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Design and Simulation of a Portable Apparatus for in-situ Thermal Response Test (TRT)

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Abstract **–** Energy consumption for air conditioning structures is quite significant, particularly in hot (or cold) dominated climates. Ground source heat pumps (GSHP) represent a clean technology that relies on stable shallow geothermal energy for air conditioning. Geothermal energy is renewable and reliable with no carbon emissions. A full analysis of the ground thermal characteristics of the targeted site is required to assess the feasibility of the GSHP system. The study focuses on modeling and constructing a portable, small-scale thermal response test that can be used to obtain in-situ ground data, essential for the GSHP system design. The parameters extracted will be obtained through numerical simulations and verified experimentally. The parameters obtained from the numerical simulations (namely the undisturbed ground temperature, ground thermal conductivity, and borehole thermal resistivity) are to be verified experimentally in a later study. The experimentation, which involved simulating the use of the TRT device for seven days, showed that a greater flow rate led to a higher mean fluid temperature and that lower flow rates resulted in a greater temperature difference between the outlet and inlet. However, the actual values of the soil parameters are yet to be measured experimentally using this TRT device. Instead, they were adapted from literature and used in the simulations. The obtained results provide a robust foundation for running the experiment once the TRT device is connected to a Borehole Heat Exchanger (BHE).

Keywords**:** Ground-source heat pump, Thermal Response Test, Geothermal energy, Borehole Heat Exchanger

1. Introduction

Ground source heat pump system (GSHP) represents a sustainable and energy-efficient alternative for heating and cooling buildings [1-2]. However, this alternative has not been fully exploited in the UAE region. The feasibility of GSHP system highly depends on the ground's thermal characteristics and the surrounding climate [3]. The primary objective of this project is to model and construct a thermal response testing (TRT) apparatus that can be used to measure the ground's thermal characteristic parameters to facilitate the design of a GSHP. Shallow geothermal systems are widely applied globally [4] with remarkable examples of high efficiency and return on investment (e.g., Zurich Airport Terminal E [5]). In addition, the usage of energy piles [6-11] and geostructures [12-14] has gained significant traction in recent years. However, limited applications have been recorded in hot climates and particularly in the Arab countries in the middle east (which is amongst the hottest and most humid regions). Accordingly, more experimentation and implementation are required to evaluate the system's suitability in these climates.

GSHP systems must be designed in accordance with the site's soil properties, which may be highly variable, affecting the system's performance. An in-situ thermal response test TRT device is utilized to obtain the underground thermal properties [15]. This test measures the ground's undisturbed temperature, the ground's thermal conductivity, and the thermal resistance of the borehole [16]. Numerous TRT construction models have been thoroughly documented in the literature, and a few examples are discussed below. At Lulea Technical University and Oklahoma State University, mobile TRT models (TED) were constructed utilizing an electric resistance heater to apply a step heat pulse to the ground, for the purpose of determining the thermal characteristics of the ground at depths ranging from a few meters to over 100 meters below the surface [17]. These models were employed in a variety of studies and tests, which have revealed that convective heat transfer significantly impacts the thermal behavior of groundwater filled BHEs, the most common BHE design in Sweden [18]. In the Netherlands, a different TRT model was developed using a heat pump, as opposed to electric resistance heaters, in order to decrease the temperature inside the BHE [17]. Likewise, Mattsson *et al.* [19] constructed a compact and portable TRT device using a similar approach, which has proven to be highly practical for in-situ testing. Present-day knowledge and expertise have greatly improved the accuracy and dependability of the TRT test findings [20]. This study herein employs the approach presented by Mattsson *et al*. [19] to replicate a portable TRT model suitable for use in the United Arab Emirates.

2. Materials and Methods

2.1. Project requirements

The objective of designing and manufacturing the TRT device is to connect it to an in-situ borehole heat exchanger, which will be located at a specific site in Dubai. Table 1 below presents the characteristics of this system, including the borehole and tube properties.

Table 1: Borehole heat exchanger characteristics.

Description	**Characteristic**
Borehole depth	25 m
Tube material	Polyethylene
Tube type	Single-U
External tube diameter	32 mm
Tube thickness	2.9 mm
Fill material	Concrete + Bentonite Clay
Heat exchanger fluid	Water
Average flow rate	20 L/min
Average velocity (according to flow rate)	0.618 m/s
Power level	1.25 kW

2.2. Operating principles

The TRT device described here employs a mechatronic mechanism, comprising of mechanical, electronic, and computer sub-sections, along with components that facilitate communication between the device and the user. The system's functioning has been schematically mapped out, as depicted in Figure 1, and a block diagram has been created (Figure 2) that illustrates the interconnection between system components.

The micro-controller regulates the relay's opening and closing based on temperature, pressure, and flow rate values measured by the sensors, in line with user and design requirements. The desired specifications are provided via the Graphical User Interface (GUI) along with the system's programming code that compares it with the sensed data. The pressure and temperature sensors, as well as the flow meter, work in a feedback loop to maintain the desired operation. All sensors require a minimum voltage of 5 V, while the heater and two pumps need a high-level power supply of 220 V. The microcontroller records the results in a data logger (micro-SD card module), which the user can access as needed. The energy counter records the electrical energy consumed by the heater. After heating by the heater, the fluid is injected into the BHE for circulation through the pipes. Upon exiting the BHE, the volume flow rate is measured by the flow meter and the fluid passes through the circulation pump. The flow regulator manages the flow rate of the water, and an expansion vessel allows for the volume expansion of water due to its temperature increase.

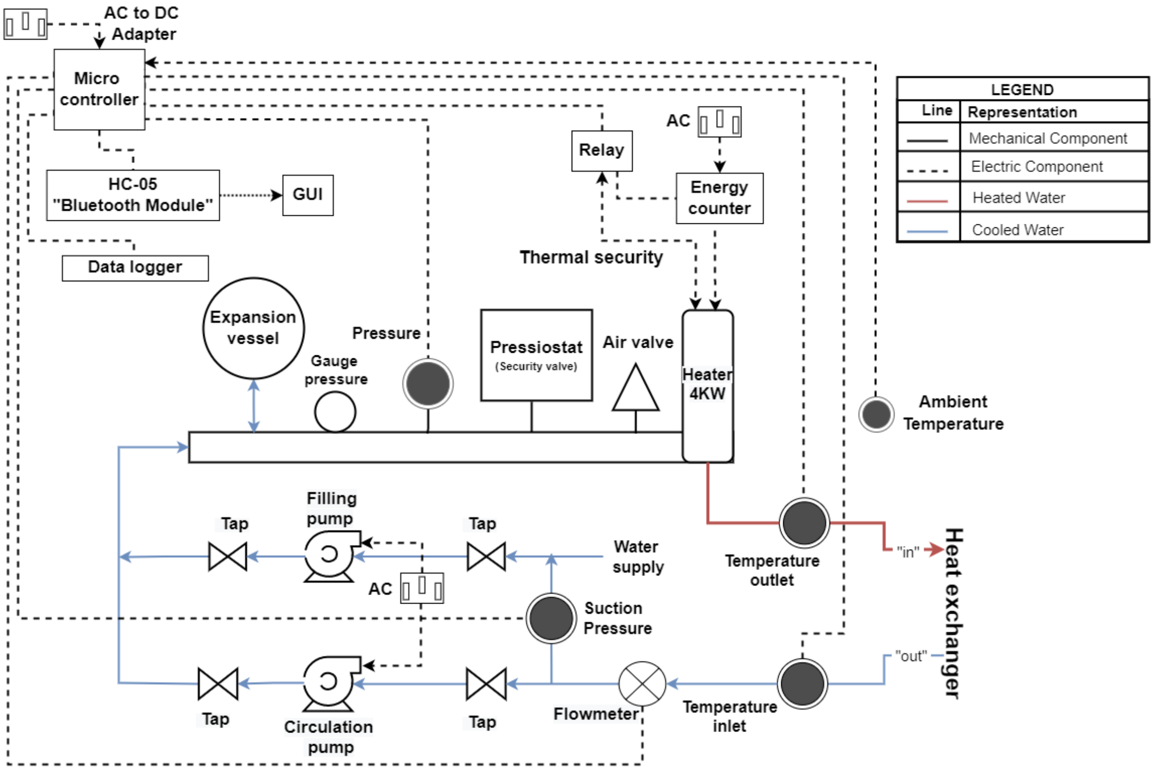

Figure 1: 2D CAD representation of the TRT System (adapted from Mattsson *et al.* [19]).

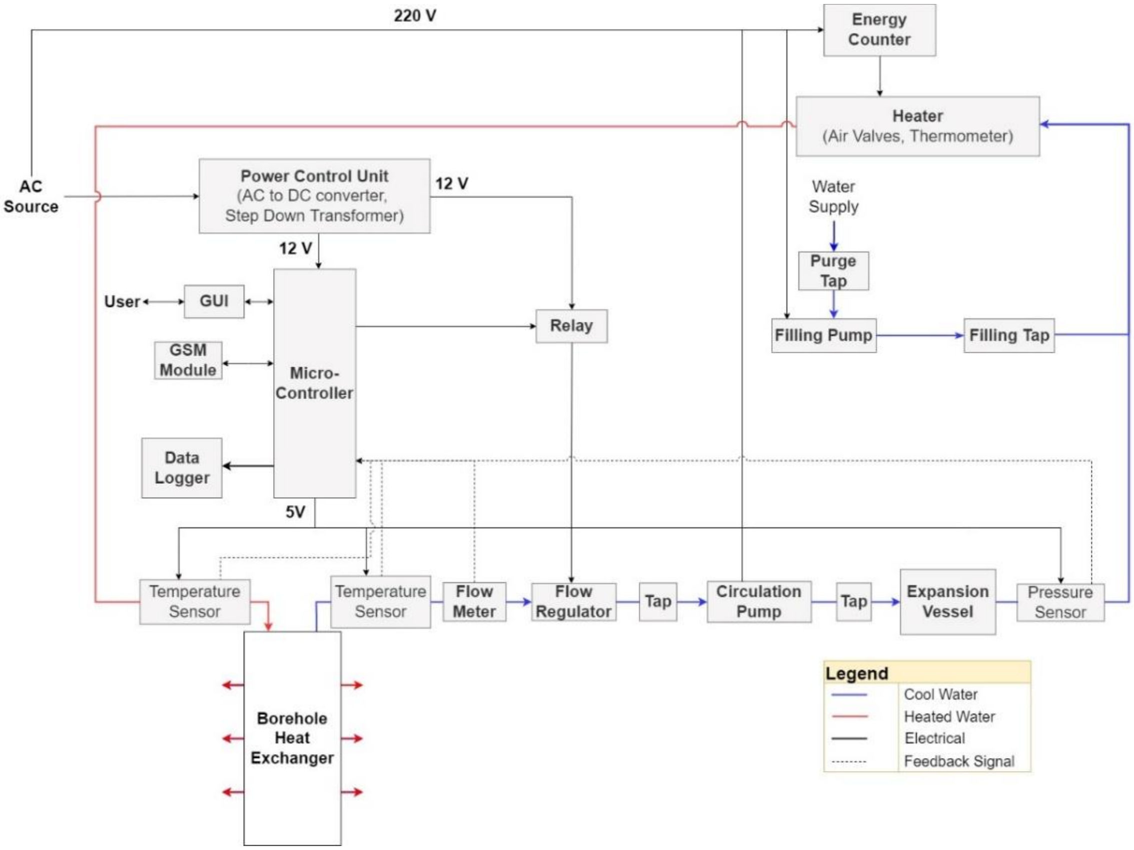

Figure 2: Block diagram of the TRT system.

2.3. Mechanical system

A practical design approach was followed; since the device must be portable it was attached to the base of a foldable platform trolley. The expansion vessel and circulation pump were fitted together according to flow rate range. Other constraints that were taken into consideration during the design process were the fitting diameters, as well as the maximum and minimum working conditions of each component, in terms of operating temperature and pressure. Multiple iterations were attempted before reaching the final design as shown in Figure 3 below.

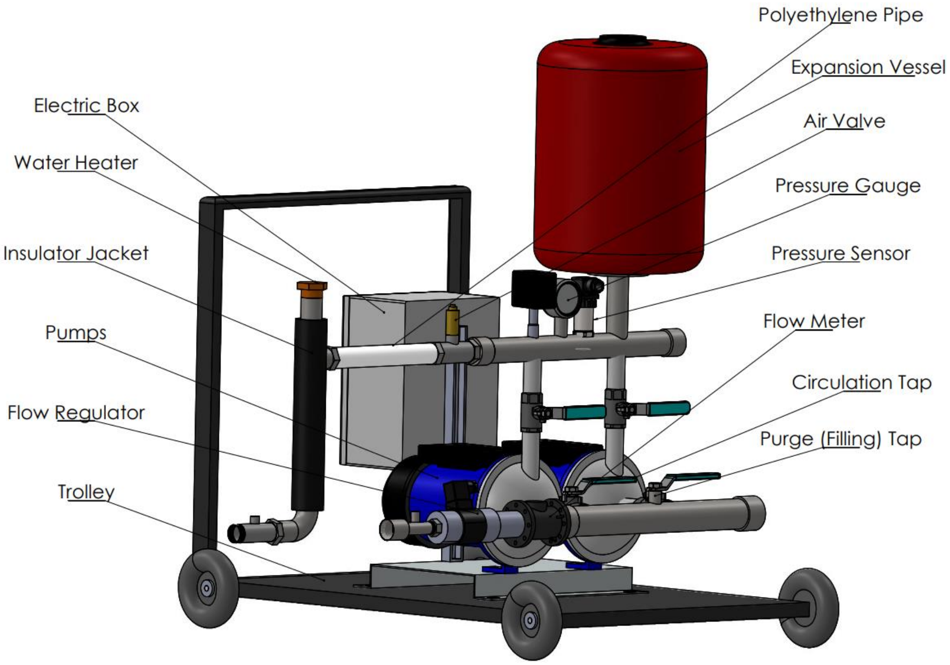

Figure 3: 3D CAD model of the TRT Device.

2.4. Electrical and control system

All electronic components are connected to a single micro-controller. MEGA Arduino was chosen because it has more pins for the connections. As depicted in the Fig. 4, two pressure sensors and two thermocouples are used in the system to measure the pressure and temperature of the fluid entering and exiting the testing apparatus, respectively. Additionally, to measure the flow rate, a flow meter is employed. In order to measure the ambient temperature, a DHT22 sensor is added.

To record the measured data, a micro-SD Card module, in conjunction with a micro-SD card was utilized. To get the real time when the sensed data is received/logged, an RTC Module is used. The HC-05 Bluetooth Module is employed to send sensed data from the microcontroller to the GUI. Lastly, the heater is connected to the energy counter which will be used to measure the amount of thermal energy that is injected to the borehole. There is a relay which is used to control the heat supplied by the heater to ensure that the supplied temperature from the apparatus is always between a specified temperature range of 40-42°C.

3. Methodology

3.1 Theoretical background

The equation to be solved to obtain the mean fluid temperature is based on the infinite line-source model that assumes the BHE as a line of infinite length, in which heat is dissipated from the BHE line in a constant radial manner via an infinite homogenous medium [19]. Following that assumption, the mean fluid temperature is derived from the solution of the one-dimensional heat conduction equation in radial direction. As mentioned earlier, the soil in which the U-Tube will be placed in the created borehole is considered to be homogenous and isotropic [19]. The transient heat conduction equation is presented in equation 1.

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \nabla^2 T \tag{1}$$

where T is temperature (K), t is time (s), and α is thermal diffusivity (m^2/s) of the medium through which conduction is happening, defined by equation 2.

$$\alpha = \frac{\lambda}{\rho c_m} \tag{2}$$

where λ is the thermal conductivity (W/m.K), ρ is density (kg/m^3), and c_m is the mass specific heat capacity (J/kg.K).). The rate at which heat is propagated within the medium is dependent on the heat diffusivity, in the sense that a higher value of α will lead to faster propagation [19]. When the heat conduction process reaches steady state, temperature will no longer vary with time. The decrease in storage coefficient, ρc_m, will strengthen the influence of the steady state condition [19]. The relationship between the heat flow and the temperature gradient within the material of conduction is determined by Fourier's law of conduction:

$$\boldsymbol{q} = -\lambda \nabla T \tag{3}$$

where q (W/m^2) is the heat flow vector of the solid material and ∇T is the temperature gradient. The most important factor when designing a Ground-Coupled Heat Pump (GCHP) system is the thermal conductivity (λ). It is a property that depends on the soil's "density, temperature, particle shape, porosity, moisture content and mineral composition" [19]. As such, the effective thermal conductivity of a particular soil is extremely difficult to predict without performing an in-situ thermal response test. The GCHP system design is also heavily dependent on the thermal resistance, R_b, between the exterior of the borehole wall and the heat carrier fluid (Esen & Inalli, 2009). Thermal resistance is contingent upon the borehole arrangement, the materials used, and their thermal properties and as a result, can be engineered to a certain degree. The actual value of R_b, like λ, can be accurately determined via the in-situ TRT. Thus, λ and R_b cannot be directly measured but instead inferred from the measurements recorded during the test. Having adopted the line source model in a homogenous medium, a solution for the time evolution of the mean fluid temperature was developed [19] as follows,

$$T_r(t) - T_o = \frac{q_c}{4\pi\lambda}\left(\ln\left(\frac{4\alpha t}{r_b^2}\right) - \gamma\right) + q_c R_b = \frac{q_c}{4\pi\lambda}\ln(t) + q_c\left(R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma\right)\right) \tag{4}$$

where T_o is the undisturbed ground temperature (K), derived at the start of the test by circulating the fluid before the heating is switched on, and then measuring the temperature. q_c is the constant heat rejection rate used for the test (W/m), t is the period over which heat is injected (s), r_b is the borehole radius (m), and γ is Euler's constant. As the mean fluid temperature evolution is logarithmic, by plotting the mean fluid temperature against ln(t), the ground thermal conductivity can be calculated using the slope of the line, k [19]:

$$\lambda = \frac{q_c}{4\pi k} \tag{5}$$

Once the value of λ for the soil is known, R_b can then be assessed using equation 4.

3.2. Simulation parameters

Since the proposed site for TRT testing is situated in Dubai, the undisturbed ground temperature is assumed to be 27°C (to be verified later by in-situ tests). q_c, the heat injection rate, in equation 4, is calculated from P/H where P is power level, and H is the depth of the borehole. The H is adjusted in accordance with the 4 flow rates incrementing from 20 L/min to 120 L/min, in order to analyze how flow is affected by the range of pump's flow rates. λ is taken as the estimated thermal conductivity of the experiment performed by Mattsson *et al.* [19] and R_b is also taken as the estimated thermal resistance of the same experiment. The storage medium ρc_m used to obtain α, is calculated using ρc_v, deriving their values from the properties of water, used as the energy carrier. All the values involved in the calculation of the mean fluid temperature are shown in Table 2. The mean fluid temperature is calculated over 7 days, which is the typical duration for running TRT.

Table 2: System parameters and assumptions.

Description	Symbol	Type	Value
Borehole radius	r_b	Design requirement	75 mm
Heat exchanger depth	H	Design requirement	23 m
Ground thermal diffusivity	α	Derived from another assumption	4.905×10^{-5} m^2/s
Ground thermal conductivity	λ	Assumption (to be verified experimentally)	2.06 W/mK
Density of water	ρ	Standard measurement	1000 kg/m^3
Mass specific heat capacity of water	c_m	Standard measurement	4200 J/kgK
Undisturbed ground temperature	T_o	Assumption (for Dubai)	300 K
Heat injection rate	q_c	Design Requirement	50 W/m
Borehole Thermal Resistance	R_b	Assumption (to be verified experimentally)	0.069 K/Wm
Euler's constant	γ	Known constant	0.5772
Time duration	t	Design requirement (7 days)	168 hours

3.3. Fluid governing equations

Computational Fluid Dynamics is used to model and analyze the flow of liquid water inside a single U-tube based on the input from one-dimensional line-source model. The inlet of the tube is modelled as velocity inlet. The tube walls are assumed to be isothermal at the undisturbed ground temperature of 300 K. Liquid inlet temperature is varied according to the running time of TRT, and the outlet temperature is obtained under steady-state condition and compared against the mean fluid temperature computed from equation 4. Ansys Fluent 2022 R1 is utilized to solve the system of fluid equations, namely, continuity, momentum, energy and two turbulence equations (k-ε turbulence model), under steady-state condition for an incompressible and Newtonian fluid.

4. Results and discussion

The results of the theoretical calculations are depicted in Figure 4 (left), which shows that the mean fluid temperature increased from 300 K to 312 K over a period of 7 days at a flow rate of 20 L/min, and higher flow rates led to higher final mean fluid temperatures. At a flow rate of 120 L/min, the final mean fluid temperature was around 332 K. It should be noted that the soil parameters used in the simulations were obtained from literature, as they have not yet been experimentally measured using this TRT device. The mean temperature difference between the inlet and outlet at the end of the 7-day running time is shown in Figure 4 (right). According to the conservation of energy law ($\dot{Q} = \dot{m} c_p \Delta T$), for the same rate of heat injection, the temperature difference will decrease as the mass flow rate increases, given that c_p remains constant, which is consistent with the observed results. Furthermore, it can be seen in the results shown in Figure 5 (half of the domain is modeled due to symmetry about the mid-plane), from 3D CFD simulations under steady-state process, that the temperature contour of the fluid flow behaved as expected. The temperature on the inlet is higher than the outlet because the temperature will keep decreasing as the water flows through the u-tube that is being cooled by the surrounding maintained at a lower temperature of 300 K (undisturbed ground temperature). The heat diffusion from the water pipes to the borehole can also be observed in Figure 5.

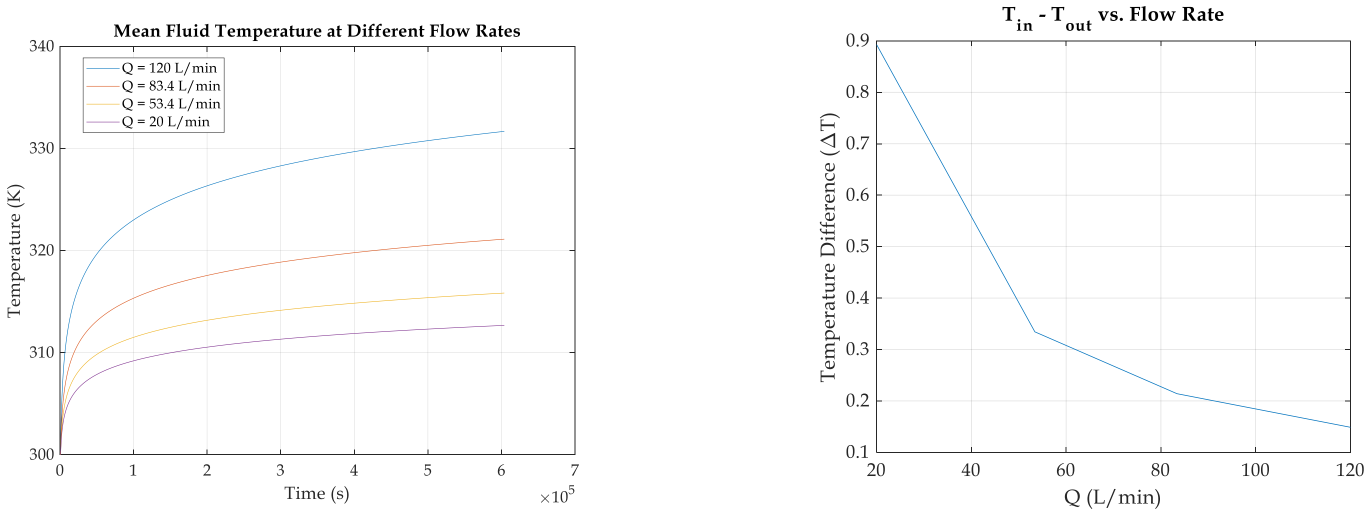

Figure 4: Mean fluid temperature over time for different flow rates (left), temperature difference at different flow rates (right).

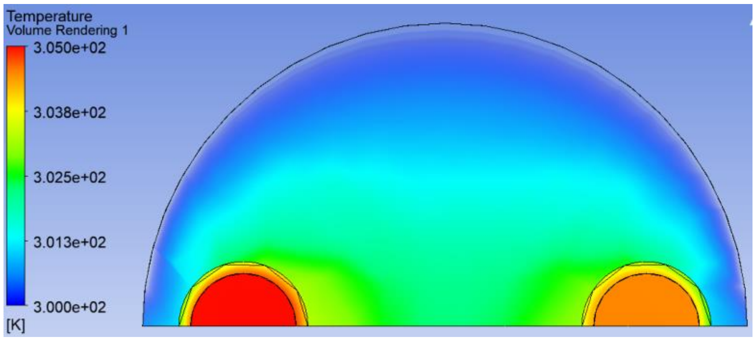

Figure 5: Temperature contour (top view of the borehole) at mean fluid inlet temperature of 305 K, obtained from 3D simulations.

The steady-state simulations with 2D and 3D CFD models are repeated for three inlet temperatures of 305, 310, and 315 K, for the same flow rate of 20 L/min, and the mean exit temperatures are compared with the theoretical values obtained from one-dimensional line-source model in order to validate the numerical simulations. According to Table 3, for the outlet temperature, the average difference between theoretical and numerical values are 0.60% and 0.13% for 2D and 3D models, respectively. Therefore, both CFD models are very reliable to simulate the heat rejection process in the borehole heat exchanger. The 2D model is computationally less demanding, thus, it can be utilized for initial design of the borehole parameters. The 3D model which is computationally more demanding is more flexible and it can be used for analyzing 3D effects, that cannot be modeled with a 2D planar geometry. For instance, modeling non-homogeneous properties of the borehole filling material or a case when the outer surface of the borehole is subjected to non-uniform convection heat transfer due to groundwater flow.

Table 3: Comparison between theoretical values (1D line-source model) and 2D /3D CFD simulations (for flow rate of 20 L/min).

Mean fluid inlet temperature (T_{in})	**Mean fluid outlet temperature (T_{out})**		
	Theoretical	*CFD 2D Model*	*CFD 3D Model*
305 K	304.10 K	304.97 K (error = 0.29%)	304.47 K (error = 0.12%)
310 K	309.11 K	306.82 K (error = 0.74%)	308.94 K (error = 0.055%)
315 K	314.11 K	311.72 K (error = 0.76%)	313.40 K (error = 0.23%)

5. Conclusion

This project aims to contribute to providing sustainable energy solutions for the UAE and beyond, and this phase represents a critical step in achieving that goal. The study presented herein demonstrated the construction and modelling of an in-situ portable thermal response testing device for use in the UAE. This device enables the determination of ground thermal conductivity and borehole thermal resistance, two critical parameters required for the construction of a borehole heat exchanger (BHE) for providing cooling/heating water to consumers. Our specific design approach focused on using a mechatronic system consisting of mechanical, electronic, and computer sub-sections with feedback loops and sensors to regulate the opening and closing of the relays, satisfying the user and design requirements, in addition to recording data for extended period of time with no or minimal user intervention.

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