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Experimental validation of the enhanced thermal efficiency of advanced materials in geothermal borehole heat exchangers (BHEs)

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In the current climate emergency, the use of renewable energies, such as Shallow Geothermal Energy, is now becoming essential. The use of this energy has a not insignificant economic cost that becomes a disincentive for their implementation. The main objective of the GEOCOND project of the European Commission H2020 programme is to promote the use of shallow geothermal energy systems. Among the developments of GEOCOND are new grout and pipes materials with enhanced thermal conductivity that reduce the implementation costs (CAPEX) of geothermal installations. In this article, we present the results obtained from these developments in an experimental facility that validates the thermal behavior of geothermal heat exchangers accurately. In particular, the results of the Thermal Response Test (TRT) carried out on borehole heat exchangers (BHE) in which the new grout and pipe materials developed in the project. These TRT are compared between them and with those obtained with other BHEs that have used standard materials on the market.

Keywords: Shallow geothermal energy, borehole heat exchangers, new materials, Plastic Pipes, Grouting Material, Increased Efficiency, Cost Saving. Multi

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INTRODUCTION

The current climate emergency is a fact that cannot be denied, and it is closely related with the patterns the way energy is managed. Inefficient use of energy or the use of non-renewable energy are among the elements that aggravate this problem. Thus, a way to fight the climate emergency is develop systems that can take profit of renewable energy and use the energy more efficiently.

Shallow Geothermal Energy is a renewable energy that could be used for climate change mitigation and for energy savings. The use of this energy is not new, e.g. houses-cave of Paterna city in Spain [1], but it is from 1945 [2] that the combination of Heat Pumps (HP) and Borehole Heat Exchangers (BHE) made the Shallow Geothermal Energy a real alternative to other forms of energy when talking about the heating and cooling requirements of buildings.

System taking profit of this energy can be installed in any kind of soil since it does not have geological requirements for its operation. The main function of shallow geothermal energy is to be the heat source/sink in a heat pump system , building up a Ground Source Heat Pump (GSHP) system.

As any other systems, the total cost of a GSHP can be divided in installation and exploitation costs. The main drawback of GSHP systems is the elevate installation cost of BHE, which it is proportional to the total length of BHE. The more efficient the BHE, the lesser length is needed for the same requirements; so the search for more efficient BHE is an always-ongoing research activity.

The GEOCOND[3] project is framed in this context: to develop and test new materials that improve the efficiency of the BHE, reducing the cost of installation of the GSHP and facilitating the deployment of this type of system.

From all the elements of the installation of a BHE, the GEOCOND project focused in grouting and pipes. Preliminary studies where used to define the limits and ranges of the main characteristics of those BHE materials in order to find the sweet point between material cost and BHE efficiency. Part of these studies has been published in [4].

The developed materials has been passed internal laboratory tests that has been checked its thermal, mechanical and chemical properties until the desired parameters has been achieved within economical and legislations limits.

Before introducing the materials in the market, it is necessary to check it in an environment as close as possible to real production GSHP. This can be done performing Thermal Response Test on new BHE made with the new materials.

Our research group at the Universidad Politècnica de València has a facility designed to study the operation of BHE [5]. Taking profit of this installation, several BHE has been constructed using GEOCOND new materials and then connected to the facility.

This paper presents the results of TRT tests performed in two of this GEOCOND BHE, and compare it with the results on previous installed BHE, that use standard materials. These tests will confirm whether or not the laboratory measured performance of the new materials corresponds to their performance in an installation so similar to the end use. If the results obtained are positive, they can be used to justify the use of the new materials in real installations. The paper is organized as follows. After this introduction, a description of the Shallow Geothermal Laboratory is given, with a more detailed description of the new installed BHE. With the physical elements already described, the methodology used to conduct the tests is depicted and then results of the different experiments are discussed. Finally, our conclusions about these new materials is given and a line of future works and experiments is presented.

DESCRIPTION OF THE LABORATORY AND BHE

1. Shallow Geothermal Laboratory and BHE location.

The Sallow Geothermal Laboratory was designed and built as part of the CHEAPS-GSHPs project [6]. It is located in Valencia, Spain, at the campus of the Universitat Politècnica de València (UPV). The main components of the installation were: a total of 4 different BHEs, a hot-water storage (500 l), a 3 way valve, a water-air heat pump (inverter type), two expansion tanks, one per circuit, a circulating pump, and many sensor elements (temperature sensors, pressure switches and flow meters). A detailed description can be found in [5].

The GEOCOND project includes the increase of the number of BHE installed in this facility. A total of seven new boreholes are installed, two of them with the solely purpose of testing the developed materials for pipes and grouting.

Fig 1 shows the BHE distribution on the field and, inside the shaded circle, the location where the new BHE will be installed. This implies around 25m pipe length from control cabinet to the BHE head. This length is a challenge to control system.

In any case, the 20-25 meters between the BHE to compare were considered small enough to suppose the same ground characteristics and consistent with samples from CHEAPS-GSHP BHE installation and the opinion of local drillers.

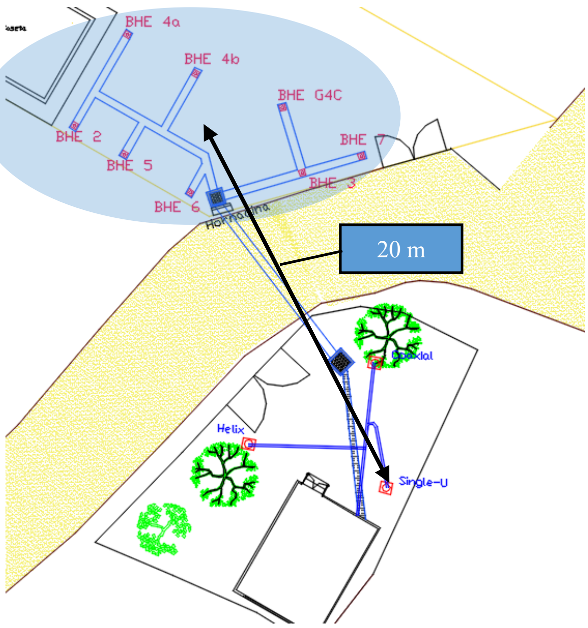

Fig.1. BHE distribution in the field

2. BHEs properties.

The three BHE studied in the present work are BHE3, BH5 and Single-U. The last one was installed as part of CHEAPS-GSHP project as a reference implementation for a BHE and, therefore, standard materials were used.

BHE3 and BHE5 were installed in October 2020 using a mix of standard and improved GEOCOND materials (see Table 1)

Table 1. BHE properties

	Grouting	Pipe	Depth	Diameter
Single-U	Standard	PE-100	14.6 m	126 mm
BHE 5	Improved	PE-100	11.4 m	140 mm
BHE 3	Improved	Improved	12 m	140 mm

As the BHE are part of an experimental facility, it was considered not necessary to go to a depth around 100 m. The initial decision was going to a total depth of around 20 m, deep enough for checking their properties and compare it. But, problems with gravels during the drilling phase made it impossible to reach that depth, getting the total length showed in Table1.

The drilling problems also makes necessary the installation of casing in all the GEOCOND BHE, with an internal casing diameter of 140mm. One the casing was installed, single-u pipes were inserted and grouted with an improve missing developed in GEOCOND project.

After the installation finished (first weeks in November) the sensing and plumbing works were initiated and some preliminary test initiated: pressure losses, avoiding leakage, etc.

METHODOLOGY

A BHE installation can be described by two main parameters: the borehole thermal resistance (R_b) and the ground thermal conductivity (λ). The usual way of determining these two values is performing a Thermal Response Test [7][8]. The UPV teams has a long experience with this kinds of tests and the related BHE models [9]–[12].

The methodology used in the Shallow Geothermal Laboratory is in continuous evolution, trying to improve it in each iteration but keeping its fundamental principles in order to be able to make comparisons between the results of different experiments.

By the time the experiments described were performed, the methodology follows three phases or stages: i) check the initial status of the ground, ii) perform a constant thermal power injection TRT and iii) let the ground recover its normal status as no TRT were performed.

Obviously, there is an initial point where all the experiment starts: the circuit is filled with water and put to a working pressure above 1 bar to detect any leakage or problem, then the circulating pump goes to full throttle to eliminate any air in the water circuit for a couple of hours. After this initial test is passed, we can go on to the first stage of the test.

1. First Stage: Undisturbed ground and T_0.

There is a third element in a TRT that has a high impact on the final results: the undisturbed ground temperature (T_0). There are several measuring methodologies to get this value. Our approach for determining the T_0 is mix of two methodologies.

The first procedure also serves to check if there is something wrong related with the underground temperature, e.g., there is still present residual heat from previous TRT in the same or near BHEs.

After the pressure check, the circulating pump is turned off for a period of 10-12 hours. After this delay, we supposed that water inside the BHE has reached a thermal equilibrium between the ground and the pipe. Then, we log the temperature at the outlet of the borehole every second, with a low flow rate (1 m^3/ h), what means a water velocity of 0.5 m/s[1]. Therefore, each second recorded means a distance of about 50 centimetres. In this way, we can obtain the temperature versus distance/depth.

This temperature vs. displacement profile reflects the surrounding ground temperature status, so we can check if it is correct the assumption that it is an undisturbed ground and calculate a first candidate for T_0

After the profile is obtained, the circuit is put in recirculating mode, i.e., the circulating pump is activated and a control systems tries to maintain the flow equal to a reference. There is no heat source connected to the system, except for the energy transferred by the circuit pipes and the recirculation pump.

The experiment log is started in this moment, recording temperatures (inlet, outlet, control, ambient, etc.), water flows, pressures and internal information related to control system.

Although outlet temperature is highly affected by environment temperature, is is widely used to get a candidate for T_0 value.

2. Second Stage: Constant thermal injection

In the second stage, a predictive controller algorithm regulates the openness of the three-way valve to assure the minimum difference between injected and reference power. The real thermal power is measured just at inlet/outlet of the borehole, therefore very precise and clean thermal

Table 2. Thermal Response Test parameters

BHE	Borehole diameter [mm]		Injected thermal power [W/m]		Flow (l/h)	Reynolds	ΔT
	External	Internal	Ratio [W/m]	Total[W]			
Ref	32	26	**80**	1168	250	**3091**	**4**
5	32	26.2	**80**	912	250	**3068**	**3.1**
3	32	26.2	**80**	960	250	**3068**	**3.3**

[1] In case of a Single-U 32/26 borehole

tests are performed, resulting in high accurate later analysis.

The parameters of the thermal test are specified in Table 2. The assumptions for this parameter election were:

- Reynolds number has to be high enough to be in a forced turbulent flow (≈ 3000)
- Same Reynolds number for all the test.
- Same value of thermal power injected per length unit (W/m)
- $\Delta \boldsymbol{T}$ has to be high enough (>1º) to reduce errors due to measuring elements and control system actuators.

As the three BHE pipe dimensions are very similar, the decision for the flow was easy: 250 liters per hour, value that assure to be in turbulent regime.

For the power injection, the 80 W/m is a compromise value that we use as a standard [5], [11], [13], [14].

RESULTS AND DISCUSSION

The results are presented in the same order that they will be obtained from a single experiment. That is, first the data for selecting a candidate for undisturbed underground temperature, then a preliminary analysis of raw data or with minimum modifications. Finally, an identification algorithm is executed over the raw data in order to obtain the R_b and λ values. Once a set of data is depicted, it is also discussed in the context of this paper.

The first stage of the experiment is the process to select an undisturbed ground temperature. This process is quite complicated in a real TRT because the engineer do not have buried sensors at different depths.

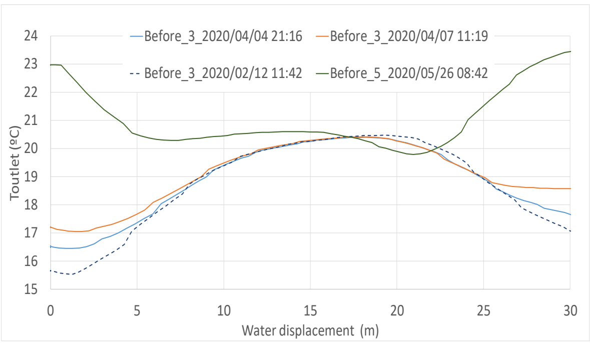

Fig.2. Underground temperature profile

After applying the process described in methodology, we get the temperature profiles in Fig. 2. The water displacement is calculated from the internal pipe section and the flow and time measured. As we can see, the closer the surface, the more variability in the measures, i.e., more influence of external temperature and climatological conditions (month, sunny or not, hour of day, etc.)

The problem with this method is that any problem during its setup make the collect data not useful. This happens with the Single-U test and BHE5 test performed in February.

In any case, we can see from Fig.2 that the underground temperature for BHE3 was between 19º C and 20ºC in February, but also in April thanks to a colder than usual spring in Valencia region. By contrast, the profile of BHE5 in may shows an undeniable rise to value over 20ºC for all depths.

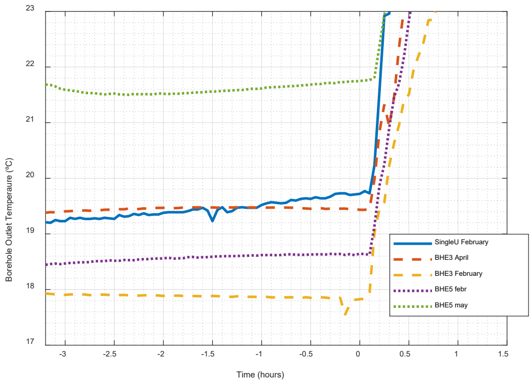

Fig.3. Recirculating outlet temperatures values

We can compare these values with the temperature measured in the outlet of the BHE during the recirculating phase (see Fig. 3).

Here we can see a difference of less than 1.5 ºC between the four TRT performed from February to April, difference that can be imputed to tha climatological conditions affecting the more than 25m of pipes.

The test performed in May, when the ambient temperature in Valencia region returns to its normal values, shows an increase of more than 2ºC from the test in April and more than 3ºC from the test in February. These values are quite different from those extracted from the temperature profile showed in Fig. 2

Table 3. Undisturbed temperatures

BHE	Exp. Name	T_0
Single-U	single-u	19.5
BHE 3	BHE3 February	18
BHE 3	BHE3 April	19.5
BHE 5	BHE5 febr	18.5
BHE 5	BHE5 may	20.5

The TRT main objective is to maintain the power injection stable at a reference value, in our experiments the value is 80W/m. In Fig 4. We can see that this objective is almost accomplished. In any non-controlled environment test, there are noise input that can mess up an experiment, more if it is evident some kind of pattern in the error.

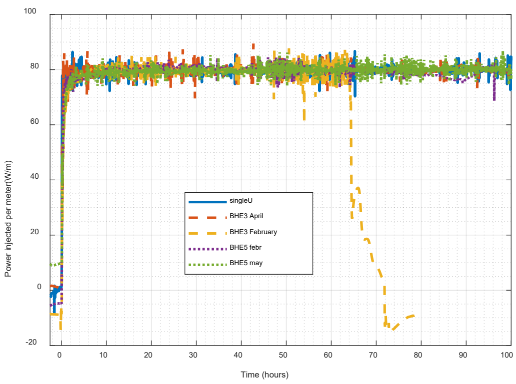

Fig.4. Power injected per unit length

The main source of error in TRT is the air temperature that follows an easily recognizable 24-hour pattern, pattern that is not observed in our experiments. In any case, we considered that "BHE5 febr" presents variations that could be due to a bad pre-set of the experimental environment and this made us to eliminate it from the last part of this study.

The length of a TRT experiment is also important, and the bibliography suggest a minimum of 72 h to declare it a valid TRT. The experiment "BHE3 February" clearly do not fulfil this condition and was removed from the last part of the study.

Once the quality of the TRT process has been analysed, we can proceed with the check if the three boreholes had any difference in their responses.

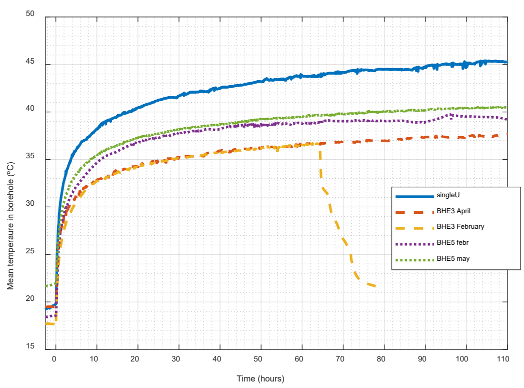

Fig.5. T_{mean} for the 5 experiments

Before the numerical analysis, Fig. 5 show the mean temperature in the BHEs for the five experiments. In this figure we can see that there are three different responses, the same number of boreholes, i.e., the same borehole had a similar response to the same test done in different dates.

The differences in this figure correspond to what was expected in GEOCOND project: the BHE with more improved materials reach a lower temperature(see Table 1).

The final part of the results is the numerical analysis of the data in order to get the R_b of each of the boreholes.

We will suppose that the λ will be the same for the three BHE because the distance between them is only 25 meters. In previous works[5] we found for Single-U that the soil thermal conductivity is in the range 2.1 to 2.5$Wm^{-1}K^{-1}$ and the R_b. from 0.16 to 0.20 mKW^{-1}. For the new experiments, Table 4 shows the parameters identified for an Infinite Line Source Model (ILS) and Table 5 shows the same set of parameters when a Finite Line Source Model (FLS) is used.

Table 4. ILS Model parameters

BHE	Exp. Name	T_0	Rb	λ
Single-U	single-u	19.5	0.17	2.1
BHE 3	BHE3 February	18	0.13	2.5
BHE 3	BHE3 April	19.5	0.11	2.5
BHE 5	BHE5 febr	18.5	0.14	2.5
BHE 5	BHE5 may	20.5	0.13	2.5

Table 5. FLS Model parameters

BHE	Exp. Name	T_0	Rb	λ
Single-U	single-u	19.5	0.17	2.0
BHE 3	BHE3 February	18	0.13	2.5
BHE 3	BHE3 April	19.5	0.11	2.5
BHE 5	BHE5 febr	18.5	0.14	2.5
BHE 5	BHE5 may	20.5	0.14	2.5

The table shows an unexpected result as BHE3 and BHE5 seems to present the same or very close R_b. Here arises a problem inherent to TRT: the undisturbed ground temperature selection. T_0 and R_b cannot be distinguished in the models. So, if we repeat the analysis for BHE3 April with a slighter higher temperature (20º) the obtained results for Rb are 0.1043 for ILS and 0.1059 for FLS.

But there is another reason for these values. In Fig. 6 the absolute error from FLSM to real data is shown for Single-U. We have tried to detect any pattern without successful: not related with ambient temperature, night and day or control cycles, etc.

In the other hand, there is Fig. 7. Here there is a clear pattern, the errors are bigger at the beginning and in the end what could be come from a wrong model being used or a bad hypothesis about the ground being equal for Single-U and for BHE3 and BHE5.

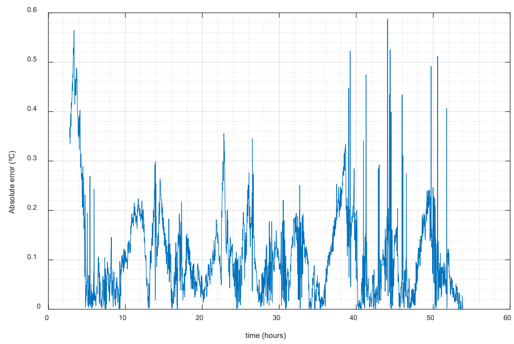

Fig.6. FLSM model error for single-u

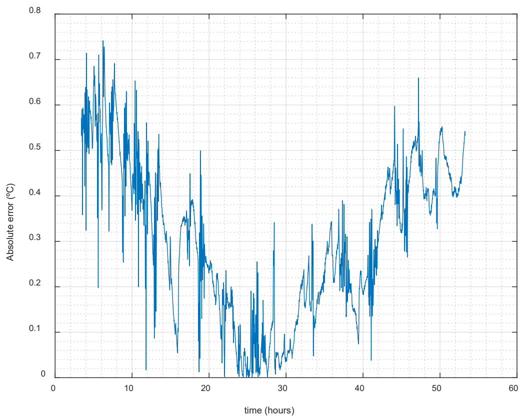

Fig.7. FLSM model error for BHE3 April

CONCLUSIONS

In the Shallow Geothermal Laboratory at Universitat Politècnica de València seven new BHE has been installed. Two of them differs form other BHE only in the materials used for their construction: BHE3 and BHE5.

The reason to add this BHE to this facility is to check the improvements in conditions as near as possible to productions environment but with the flexibility of tests of a laboratory: power injections control, selection of the flow, measuring pressure losses, etc.

The first comparison show Rb values in lines what was expected and closer enough to previous simulations.

Nevertheless, some have arisen during the analysis of the results. The soil conductivity identified by the models is higher in this new BHE than in the previously installed. The two BHE fields are very near, only a rural way between them, 25 m from the Single-U BHE of first installation and the centre of the new testfiels, but the underground seems to present difference that were hidden in the design and deployment of the new BHE.

In any case, the promising results enforces the consortium to go on with the test of the new materials, trying to give to market as soon as possible.

Finally, the analysis of Fig. 7 suggest the researches that a possible underwater flow is present in the new test-field and this hypothesis has to be solved witch is in the research line of the group related to improve and check BHE models and materials that make shallow geothermal energy system easier to design and cheaper to build.

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