels for production of electric energy, as well as the level of flue gases (CO, CO_2, SO_2 и NO_x) emissions. If they will be world widely used, these systems could play a key role in decrease of pollution that leads to global warming.

For designing these systems, knowledge is needed on the thermophysical properties of ground such as thermal conductivity (λ) and thermal diffusivity (a). A reliable method for measuring quantites needed for determining these properties is the Thermal Response Test (TRT). Based upon an analysis of the available data reduction methods, Slope Determination Method is recommended, as simple and precise. It is expected that TRT will soon become the standard procedure for determining thermal conductivity, as well as thermal diffusivity, of the ground in Balkan countries.

Measurements during the TRT test are done by a mobile apparatus *in situ*, i.e. by means of the test set-up, the preliminary design of which is given here, in accordance with financial and other conditions in our country. The next step would be the realization of the preliminary design of the set-up and running tests at the FME borehole. After the performed investigations one should eliminate the observed shortcomings of the test set-up so that it could produce reliable and precise results at many sites throughout Balkan area.

Nomenclature:

a	thermal diffusivity, m^2/s
m_{TR}	thermal resistance, mK/W
Q	heat flux per meter of pipe, W/m
r	radius, cm
t	time, s
T	temperature, °C; K
C	Euler constant (= 0.5772)
λ	thermal conductivity, W/mK

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