Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Innovative Coaxial Heat Exchangers for Shallow Geothermal

Luc POCKELE'[1], Giulia MEZZASALMA[1], Davide RIGHINI[2], Jacques VERCRUYSSE[3], Francesco CICOLIN[4], Gianluca CADELANO[4], Antonio GALGARO[5], Giorgia DALLA SANTA, Michele DE CARLI[6], Giuseppe EMMI[6], Dimitris MENDRINOS[7], Riccardo PASQUALI[8], Adriana BERNARDI[4]

[1] RED srl, Viale dell'Industria 58/B, 35129 Padova, Italy

[2] Hydra srl, Via Imperiale 6, Traghetto di Argenta, 44011 Ferrara, Italy

[3]GEO-GREEN sprl, Rue de Priesmont 63, 1495 Marbais, Belgium

[4]CNR-ISAC, Corso Stati Uniti 4, 35127 Padova, Italy

[5]Department of Geosciences, University of Padova, Via Gradenigo 6, 35131 Padova, Italy

[6]Department of Industrial Engineering, University of Padova, Via Venezia 1, 35131 Padova, Italy

[7]Centre for Renewable Energy Sources and Saving. Pikérmi, Greece

[8]SLR Environmental Consulting Ireland Ltd. 7, Dundrum Business Park, Windy Arbour, D14, Ireland;

luc.pockele@red-srl.com

Keywords: ground source heat exchanger, drilling, shallow geothermal system, coaxial heat exchanger

ABSTRACT

One of the main innovations of the H2020 "Cheap and efficient application of reliable Ground Source Heat exchangers and Pumps" (acronym Cheap-GSHPs) research project, was the development of a coaxial ground source heat exchanger and drilling machine components to reduce the total installation cost using the piling method. These developments include the geometry of the heat exchanger, primarily a larger diameter and a co-extruded internal plastic pipe, to improve thermal extraction as well as the development of a drilling head combined with high pressure water injection to reduce the installation time. All these innovations, reduce significantly the installation costs in unconsolidated soil, especially when borehole stabilization measures are needed. The drilling machine remains small and compact since the installation method used requires much less power. A patent request has been filed in Italy (patent request n.102018000011157 of 17/12/2018). The enlarged coaxial heat exchanger was installed at five demonstration sites using the new drilling machine components and installation methodology. Historical buildings are part of these demonstration cases supporting the applicability of this technology in this type of buildings. All sites are monitored and demonstrated important gains of thermal energy extraction rate under transitory operating conditions when compared to the state of art. The developments are being improved further as part of the on-going "Most Easy, Efficient and Low Cost Geothermal Systems for Retrofitting Civil and Historical Buildings" (acronym GEO4CIVHIC) H2020 research project. One of the objectives of this latter project is to improve the power of the drilling head and making the machine more compact to enable the cost-effective application of this installation method and the coaxial heat exchanger in retrofitted buildings in built environments and historical districts. This paper evaluates the yield obtained and the potential cost reduction of this novel heat exchanger combined with this innovative drilling technique.

Cheap-GSHPs project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 657982. GEO4CIVHIC project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 792355.

1. INTRODUCTION

In closed loop shallow geothermal systems, the heat is exchanged between the building and the ground by means of Ground Source Heat Exchangers (GSHEs). These can be of different shape and length. Usually, a borehole with a dimeter of about 15cm is drilled and one single-U or double-U probe is inserted. Then, the borehole is sealed with grout. The heat exchangers can be U-shaped, or in the coaxial configuration. In the latter case the tubes have different dimeters and are inserted one into the other. The heat carrier fluid flows downwards in the annular space and upwards in the internal tube or vice versa. Coaxial GSHEs can be installed in two ways: drilling of a borehole and subsequently inserting the external and internal tubes followed by grouting or by piling the external tube into the soil and inserting the internal tube afterwards.

One of the innovations in the Cheap-GSHPs project, is the development of a coaxial GSHE and related drilling machine using the piling technique. The AISI 304 steel pipes are piled into the ground by using a pile-driving machine with a roto-vibrating head. The aim is the reduction of the installation cost, thanks to the direct piling of the external tube without the use of a support casing, in combination with a higher heat exchange rate thanks to the larger diameter and the direct contact between the coaxial external tube and the ground.

The history of developments of this methodology describes the state of art at the start of the project. The piling technique was developed to cut down the installation time and, therefore, the cost of drilling in soft unconsolidated soil. Usually in such undergrounds the traditional drilling technology requires the use of casings to avoid the collapse of the borehole and large amounts of water as drilling fluids to remove the drilling residues. These aspects lead to significant drilling costs. The starting point of the piling technique consists in the installation of stainless-steel tubes with a diameter of 50 mm as a new type of GSHE. These tubes fulfill a dual function as drilling rods and as geothermal pipes. The idea behind the installation technology is to drill directly with a stainless steel pipe that will become a part of the BHE using the piling technique. Hence, the new coaxial borehole heat exchanger is built with an external stainless-steel pipe to avoid corrosion problems and an internal plastic HDPE or PEXa pipe. The installation of coaxial steel GSHE's with the piling methodology was patented in Italy by TecnoPenta Sas in 2006. Following the original patent, Hydra Srl (a Cheap-GSHPs project partner) and TecnoPenta Sas obtained another Italian patent (patent number 0001398341), that covers the installation of this GSHE using the piling methodology with a vibrating head. The drilling machines were marketed under the name "Vibrasond" (figure 1). One of the objectives of this project is to achieve the installation of coaxial probes with an external diameter larger than 50 mm, in more difficult unconsolidated soils to depths up to 100 m and with shorter installation times. The development in the Cheap-GSHPs project consisted in designing and manufacturing a drilling head with rotation and vibrating functionalities as well as the use of small quantities of water injection through the drill bit during the piling operation. Both developments were tested in the field in Molinella (in the Po Plain, Italy), providing experience and learning for the installations in the demonstration cases. This technique has been applied in 2 demonstration cases (Pikermi Attiki in Greece and Mechelen in Belgium) to evaluate the installation time and the heat exchange rate in different geological settings and building energy loads.

Figure 1: The newly developed drilling machine JOY 4 (left) and the "Vibrasond" machine (right)

It is generally known that using a fluid, such as water, facilitates drilling operations and is necessary in conventional drilling. Conventional drilling methods often uses large quantities of water. The use of water in the installation of the coaxial GSHEs into the ground using the piling methodology is less common. However, the roto-vibro technique brings improvements either in a reduction of installation time and hence cost or by widening the application of the piling methodology in different soil types. The original Vibrasond technique did not use water due to the fact that the stainless-steel tube had to be closed for water recirculation during the heat extraction operation. The design of water nozzles as part of the project has allowed water to be used during the drilling operation and then to seal the nozzle assembly for the geothermal operation.

2 ROTATING AND VIBRATING MACHINE HEAD FOR PENETROMETERS

2.1 Drilling head improvements

The first improvement is the development of a rotating and vibrating machine head. The combination of vibration, rotation and downward push, allows the installation of probes of larger diameters (60-80 mm) to be installed in more types of soils than with the Vibrasond technique that used only vibration.

The drilling unit manufactured by HYDRA, is a stand-alone machine with four main elements: a frame, a power pack, a crawler and a mast (see figure 1). The newly developed drilling head, called Roto-Vibro head (RV1), combines the effect of rotation with the effect of vibration. This unique head differs from the others since it is characterized by higher torque and low frequency in comparison to the previously used sonic heads. Such a solution was adopted as it is able to provide high torque to drill through harder material. The lower vibration frequencies produce less stress to the mechanical components but are still able to reduce the wall frictional forces especially in combination with a small flow of water. In addition, a low-cost drilling bit that remains in the borehole was manufactured on purpose; the design of the tip of the GSHE was completed in order to loosen the underground when the machine head is rotating. In more difficult soils, a tri-lame or a tri-cone can also be deployed.

A first series of tests was performed at the test site of Molinella (Italy) in order to compare the RV1 head performance using one or more of its functionalities. The lithological sequence is typical of a quaternary floodplain deposition environment, dominated by silt and silty clay deposits, alternated with sandy layers, as described in (Galgaro et al., 2017; Zarrella et al., 2017). All the tests were carried out without water injection in order to stretch all the tests to their limit. The rods used had a length of 2m. Only one operator was used for all the operations. Each trial consisted of drilling 12 m and measuring the time required to achieve this depth. The average time reported below consists of the total drilling time, which means that the time includes the effective drilling time plus the rod handling and assembly time. Overall, about 40 % of the measured time comprises the drilling time and the remaining 60 % of the time for the handling and assembly of the rods. The tests show significant improvement with the employment of vibration in the drilling operation. Moreover, the best results were obtained when the rotation was coupled with vibration. Figure 2 illustrates the percentage time drilling reduction for the different drilling head tested.

In addition, the penetration capability test was carried out to understand the time needed to reach a depth of 48 m with the full capacity of the RV1 in real drilling conditions with 76mm rods. The drilling was carried out with the simultaneous effects of rotation, vibration and thrust. Water was injected during the test, with the following operating conditions: 20 lt/min and 90 bar of maximum pressure. During the test, a depth of 48m was reached in 53 minutes, including rod handling and assembly time. During the test a pushing speed of approximately 15 s/m was achieved whist the time for rods handling was measured at approximately 45 s/rod. Only one operator was involved in the test (see Bernardi et al., 2019, Chapter 3).

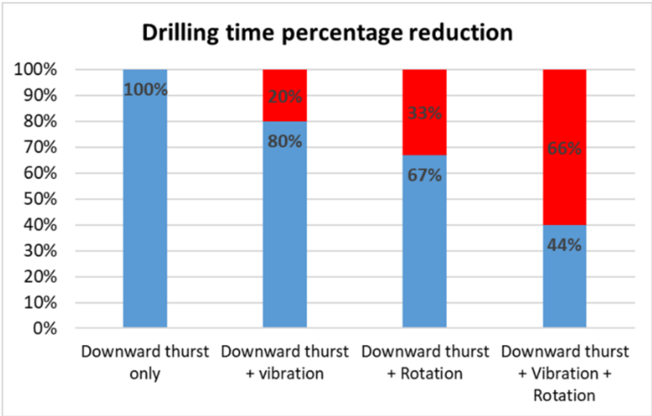


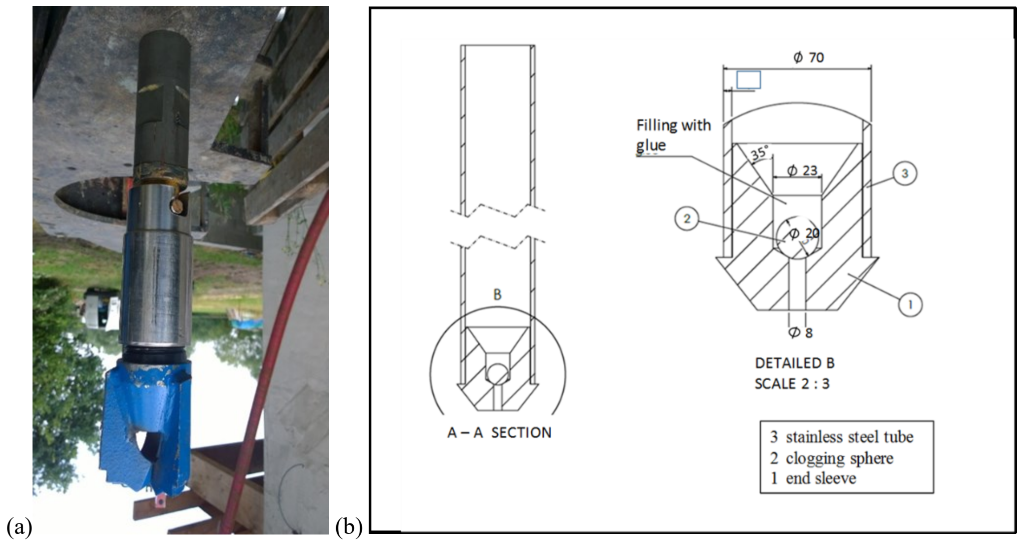
Figure 2: Drilling head performance comparison: time percentage reduction (from Bernardi et al., 2019).

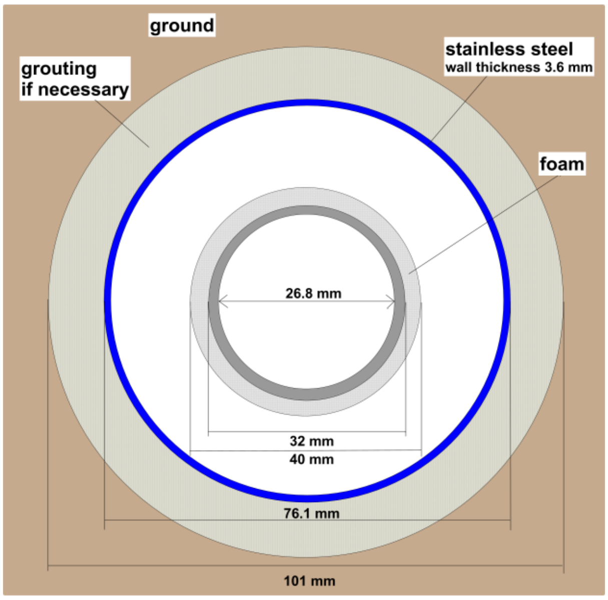
The range of operation for this technique is unconsolidated ground such as sand, silt and clay. Usually, in such undergrounds the traditional drilling technology requires the use of casings to avoid the collapse of the borehole, large amounts of water as drilling fluids and disposal of the drilling residues. These lead to significant costs. The piling method is, therefore, cheaper and also less invasive than traditional methods.

2.2 Injection nozzle assembly at the tip of the coaxial GSHE

The second development concerns the design of a water injection nozzle integrated in the drill bit injecting water during the piling operation using a high-pressure pump. After drilling, the nozzle assembly needs to be sealed. Only small quantities of water are injected to loosen the soil and to decrease the friction on the walls of the stainless-steel pipe being piled into the ground. Finally, to increase the mechanical couple at the rotating drill bit an internal shaft has been connected to this drill bit.

To further improve the piling methodology performance, a high-pressure water injection system was designed. The water pump selected for the water injection is a Triplex pump. Conversely to the conventional drilling where the recirculation of water is characterized by high flow rates and low pressures to remove the cuttings, here the working conditions requires the flow to be set to c. 20 l/min and the pressure to be defined by the resistance of the injection system and the soil resistance that the water has to overcome. In fact, the objective is only to create a thin water layer on the tube outer surface that lubricates, as well as softening, weakening and displacing the unconsolidated soil at the tip of the probe. The water is injected within the internal rods trough the drilling tip, where proper nozzles are installed. The design of the nozzle system needs to be able to allow water flow during the drilling activities and, once the desired depth is achieved, to close the tube in order to be used as heat exchanger. Three different nozzle designs where performed and, finally, the best design was chosen and optimized based on the results obtained in field tests (see Figure 3) (see Bernardi et al., 2019, Chapter 3).





(c)

Figure 3: The drill bit (a), (b) one of the nozzles designed and (c) the sketch of the coaxial BHE section (ALL PROPERTY RIGHTS RESERVED BY Hydra srl – This drawing shall not be reproduced without written consent. Any infringement will be legally pursued) (from Bernini, 2016)

2.3 New inner and outer coaxial GSHE tube material

Different material options for the inner and outer tube of the coaxial GSHE have been studied based on their installation methodologies (traditional drilling of the well completed with sealing grout or piling technique). Several thermoplastic and metal based materials have been investigated for their use as borehole heat exchanger (BHE) piping material. These include mild steel, galvanized steel, various coating options, stainless steel, copper and its alloys, aluminum, titanium, as well as reinforced polymers and other plastic materials including thermally enhanced polyethylene. The general assumption is that the BHE is installed into the ground by standard drilling which will disturb the natural underground conditions. The GSHE service life was estimated in function of their material characteristics, the installation methodology, the operating parameters and underground conditions. In addition, the length of a reference BHE for a 5 kW (thermal) heat pump used in a central European climate was estimated using the Earth Energy Designer (EED) software. The cost per geothermal kW of the coaxial BHE was evaluated using the sale price of pipes for the different materials examined. An internal pipe of HDPE of 32 mm in diameter with a cost of 1,38 €/m was used. As this exercise addresses the materials a typical drilling and grouting costs of 36 €/m was assumed to avoid the introduction of another variable. The results are reported in Figure 4.

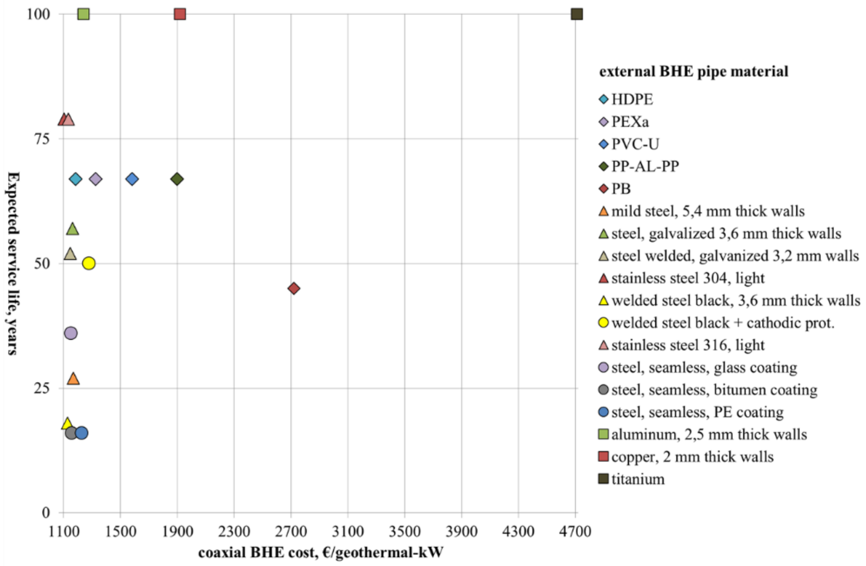


Figure 4: Expected service life versus coaxial BHE cost/geothermal kW extracted for moderate corrosive geologic formations and groundwater (pH 6,5 and resistivity 25 Ohm.m).

The effective borehole thermal resistances for each one of the cases presented in Figure 4 are presented in Table 1.

Table 1: Effective borehole thermal resistances of the BHE types considered in Figure 4.

BHE external pipe material	Outer diameter, mm	Wall thickness, mm	BHE length, m	Effective Borehole Thermal Resistance, (m.K)/W
HDPE	63	3.8	118.5	0.1862
PEXa	63	3.8	121.3	0.1959
U-PVC	63	3.0	135.8	0.2452
PP-Al--PP	63	5.8	169.0	0.3586
PB	63	10.5	188.8	0.4266
Mild steel	60.3	5.54	103.6	0.1359
Steel, galvanized, seamless	60.3	3.6	105.5	0.1420
Steel, galvanized, welded	60.3	2.5	106.4	0.1453
SS 304L	60.3	2.0	107.0	0.1474
Steel, black	60.3	3.6	105.5	0.1422
Steel, black, cathodic prot.	60.3	3.6	105.5	0.1422
SS 316	60.3	1.5	107.4	0.1485
Steel, glass coating	60.3	2.9	106.1	0.1443
Steel, bitumen coating	60.3	2.9	106.6	0.1460
Steel, PE coating	60.3	2.9	112.7	0.1666
Aluminum	63	2.5	106.1	0.1443
Copper	64	2.0	106.4	0.1451
Titanium	73.02	3.05	104.7	0.1393

Thermoplastics and coated metals cannot be used with the piling methodology. Thermoplastic materials cannot withstand the compression load during the piling operation. Galvanized metallic materials cannot be considered due to the risk of damaging the coating or the galvanized layer during the piling process (Mendrinos et al., 2017). In addition, due to the absence of grouting, the borehole resistance between the external metallic tube and the soil is significantly lower than that of convention grouted heat exchangers, thereby increasing the yield of the coaxial GSHE. From this analysis, stainless steel 304L and duplex stainless steel (2205) have been found to be the materials of choice, having the lowest cost per extracted kW and service lives of at least 50 years.

The soil conditions when using stainless steel as outer tube material need to be checked on a case by case basis. Many factors can influence metal corrosion in the underground, almost all related to the chemical and physical characteristics of the underground. These are the conductivity, the permeability, the pH or acidity and the water content. These factors are also correlated amongst them. In addition, the presence of sulfates and chlorides, biological agents and eddy-currents can have an important influence and may require protective measures. Where cathodic protection is required, a BHE cathodic protection layout using a Magnesium sacrificial anode or a BHE cathodic protection layout by imposed current anode can be considered Commercially available special alloys or cathodic protection equipment needs to be considered to prevent corrosion if this is deemed necessary. Experience of these installations in Belgium and Italy have shown that when underground conditions are not particularly aggressive, stainless steel tubes have an acceptable service life.

An insulated inner tube has been developed; the insulation of the inner tube should prevent the heat carrier fluid going up being cooled down by the colder fluid coming down through the external tube. Numerical simulations performed during the design phase showed that efficiency improvements are limited. In addition, the beneficial effect of using the insulated pipe is the velocity increase of the fluid at moderate flow quantities, which improves the convective exchange coefficient through the pipe wall. Because the insulated pipe has a greater thickness, it reduces the annular flow section and, at the same flow rate, the fluid velocity increases leading to an increase of the convective exchange.

In conclusion, stainless steel is used to avoid corrosion problems whilst the internal pipe is a co-extruded internal plastic pipe (figure 5).

Figure 5: The external coaxial tubes and the internal pipe at the Molinella test site.

3. DEMONSTRATION SITES AND COSTS AND HEAT EXTRACTION RATES COMPARISON

These Ground Source Heat Exchanger (GSHE), with a larger diameter and a co-extruded internal plastic pipe, have been installed in demonstration sites using the new drilling machine and the new installation methodology. All sites are monitored and demonstrated important gains of thermal energy extraction under transitory operating conditions when compared to the state of art. The results of this monitoring are discussed in more detail in paragraphs 3.1 and 3.2. The efficiency increases from the larger diameters, from the inner tube developments and the shorter installation times with smaller machines favor this methodology in unconsolidated soil where casings are needed to stabilize the borehole.

The enlarged coaxial stainless-steel heat exchanger was tested on site in Pikermi Attiki (Greece) and in Mechelen (Belgium) in order to consider different geological settings, climates and building thermal requests. The installation times were measured as well as the energetic performances. The heat exchange capacity was measured by Thermal Response Tests performed both on the coaxial probes as on the traditional ones. Thermal energy meters were installed on each coaxial heat exchanger and on the double-U's (see Bernardi et al., 2019, Chapter 6) to measure the extracted energy during the different cycles of the heat pump.

3.1 Demonstration site: residential eco-house in Belgium

In Mechelen (Belgium) the demonstration building was a two story single-family house, with a total surface area of 170 m^2 and a 12 kW geothermal heat pump. It is a NZEB building with a wooden structural frame and 35 cm thick pressed straw bale walls ,. A chalk render protects the straw bales from the rain and a clay internal render provides breathing functionalities. The windows are triple glazed filled with Argon. The building is equipped with radiant floor and ceiling panels. 6 BHE's are installed down to 78 m depth: 2 double U's, 2 coaxial with diameter of 50 mm and, finally 2 coaxial of 76 mm (one with an insulated internal tube). The geological context is characterized by the presence of the over-consolidated Boom clay. In this demonstration case the feasibility of the piling method in hard clay layers was proven at rates of 1-2 meters/min. The thermal response tests confirm (figure 6) the lower borehole resistance of the steel coaxial BHE's compared to double U's. The borehole resistance of 0,076 for double U's fits very well with the average values found in that region with TRT tests. By integrating the surface area under the energy extraction curves, the thermal energy meters demonstrate up to 20% higher energy extraction rates during heat pump operation cycle when compared to the double-U's.

BHE	Borehole resistance (K/Wm)	Conductivity (W/mK)
Coax 76 mm w/insulated	0,036	2,06
Coax 76 mm w/o insulated	0,061	2,27
Double U	0,076	2,16
Coax 50 mm	0,048	2,31

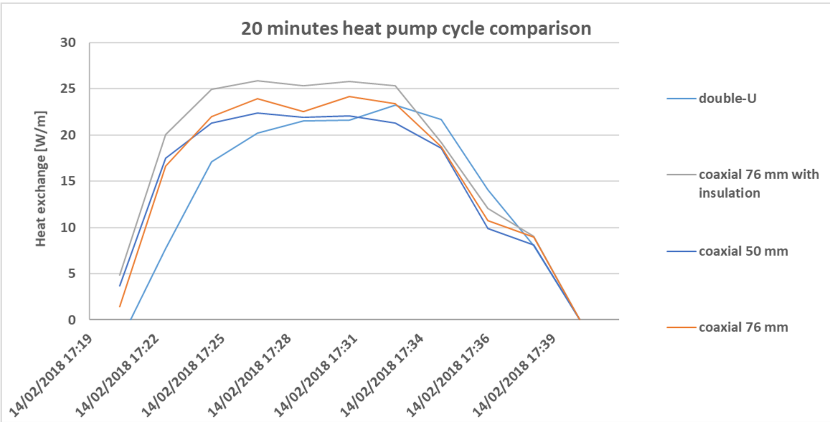


Figure 6: The performances measured at the demonstration site in Belgium.

3.2 Demonstration site: Bioclimatic office building in Pikermi Attiki in Greece

This is a NZEB building constructed in 2001, that integrates several renewable energy technologies. The ground source heat pump produces 21 kWth of heating at 45°C and 16 kWth of cooling at 10°C. The tested bore field is composed by 4 BHEs (single-U, double-U, coaxial, spiral) & open loop doublet. The site has a real time monitoring system that displays online all the thermal and energetic parameters, graphs and calculations allowing user friendly assessment of the demonstrated systems (see the project homepage of Cheap-GSHPs (https://cheap-gshp.eu/).

Also in this case the stainless steel coaxial BHE shows to be very reliable, very high energy output (equal to 2.643 W/mK), low borehole thermal resistance (equal to 0.050mK/W) and low cost per kWth of geothermal yield (Capozza et al., 2016). Compared to the double U probe, coaxial probes reached a 30 % higher yield (80-100W / m compared to 50 W / m) during the operational phase of the heat pump in heating mode.

CONCLUSIONS AND FURTHER DEVELOPMENTS

The developments in the geometry and composition of the coaxial heat exchanger improve the thermal exchange yields. The monitoring data of the instantaneous energy exchange with the soil support this fact as explained in paragraphs 3.1 and 3.2. The drilling head developments and the use of high-pressure water injection reduce the installation time as shown in figure 2. In the demonstration cases this increased rate of penetration and avoiding the need to consolidate the borehole with a casing results in a reduction of installation times in the order of 30 – 50 %. A patent request has been filed in Italy covering the above described improvements of the drilling method (patent request n.102018000011157 of 17/12/2018). Despite the limitation of this technique that can be applied primarily in unconsolidated soil such as sand and clay the following advantages have been confirmed within the Cheap-GSHPs project and further developments within the GEO4CIVHIC project will further enlarge its field of application:

(I) The external tube is in tight or direct contact with the soil and this leads to the reduction of the borehole resistance (Rb). In addition, the use of stainless steel with its high thermal conductivity (≈ 16 W/(m K) enhances the heat exchange between the underground and the probes. The heat exchange rate has been shown to be up to 30% higher with respect to a traditional Double-U in transient operating mode (figure 6).

(II) The use of the piling methodology removes the need for grouting the borehole, resulting in substantial savings in terms of time, complexity and cost of the heat exchanger installation. This technique also avoids all the common operations of drilling with rods and casing, saving in rod handling time due to the fact that the stainless steel rods remain in the borehole and are then used as heat exchanger. Thus, we get a faster installation in soils that usually require the use of casings.

(III) The higher installation speed and the better thermal exchange with the soil lowers the total installed cost with 20-30 % compared to state of art in unstable soil conditions where the use of a stabilizing casing is necessary. Therefore, shallow geothermal technology could gain market share in several markets where prices today are in the order of 40 – 50 €/m and become more competitive against other renewable energy based heating and cooling systems like air to water heat pumps.

(IV) The installation method requires a lot less power to displace the soil than required by removing the soils. Smaller, less capital intensive drilling machines and ancillaries can be used whilst the method is also much less invasive.

In conclusion, the potential cost reduction of 20 -30 % has been confirmed, in several demonstration cases for situations where the borehole needs to be supported by casings and/or where the market competition is not well developed. In situations where the soil is sufficiently stable to avoid casings and where the market is very competitive and mature, this methodology is able to match the state of art costs but with a less invasive and more compact drilling rig.

The velocity of installation, compactness of the drilling machine and high energetic performance make this technology particularly interesting for the application to historical buildings. For this reason, this technology conceived within the Cheap-GSHPs project is the starting point for the further developments and optimizations foreseen within the EU funded project GEO4CIVHIC that aims at applying the shallow geothermal technology in retrofitted buildings and historical buildings in built environment.

Cheap-GSHPs project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 657982. GEO4CIVHIC project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 792355.

REFERENCES

Bernardi, A. and all the partners of Cheap-GSHPs EU Project: Cheap and Efficient Application of Reliable Ground Source Heat Exchangers and Pumps – Technical Manual of Cheap-GSHPs EU project (English version). 2019

Galgaro, A., Dalla Santa, G., Cultrera, M., Bertermann, D., Mueller, J., De Carli, M., Emmi, G, Zarrella, A., Di Tuccio, M., Pockelé, L., Mezzasalma, G., Psyk, M., Righini, D., Bernini, M., Bernardi, A: EU project "Cheap-GSHPs": The geoexchange field laboratory. Energy Procedia, 2017, 125, 511–519. https://doi.org/10.1016/j.egypro.2017.08.175

Mendrinos, D., Katsantonis S., and Karytsas C. Review of Alternative Pipe Materials for Exploiting Shallow Geothermal Energy. Innovations in Corrosion and Materials Science, 2017, 7, 13-29

Zarrella, A.; Emmi, G.; Graci, S.; De Carli, M.; Cultrera, M.; Dalla Santa, G.; Galgaro, A.; Bertermann, D.; Muller, J.; Pockelé, L.; Mezzasalma, G.; Righini, D.; Psyk, M.; Bernardi, A. Thermal response testing results of different types of borehole heat exchangers: an analysis and comparison of interpretation methods. Energies 2017, 10, 801, https://doi.org/10.3390/en10060801