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Numerical modelling as a supplementary tool for Thermal Response Test

T. Amanzholov[1], B. Akhmetov[2*], A. Georgiev[3,6], A. Kaltayev[1], R. Popov[4], D. Dzhonova-Atanasova[5], M. Tungatarova[1]

[1]*Al-Farabi Kazakh National University, Almaty, 050000, Kazakhstan*
[2]*Research Institute of Mathematics and Mechanics, Almaty, 050000, Kazakhstan*
[3]*Faculty of Mechanical Engineering, Technical University - Sofia, Plovdiv Branch, 25 Tsanko Diustabanov Str., 4000 Plovdiv, Bulgaria*
[4]*Faculty of Physics, Plovdiv University "Paisii Hilendarski", 24 Tzar Assen Str., 4000 Plovdiv, Bulgaria*
[5] *Institute of Chemical Engineering, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 103, 1113, Sofia, Bulgaria*
[6]*European Polytechnic University, Dept. of "Green Energy", 23 Kiril and Metodiy str., 2300 Pernik, Bulgaria*

Nowadays, development of efficient thermal energy storage systems is becoming very important since they assist in storing gained heat from renewable energy sources at medium or large scales in an effective way with the purpose of balancing the demand and supply of energy. One of the technologies which allow thermal energy accumulation in a large-scale is Borehole Thermal Energy Storage (BTES). Such technology gives opportunity to store heat into the ground and/or groundwater in summer, and extract it during winter. To evaluate the BTES performance, the ground thermal properties must be known. One of the in situ methods for this purpose is the thermal response test (TRT). But, TRT gives an overall evaluation of the thermal properties of the ground. Therefore, for more precise evaluation, mathematical modelling is used as a supplementary tool for TRT technique. The current paper focuses on experimental TRT technique and mathematical modelling of a TRT process.

Keywords: Borehole Heat Exchanger, Thermal Response Test, numerical modelling

INTRODUCTION

Technologies for harnessing thermal energy from renewable energy sources are being developed and improved at a good pace worldwide. Consequently, the improved efficiency of such technologies gives opportunity to gain thermal energy at a large amount in a short time. But, in order to effectively use the harnessed energy, heat storages are needed.

There are several types of thermal energy storage techniques and storage types vary with storage capacities. Typical storages for accumulation of thermal energy in a large amount are the underground thermal energy storage (UTES) systems. One of the most common systems among UTES is the borehole thermal energy storage (BTES). BTES is attractive since: it can be installed almost everywhere except in locations with underground caverns or high pressure geysers; and it is a long-term system if borehole heat exchanger is installed by carefully following the installation rules [1, 2].

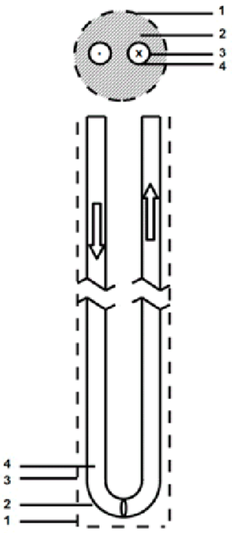
An accurate estimation of the borehole heat exchanger thermal performance can be obtained when the thermal properties of the ground and the borehole are properly evaluated.

A team from the partner universities, Al-Farabi Kazakh National University and Technical University of Sofia, Plovdiv Branch, installed a 50m BTES with a single U-pipe borehole heat exchanger (BHE) in order to test the performance of the BTES and to evaluate the thermal properties of the ground. A vertical U-tube ground heat exchanger, shown in Fig.1, is a key component in any geothermal energy utilization system [3]. The BTES system developed by the authors consists of a high-density-polyethylene (HDPE) U-tube with inner diameter of 25 mm and outer diameter of 32 mm. The U-tube was inserted into 50 m deep borehole and grouted with the mixture of betonite and cement.

Knowledge about thermal properties of the surrounding soil of BTES is very important for estimating the efficiency of the system. One of the well-known experimental methods for evaluation of the ground thermal properties is the thermal response test (TRT). During the TRT, a constant amount of thermal energy is transferred into the ground by using a TRT installation connected to the BHE and the temperatures of the circulating heat carrier fluid are recorded at the inlet and outlet sections of the BHE [4].

After the temperature measurements, which usually last about 7 to 10 days, analysing the

* To whom all correspondence should be sent:
eng.akhmetov@gmail.com



1 - borehole wall; 2 - grout; 3 - interior of U-tube; 4 - U-tube wall.

Fig.1. Single U-type borehole heat exchanger [3]

recorded data by means of the line source theory, the effective thermal conductivity of the ground λ_{eff}, and the borehole resistance R_b, are evaluated. Thus, the equation obtained on the base of the line source theory is [5]:

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

$$\text{for} \quad t \geq \frac{5r_b^2}{a} \qquad (1)$$

$$T_f(t) = k \cdot \ln(t) + m, \qquad (2)$$

where $$\lambda = \frac{Q}{H \cdot 4\pi \cdot k} \qquad (3)$$

where T_f- is average temperature, °C; λ - is thermal conductivity of the ground, W/mK; H - is depth of borehole, m; Q - is heat flux, W; t – is time from start, s; R_b- is borehole thermal resistance, mk/W; r_b - is radius of the borehole, m; a - is thermal diffusivity, m²/s; T_g - is initial temperature before the charging of borehole, °C; γ=0.5772 - is Eulerian constant.

But, Eqn. (1) gives an overall evaluation of the effective thermal conductivity λ_{eff} and the borehole thermal resistance R_b. In other words, the Line Source Model (LSM) [5] does not take into account subsurface layers of the ground around the borehole, but only assumes that the surrounding medium is homogenous and non-porous, without any groundwater flows. Therefore, the heat transfer process is only conductive. Moreover, the line source model includes the borehole thermal resistance between the fluid and the surrounding formation. Other limitations of the LSM were discussed by Wagner at al. [6].

In the current paper we apply numerical modelling techniques, which consider geological heterogeneity, groundwater flows, and heat transfer in porous media, the properties of the material of the BHE pipe, the grouting material and the subsurface layers.

NUMERICAL SIMULATION

On the contrary to the Line Source Model, the numerical approach allows for the simulation of subsurface physical as well as hydrodynamic processes during a TRT [7, 8]. The numerical

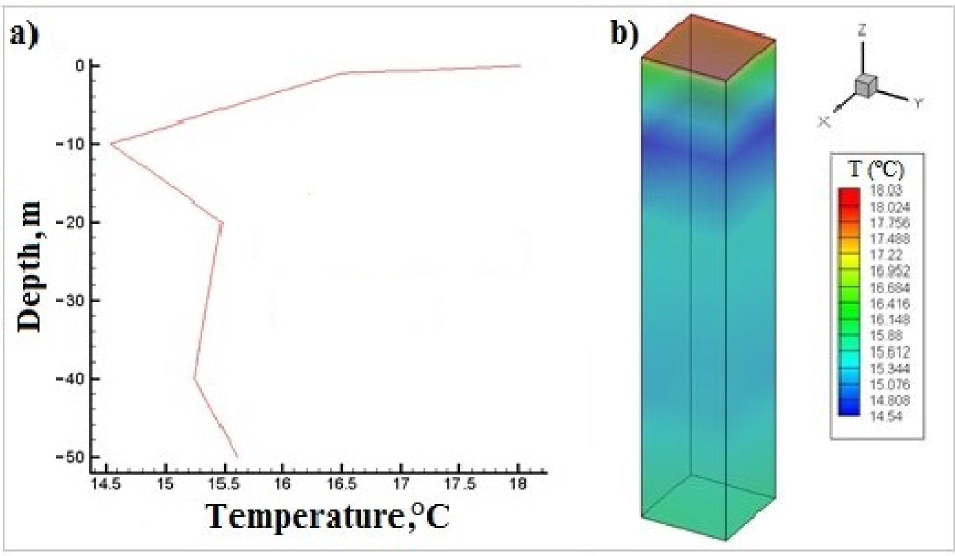


Fig.2. Initial temperature distribution in the soil: a) testing data; b) simulation data

model, coupled with the results of the experimental studies, can be used to simulate the TRT and the working modes of BHE under realistic conditions.

Experimental data of a TRT, carried out in August 2015 at the Technical University of Sofia, Plovdiv Branch, was taken as input data for the numerical modelling purposes. The initial temperature distribution around the BHE was obtained by circulating the working fluid through the BHE and the TRT installation without providing any thermal energy to the loop about 1 hour.

Fig.2a presents the temperature distribution along the borehole obtained from the temperature measurements of the buried Pt 100 sensors. Applying these results in the modelling by linear interpolation of the temperatures between two adjacent sensors, initial temperature distribution in the soil can be introduced to the numerical approach (Fig.2b).

Moreover, ground heterogeneity was also included in the modelling. In fact, types of the soils were determined while drilling the borehole, and thermal properties of these materials were taken from paper [9]. Thus, the properties of the soil layers surrounding the BHE are given in Table 1. In addition, when drilling the borehole, the presence of the aquifer was noticed around 10 m depth. This is also confirmed by the significant decrease of the temperature gradient at 10th meter, which is due to the groundwater (Fig.2a). In the modelling, the thickness of the groundwater layer was taken as 10 m, starting from 5 meter depth. And velocity of the groundwater flow was taken as 0.1 mm/s which is quite reasonable for most of the time.

Table 1. Properties of the underground materials [9]

Material	Thermal conductivity (W/m K)	Volumetric heat capacity (MJ/m³)	Density (kg/m³)	Depth (m)
Sandy soil	0.3	800	1600	0-0.4
Technical ground	0.83	1970	800	0.4-2.0
Clay	1.58	2000	1550	2.0-9.4
Saturated sand	2.2	2000	1480	9.4-50.0

The temperature at the inlet section of the BHE, measured during the TRT, is also taken as input data to the modelling. Measurement results of the ambient temperature variation during the test, and temperature development at the inlet and the outlet of the BHE are presented in Fig.3. The numerical modelling was carried out in three dimensional space with a size of $10\times10\times60$m (length $\times$width $\times$depth).

The dimensions of the BHE are listed in Table 2. The diameter of the borehole is taken as 165 mm, and the inlet and outlet pipes are considered to be evenly located in the borehole. Therefore, shank spacing between the pipes is about 28 mm.

Mesh resolution is not regular, but increases towards the borehole where the temperature gradients are steepest. Groundwater was determined during the drilling of the borehole at a depth of about 12 m. Therefore, in the modelling meshing is finer at the groundwater flow level and

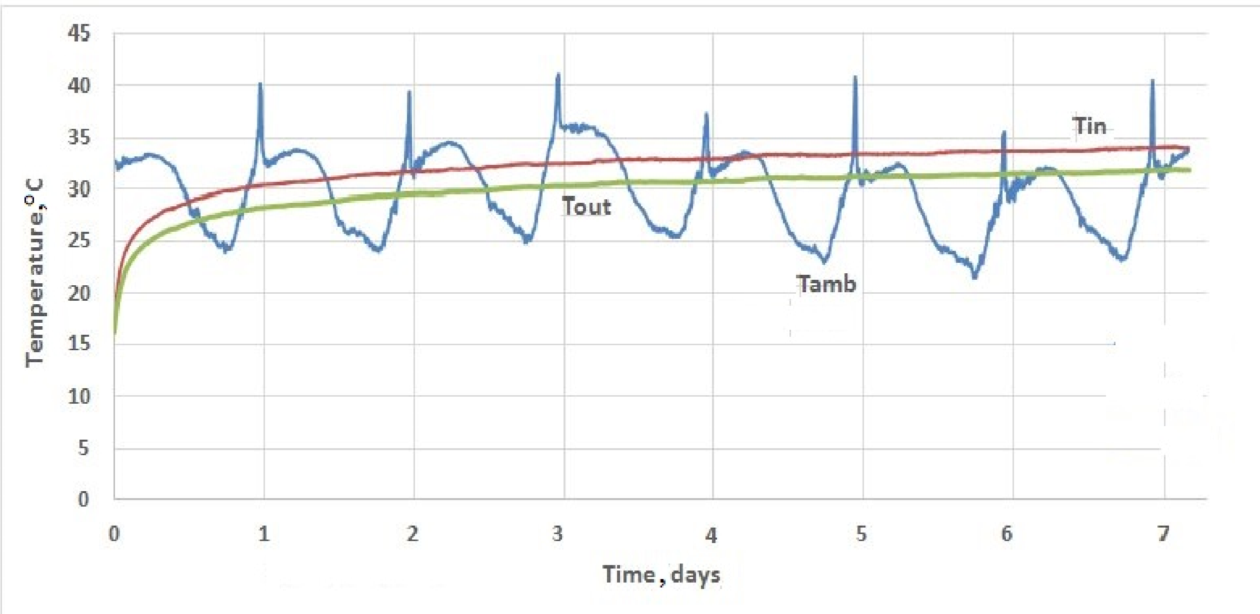


Fig.3. Ambient temperature variation and development of the temperature at the inlet and outlet sections of the BHE during experimental TRT

at the bottom of the borehole because of significant temperature gradient (Fig.4).

Table 2. Dimensions of the borehole heat exchanger

Name	Value (meter)
Inner radius of the BHE pipe r_{in}	0.0125
Outer radius of the BHE pipe r_{out}	0.016
Radius of the borehole r_b	0.0825
Depth of the BHE d_{BHE}	50

Equations

Inside the BHE, fluid flow is modelled by the pipe flow equations together with conservation law [10]. This approach uses "edge elements, solving for the tangential cross-section averaged velocity along the edges, to avoid meshing the cross section of the pipe with a full 3D mesh. This means that the modelled variables are averaged in the pipe's cross sections and vary only along the length of the pipe" [10]:

$$\rho\frac{\partial u}{\partial t}+\rho u\cdot\nabla u=-\nabla p-f_D\frac{\rho}{2d_h}u|u|+F \quad (4)$$

$$\frac{\partial A\rho}{\partial t}+\nabla\cdot(A\rho u)=0 \quad , \quad (5)$$

where u is the cross section average velocity, m/s; ρ is the fluid density, kg/m^3; p is the pressure, Pa; f_D (dimensionless) the Darcy friction factor; F is a volume force term, N/m^3 and d_h is hydraulic diameter, m. Moreover, the energy equation for an incompressible fluid flowing in a pipe is [10]:

$$\begin{aligned}&\rho AC_p\frac{\partial T}{\partial t}+\rho AC_p u\cdot\nabla T=\\&\nabla\cdot A\lambda\nabla T+f_D\frac{\rho A}{2d_h}|u|^3+\dot{Q}\end{aligned} \quad , \quad (6)$$

where A is the pipe cross section area, m^2; C_p is the specific heat capacity at constant pressure, J/kg K; T is the temperature, K; λ is the thermal conductivity of the water, W/mK.

For heat transfer in porous media, the following equation is solved [11]:

$$(\rho C_p)_{eff}\frac{\partial T}{\partial t}+\rho C_p u\cdot\nabla T+\nabla(\lambda_{eff}\nabla T)=\dot{Q} \quad (7)$$

where $(\rho C_p)_{eff}$ is the effective volumetric heat capacity at constant pressure, J/m³.K; u is the fluid velocity m/s; λ_{eff} is the effective thermal conductivity of the ground, W/mK, and $\dot{Q}$ - heat source term for equations (6) and (7) measured in W/m^3. For Eqn. (6) it is zero since there is no any heat source in the pipe.

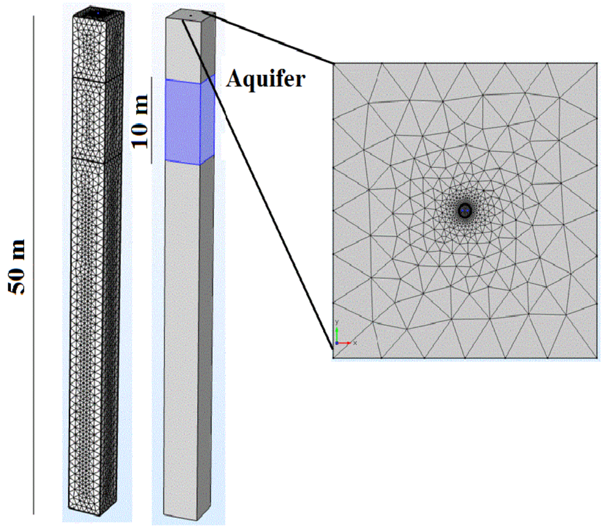


Fig.4. Overview of the modelling domain and numerical discretization

In order to model the TRT process, both hydrodynamic and energy equations need to be solved with appropriate initial and boundary conditions. As mentioned above, initial temperature distribution inside the borehole as well as in the subsurface layers was set up as given in Fig.2. At the edges (i.e. boundaries) of the geometry outflow thermal boundary was set up, although the dimensions of the computational domain are large enough to minimize boundary effects for the time of the TRT (7 days in our case). The experimental inlet temperature was applied as an inlet boundary condition for the numerical simulation of the TRT process. Once the inlet temperature and velocity is given, fluid flow and heat transfer in the BHE pipe is calculated based on Eqns. (4)-(6). The resulting temperature distribution in the BHE obtained by numerically solving these equations is used as a heat source in Eqn. (7) to model the heat transfer in subsurface layers in three dimensional space.

RESULTS AND DISCUSSION

To analyze the correctness of the numerical modelling results, they were compared with the experimental data. During the experimental TRT heat was injected using electrical heater in the installation with a constant power of 2 kW to the ground, with water flow rate of 600 l/h through the BHE while measuring the inlet and outlet temperatures. The results of the comparative analysis in respect to the inlet and outlet temperature developments are presented in Fig.5, which illustrates a good agreement between the experimental and the numerical data. Although, the inlet temperature for the modeling was taken from experimental studies, the data was interpolated first and its approximate equation was obtained and then used in the modelling. The interpolation was necessary because recording time interval during the test and time step in the modelling were different. That is the reason of some deviations occurred when inlet temperature of experimental and numerical studies are compared. But, the most significant results is the outlet temperatures agreement. Therefore, it can be concluded that the modelling approach is correctly set up and its results describe the TRT process taking into account heterogeneities of the soil, groundwater flows, and heat transfer in porous media which are not considered in the LSM.

Based on the results of the numerical simulation, which is more reliable tool compared to the analytical methods, it is possible to evaluate the temperature field around the borehole (Fig.6). Moreover, the numerical model easily accounts for different heat injection rates by specifying the water temperature at the inlet of the BHE to simulate the process, for instance charging or discharging of the BTES system for a desired time duration. Moreover, the number of the boreholes can be increased up to the desired number of BHE depending on the thermal demand for the users, thus, creating a large scale borehole thermal energy storage, and the performance of the system and its working modes can be modelled together with the temperature field in subsurface layers.

CONCLUSIONS

As commented above, the Line Source Model, typically used to analyse a TRT, assumes that the surrounding soil is homogeneous, heat transfer is in the form of conduction only, and no aquifer flows are present. In the current paper, on the contrary to the analytical approach, we developed numerical technique, using a 3-D finite-element numerical model, which takes into account major and necessary physical process and parameters such as heterogeneities of the subsurface layers, ground water flows and conductive and convective heat transfer in porous media. In other words, the numerical simulation helps to reduce the errors in estimating the thermal properties, which originate from the analytical methods such as the Line Source Model, especially when the real test conditions do not satisfy the assumption of the analytical approach.

The experimental verification of the numerical technique shows a good agreement with experimental data form the TRT studies carried out at the Technical University of Sofia, Plovdiv Branch. With the help of the developed numerical tool, it is possible to simulate the underground temperature field during TRT, and to understand the thermal energy transfer across the subsurface layers of the ground.

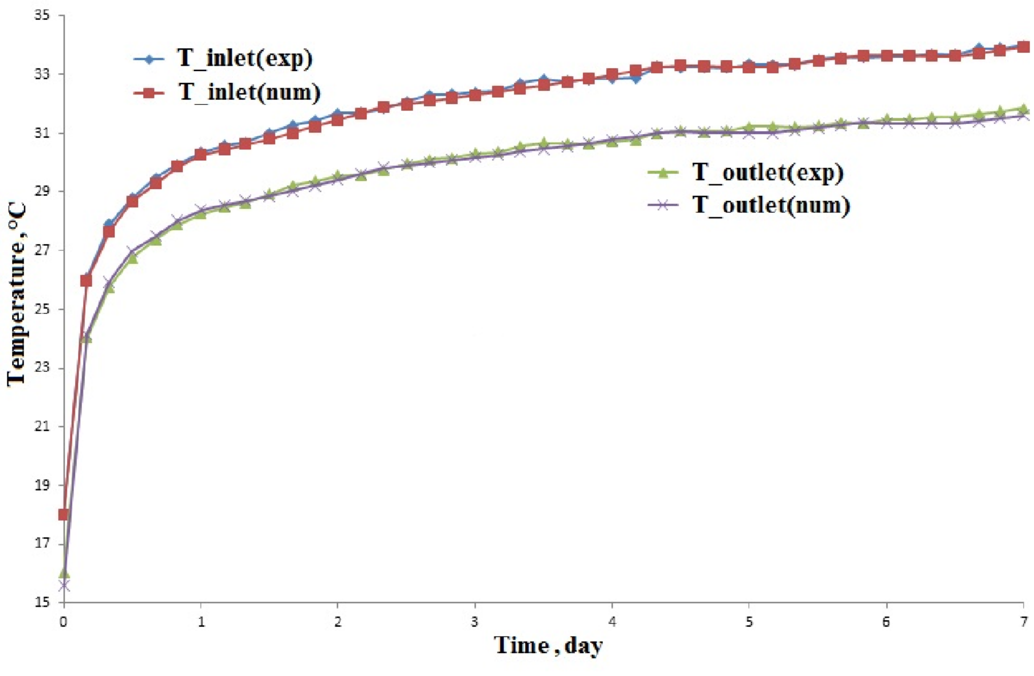


Fig.5. Comparison of inlet and outlet temperatures of experimental and numerical studies

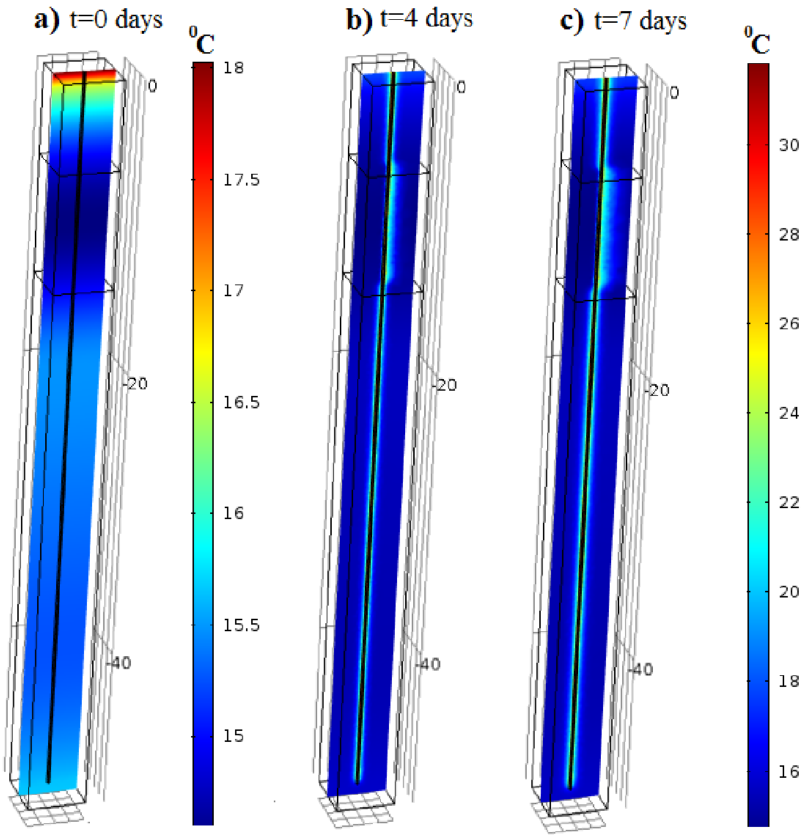


Fig.6. Temperature distribution at a) the beginning, b) after 4 days and c) after 7 days for the TRT simulation

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