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Determination of boundary conditions from experimental data for computational fluid dynamics simulations for phases change material solutions in the ground mass with emphasis on ground heat exchangers

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The main disadvantage of horizontal ground heat exchangers is that the area above them cannot be used for agricultural purposes, and the shallow location of the horizontal pipes leads to frequent temperature fluctuations. This can be overcome by appropriate solutions for a thermal storage regulation unit. The purpose of this work is: 1) systematization of research on ground heat exchangers with phases change material by means of pictorial illustrative table; 2) analysis of the results for the measured temperatures for the ground depths of 2 m and 6 m, for the summer period and determination of the thermal conductivity of the researched soil layer. The results are shown graphically. This data is suitable for running computational fluid dynamics simulation and the resulting temperature variation data can be entered as input data for the thermal energy storage based of phases change material low-paraffin waxes type.

Keywords*:* Ground source heat pump (GSHP), ground heat-exchanger (GHE), thermal energy storage (TES), phases change material (PCM), paraffin wax, renewable energy sources (RES)

INTRODUCTION

The use of alternative and sustainable ways with the participation of renewable energy sources for air conditioning of homes, industrial buildings and agricultural sites gives an advantage in two aspects: reducing the impact on the environment and saving primary energy. Geothermal energy combined with geothermal installations can undoubtedly contribute to this goal [1-3]. Geothermal installations significantly save primary energy, which also contributes to the environmental impact [4]. According to the statistical office of the European Union - Eurostat 2022 [5], from the total production of energy, the energy from renewable energy sources is different, as follows: Sweden - 62.6%, Finland - 43.1%, Latvia - 42.1%, Austria - 36.4%, Bulgaria - 17.0%, Malta - 12.2%. Geothermal energy is 1.22% of the total acquired energy sources in Bulgaria in 2021 [6].

In the last few decades, considerable efforts have been made to develop geothermal systems for building installations, as well as to solve the various problems in their design. Extensive studies have been conducted in different countries on the use of these systems [7-9], for modeling of the plant components [10], for capacity control [11], for unbalanced load balancing [11], for thermal efficiency optimization [8] and others. In a review, for the use of heat pumps it was found that about 2 to 4 GW of thermal energy could be obtained [12]. In the case of vertical ground heat exchangers, the main disadvantage is the initial investment for drilling, difficult access to the pipes at depth in case of depreciation or need for repair. It should also be noted that the lifetime of some materials for geothermal heat pumps is up to 35 years [13]. On the other hand, at the horizontal ground heat exchanger (HGHE) by good research and design, only climatic conditions remain difficult to predict and compensate for their negatives [14, 15]. For example, with a small temperature difference to the ground, the size of the heat exchanger will be very large [16, 17] or expensive [18]. Some of the physical complexities of horizontal ground heat exchangers are related to the annual behavior of shallow soil areas, which is affected by temporal climate changes over a year [19, 20].

A key point for shallow-placed systems is that site-specific measurements of soil temperature are required to correctly determine the initial boundary conditions. In study [21], an example temperature map at different depths is presented, in which the variations of ground temperature tend to be independent of the ambient air temperature at depths greater than 5 m. Compilation of such ground temperature maps is possible by mathematical modeling and simulations, but the best option is to measure the temperature of the ground *in situ*, as argued in study [22]. Another disadvantage is the need for a free area exposed to direct sunlight, with an area about 2.5 times larger than that of the

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building to be heated. Statistics show that the typical shading coefficient (SCC) for a tree providing light shade is 0.55, and for a tree providing heavy shade is 0.25 [23].

In study [24] it is estimated that the performance of the horizontal ground heat exchanger at 6 m depth using a tank of 0.6 - 0.9 m in diameter filled with PCM suspended in water is an alternative to the conventional vertical ground heat exchanger. The study of the lithological construction and the calculation of the heat transfer of the ground mass at a given place is of extreme importance for the design and modeling of geothermal installations [25]. The precise results for the coefficient of thermal conductivity and the thermal resistance are also necessary for the introduction of boundary conditions in mathematical modeling and computer simulations. The thermal response test method is suitable for determining the thermal conductivity of soil layers in the presence of a constant temperature source [26, 27].

The purpose of this work is: 1) review and systematization of research on ground heat exchangers with PCM; 2) selection of a depth for measuring the temperature in the ground suitable for a study of ground heat exchangers with participation of PCM; 3) analysis of the results for the measured temperatures for the ground depths of 2 m and 6 m, for the summer period and determination of the thermal conductivity of the researched soil layer.

RESEARCH FOR RENEWABLE THERMAL STORAGE IN THE GROUND MASS, GROUND HEAT EXCHANGER AND PHASES CHANGE MATERIAL

In the technical characteristics of geothermal installations, data on the cooling of the ground mass over time, as well as on heat recovery measures, are rarely provided. In order to ensure that the geothermal system will be a system with renewable energy sources and environmentally friendly, effective and carefully selected measures are needed to recover the heat in the ground mass.

Solutions using excess heat from solar systems are proposed in scientific circles, including geothermal installations with heating of the adjacent soil [27-29]. Trillat-Berdal *et al*. (2006) [30] “injected” excess heat into the ground through a borehole heat exchanger with a propylene glycol carrier and measured the warming of the surrounding ground mass. Experimental data on terrestrial-solar heat storage are also presented by Georgiev *et al.* (2020) [31].

Other researchers propose the use of combined approaches with solar sources and additional elements filled with suitable materials, for example, phases change materials for heat storage [32]. These measures will prevent excessive warming of the land mass and maintain the heat balance for the cooling process on hot days. In [33] Mohanraj *et al*. (2021) present the production of solar pure water due to condensation with the participation of phase change materials and a heat pump.

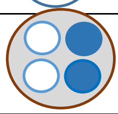
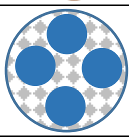
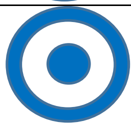
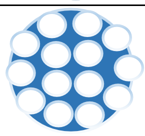
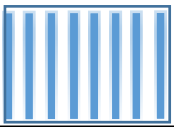
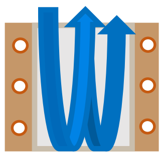
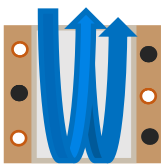
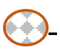
On the other hand, more and more often, mathematical modeling and software simulations are used to generate an effective solution, by optimizing existing technologies or predicting innovations [34]. Such theoretical studies are also performed with modern computer simulation packages for computational hydrodynamics, as computational fluid dynamics (CFD) [35, 36]. The simulation of two-phase flows associated with a phase change is presented in studies [37, 38]. The heat conduction outside the heat exchanger can be represented by the model of a cylindrical source surrounded by a homogeneous medium with constant properties, in this case it is the ground [39-41].

Wang *et al*. (2014) [42] have conducted a numerical simulation of heat transfer for three models with grout and soil. The results show that the ground area can be effectively reduced with phase change materials such as backfill. Increasing the efficiency of heat exchange in the ground, as well as simulating the distance and storage volume of the drilling rigs, are also presented, through the transient system simulation (TRNSYS) program [43].

The thermal energy storage (TES) based on phases change material is one of the effective strategic technologies for balancing the heating flux and cooling flux [44, 45]. Phase change material in ground source heat pump can be used in all elements of installations at heating, at cooling and at power generation [46, 47]. The right PCM types - paraffin wax, non-paraffin organics, hydrated metallic salts [48] will lead to a reduction in the total length of the borehole, which is equivalent to a reduction in the investment cost of setting up the system. For GSHP applications, organic PCM like paraffin is the most common choice [49, 50]. The low-paraffin waxes (L-PW) are presented with a cooling application, but use for ground heat exchange would be suitable to compensate for thermal fluctuations over time [50-53].

The idea for a cylindrical heat exchanger with PCM is presented in [55]. Pardiñas *et al.* (2017) [56] proposed conductive baffles in the tank. In Pagkalos *et al.* (2020) [57] the heat exchanger is immersed in paraffin PCM. The GSHP efficiency is improved due to natural convection of water and additional load capacity provided by PCM in underground thermal battery, as reported in [58]. PCM capsules in storage tank with a solar hot water heating system are placed between heat pump and ground heat exchanger [59]. In Qian *et al*. (2020) [60] specifications of ground heat exchange are as follows: borehole diameter 0.133 m, fluid flow rate 0.732 kg s^{-1}, thermal conductivity of HDPE pipe 0.4 W m^{-1} K^{-1}, soil thermal conductivity 2.96 W m^{-1} K^{-1}, shank space 0.042 m. Some studies investigated PCM as grout, [49, 50]. When PCM is added to the grout of vertical ground heat exchange, the length of the pipes is reduced and the heat pump works more stably and efficiently [61].

Table 1. Position of phases changes material (PCM) in ground heat exchanger (GHE)

Position of PCM in GHE	Summary scheme	Description	References
In the center of the pipe		Double tubes	[61]
Outside of the pipe		Double tubes	[62]
Combinations of pipe		Triple tubes	[63]
		GHE with PCM pipes	[69-71]
Grout and PCM		Grout modified	[43, 45, 57, 59, 67-70]
Underground PCM storage tank		Cylindrical tank as thermal battery	[50]
		Cylindrical tank	[46, 72, 73]
		Panels tank (3m x 5m)	[73]
Soil and PCM		Soil modified with microencapsulated PCM	[74]
Increasing of the thermal conductivity of PCM		Conductive baffles in tank	[47, 63]
		Steel balls encapsulated with paraffin	[29, 50, 64, 75]
 - PCM  - Fluid flow  - Grout  - Grout and PCM  - Soil  - Thermal conductivity			

In Righetti *et al.* (2020) [62] the 70 °C paraffin wax included in three 3D aluminum periodic structures is investigated for purposes of a latent heat storage tank. The paraffin with 20% Cu nanoparticles in the blade shape showed a notable potential to absorb thermal energy from the heat transfer fluid and decrease the outlet water temperature [49]. The soil and PCM backfill with low and high phase change temperature should be used for summer and winter modes [63, 64]. The principal positions of PCM in geothermal installations are given in Table 1.

The researchers of study [65] looked at PCM in the center of the heat exchanger tubes. Other studies were with PSM around the tubes [66]. In study [67] three concentrically arranged tubes are used as the PSM inter layer and were surrounded by the heat transfer tubes.

The filling mass around the pipes, the so-called grout, can also be replaced by PCM or partially modified with PSM [48, 49, 61, 63, 71-74]. Some researchers use tanks with PCM as a separate module to the systems for geothermal installations. These tanks may consist of concentric tubes [49] or be multi-tube in cylindrical tanks [51, 75, 76] and panel type tanks [77]. The surrounding ground mass is also modified with PSM [79]. Some of the researchers try to propose solutions and variations with the participation of additional materials and structural elements to increase the conductivity of the environment [32, 52, 79].

The following important conclusions have been drawn in [80] for the horizontal ground heat exchanger as a flat-panel installed 1–1.5 m under the ground surface: the use of PCM in proximity or coupled directly with the horizontal ground heat exchanger seems to work better than solutions with greater distances or with PCM added to the backfill material. The use of PCM in addition to the flat-panel horizontal ground heat exchanger allows to obtain an improvement in heat pump performance with a consequent energy saving of about 10%. Consequently, a reduction of the horizontal ground heat exchanger field size can be obtained for the same energy consumption. The installation of the PCM has been considered as a thin sheet of material of 5 mm close to the flat-panel heat exchanger, this sheet can be in direct contact with the HGHE, or it can be moved far from heat exchange surface.

Studies have been found showing the horizontal ground heat exchanger to be competitive with the vertical ground heat exchanger if phase change materials are included. The number of works in this direction are few and in most cases without specific studies on the temperature and conductivity of the ground mass.

RESULTS FOR THE MEASURED TEMPERATURES FOR THE GROUND DEPTHS OF 2 M AND 6 M FOR THE SUMMER PERIOD AND DETERMINED THERMAL CONDUCTIVITY OF THE SOIL LAYER

Thermal characteristics can be calculated using the thermal response test method [25, 26]. The thermal conductivity λt of the ground is given by the equation for an interpolated straight line α as the slope *versus* duration Ʈ of α in a plot of the evolution of the temperature T *versus* the logarithm of time:

$$T = \alpha \ln(\tau) + n \quad (1)$$

$$\lambda_t = \frac{Q_{GSR}}{4\,\pi\, H\, \alpha} \quad (2)$$

where T - ground temperature at 2 m depth [°C]; α - an interpolated straight line; τ - duration in 72 h [h]; Q_{GSR} - the average value of global solar radiation (GSR) as heat power [W/m^2 per hour]; H - depth [m]. The purpose of our study is to search for suitable data from measured values of the temperature in a soil layer at a depth of 2 m for the summer period, from which to estimate the thermal conductivity of the soil layer at a depth of 6 m by the thermal response test method. This will allow theoretical calculations to be made by CFD method for a tank full of L-PW waxes at a depth of 2 m, which can be considered as a low-temperature heat source TES [81, 82].

For this purpose, ground temperature measurements were carried out with dataloggers placed at a depth of 2 m and 6 m, with a temperature measurement interval of 1 h, in a private property in the Gorna Banya area, Sofia, Bulgaria. Such an established interval at the depth of 2 m is for the period 27.08 - 16.10.2023, when temperatures were measured from 16.9 °C through 17.3 °C to 16.9 °C, Fig. 1.

The average temperature for this period of 51 days was 17.15 °C. Fig. 1 shows the obtained temperature data for depths of 2 m and 6 m for an interval of 51 days of the summer season, in the Gorna Banya area, Sofia, Bulgaria. For the measured temperature values for 6 m depth, it was calculated that the regression dependence is 0.2618, responsible for thermal conductivity of the soil layer between 2 m and 6 m depth, using the thermal response test method calculated for the period 30.08 - 10.10 2023 in Sofia, Fig. 2.

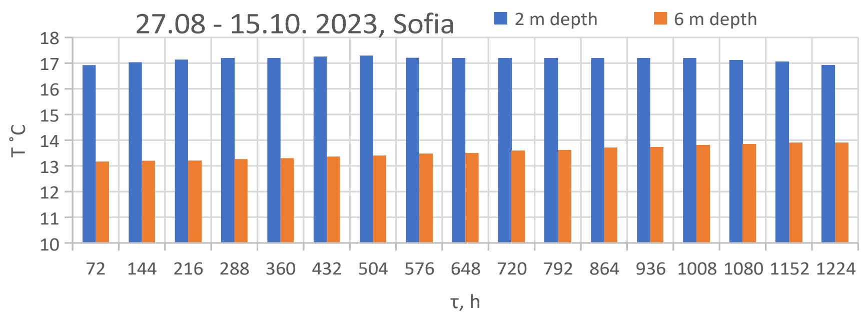


Figure 1. Temperature data obtained from dataloggers placed at depths of 2 m and 6 m for an interval of 51 days during the summer season, in a private property in the Gorna Banya area, Sofia, Bulgaria

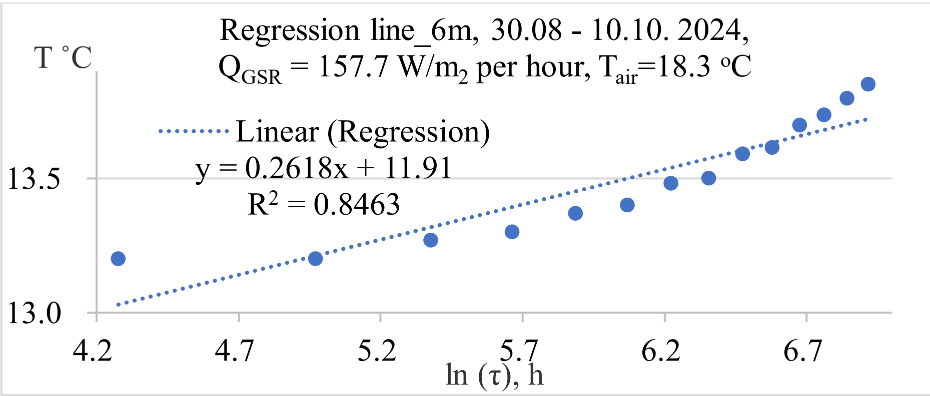


Figure 2. Regression line for 6 m depth by thermal response test method

The average air temperature was 18.3 °C and the average sun ray QGSR was 157.7 W/m^2 per hour [84]. Therefore:

$$\lambda_t = Q_{GSR} / 4 . \pi . H . 0.2618 = 7.99 \text{ W/m K} \quad (3)$$

These data are suitable for conducting CFD simulations as the obtained temperature variation data can be entered as input data for the thermal energy accumulator playing the role of a low-temperature permanent source based on phase change material as L-PW waxes and make predictions for charging the ground layers with heat power at a depth of 6 m.

CONCLUSIONS

The heat balance in geothermal energy is a key to the long-term use of this so-called renewable energy source. The main disadvantage of geothermal installations is that the ground cools over time and needs compensation for heat losses from other renewable sources. The literature review points to thermal storage as a solution to temperature fluctuations in GSHP and the different location of PCM in ground heat exchangers is illustrated.

The study shows that horizontal ground heat exchangers with PCM are competitive with vertical ground heat exchangers. A disadvantage of horizontally located heat exchangers in the ground mass is that the area above them cannot be used for agricultural purposes, and the shallow placement of the horizontal pipes leads to frequent temperature fluctuations.

Applications of phase change materials in geothermal systems are relatively new ideas and not well studied. The small number of studies testified to the lack of information on horizontal heat exchangers with PCM and provided the basis for starting a project "Research on the optimization of geothermal installations, including phase change modules as a renewable source of thermal energy by computational methods of fluid dynamics".

For the purpose of the project the temperature in the ground mass at a depth of 2 m and 6 m for the summer period was measured. From the obtained data, the temperature conductivity of the specific place for a depth of 6 m was determined, as well as the boundary conditions were specified for the CFD simulation of a reservoir with L-PW waxes proposed as a heat accumulator, temperature compensation and low-temperature heat source placed at a depth of more than 2 m.

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