Experimental comparison of a geothermal rainwater tank and other ground-coupled heat exchanger technologies for passive cooling

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Résumé - Les récupérateurs d'eau de pluie géothermiques sont de nouvelles solutions hybrides pour le rafraîchissement passif des bâtiments et la gestion de l'eau. Ces systèmes géothermiques de très basse énergie sont composés d'une cuve enterrée et d'un échangeur hélicoïdale immergé dans celle-ci. Cet article présente l'étude expérimentale d'un prototype grandeur nature. Une comparaison aux résultats expérimentaux d'autres technologies passives obtenus dans la littérature est ensuite entreprise pour valider les performances et la viabilité du système présenté.

Nomenclature

E	Energy, Wh	*Indices and exhibitors*	
H	Hours, h	$cons$	consumption
HR	Relative Humidity, %	op	operation
P	Power, W	out	outside
T	Temperature, °C	w	water

1. Introduction and context of the study

In the well-known context of climate change, characterized by increasingly frequent and severe heatwaves with more frequent and severe heatwaves[1], the building sector (residential and tertiary) is in great need of resilience in terms of summer thermal comfort and reduction of CO_2 emissions. France's heavy reliance on air conditioning, consuming nearly 15.5 TWh of electricity [2], underscores the need for sustainable alternatives. Surface geothermal energy emerges as a promising solution, offering higher Coefficient Of Performance (COP) for heat pumps, up to 40% energy savings compared to conventional air-source systems, and mitigating the urban heat island effect [3].

Moreover shallow geothermal energy can also be used as passive heat source, *i.e.* without the use of refrigerant and compressors, resulting in even lower CO_2 emissions and electricity consumption. In France, according to the AFPG (Association française des professionnels de la géothermie), geothermal systems in general and ground-coupled heat exchangers for passive cooling of buildings in particular are promising solutions that need to be developed [4].

In this context, this project aims to develop a new passive system using buried rainwater tanks as geothermal probes by immersing a water-to-water heat exchanger (HX). This article

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Figure 1 : *Two helicoidal heat exchangers in a rainwater tank - Location : Saverne, France.*

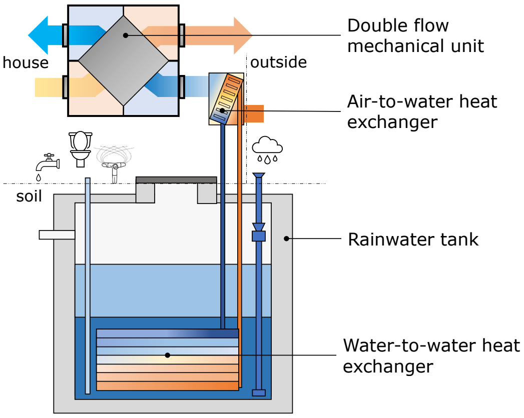

Figure 2 : *Schematic diagram of a geothermal rainwater tank.*

focuses on the experimental study of a full-scale experimental prototype and its performance comparison with other technologies of passive cooling systems. A model has been established and will be validated in another paper thanks to the experimental data presented here.

2. Concept of geothermal rainwater tanks

The basis of our solution consists in a new or existing buried rainwater tank, initially used to collect rainwater for non-potable use and to relieve the sewage system. In France, the water resources management legislation locally enforces on site water management which could democratize the use of such rainwater tanks [5]. The collected rainwater is mainly used for gardening but also for flushing toilets. A helicoidal water-to-water HX in copper (see Fig. 1) or polyethylene is placed in the tank in order to take advantage of the heat storage capacity of water as a by-product. Using an air-to-water HX connected to the ventilation supply duct, the tank provides cooling energy to the building during summer (Fig. 2). The heat exchanger in the double-flow mechanical unit can obviously be by-passed if not useful.

The principle is to use the same installation for three purposes (rainwater harvesting, water management, cooling the building), which, in principle, allows savings in terms of costs and materials (to be quantified), for example by avoiding the need to drill boreholes for geothermal probes or the construction of a climatic well.

3. Quick literature review of passive near-surface geothermal technologies

Regarding **geothermal rainwater tank**, the literature is rather scarse. The specificity of the present system is that the water inside the tank remains at atmospheric pressure and its level varies. Most of the articles dealing with buried water tanks do not study water level variation. Additionally, the studies are often focused on coupling the tank to a ground-source heat pump as heat source and do not study passive operation [6, 7, 8]. Finally, the projects usually deal with either experimental prototypes [9] or models [10] but rarely both [8].

We will concentrate here mainly on a quick literature review of passive near-surface shallow geothermal technologies or Ground-Coupled Heat Exchanger (GCHE). Strictly speaking, this limits our study to systems between 0 and 200 m with operating temperatures below 30 °C.

- **Earth-Air Heat Exchanger** : Earth-Air Heat Exchangers (EAHE) also known as climatic wells, have been broadly studied in recent years. Bordoloi conducted an intensive review on the subject, which is a good starting point for interested readers [11]. EAHE is a passive technology that consists of a buried pipes (from 1 to 3 m depth) into which outside air enters and is being cooled or heated (depending on the season) by the surrounding ground before entering in the building's ventilation system. The underground soil temperature is indeed more stable than outside air temperature and allows to save cooling or heating power. There are various setups of EAHE (horizontal, slinky, one or parallel tube, ...) and their performances mainly depend on the pipes configuration,their length, diameter and depth, the air flow velocity, the temperature difference between earth and ambient air and the thermo-physical ground properties.
- **Geocooling with Ground Source Heat Pump (GSHP)** : Geocooling or geothermal "free cooling" is the direct use of the ground temperature through a hydraulic loop to cool buildings without the use of ground source heat pump. The literature study shows that such systems are seldom installed without heat pump. The ground coupled heat exchanger can also take several forms : horizontal, vertical single-U, vertical double-U, basket-shaped, on pile foundation,... Among the articles dealing with GSHP, not all of them deal with passive cooling and the majority that do, mention vertical heat exchangers rather than other GCHE [12, 13, 14]. Due to the large differences in implementation, it can be difficult to compare geothermal rainwater tanks and such systems.

4. Experimental Study

4.1. Experimental set-up and measurement

Three geothermal rainwater tank prototypes are installed in different locations in Alsace, France, in a semi-continental climate. For the sake of conciseness, this article focuses on one of the prototypes, located in Haguenau.

It consists of an 11 m^3 tank made of precast concrete (see Fig.3 below) with a hundred meter long copper coiled heat exchanger (external diameter of 22 mm). The surrounding ground is dry sand. A 1 kW cooling heat exchanger, placed upstream of the double flow mechanical unit, allows heat to be transferred from the water circuit to the supply air ventilation of a 150 m² family house built in the 1930's but recently renovated to comply with the current French Energy Performance of Buildings Code.

Presently, the Haguenau prototype is monitored with more than 25 sensors connected to data-loggers, with a minimum time-step of 10 minutes. The devices were installed in the summer of 2021 and consolidated data are available since the beginning of 2022. The main measured data with their sensor references are :

- Water temperature stratification thanks to 5 fixed data-loggers (ref. HOBO MX2203 - $\pm 0.2°C$) evenly distributed over the height of the tank (0 m, 0.5 m, 1 m, 1.5 m, 2 m).
- Water level through total pressure of the bottom of the tank (ref. HOBO U20L-04 - $\pm 1cm$).
- Air temperature and humidity inside the tank (ref. HOBO U23-002A - $\pm 0.25°C$ and $\pm 2.5\%$ from 10 to 90 %, $\pm 5\%$ below and under this range).
- Temperatures at the air-to-water heat exchanger limits (both air : ref. HOBO U23-002A - $\pm 0.25°C$ and $\pm 2.5\%$ from 10 to 90 %, $\pm 5\%$ below and under this range - and water : type K thermocouple - $\pm 1°C$).
- Meteorological data including rainfall, global solar radiation, air temperature and humi-

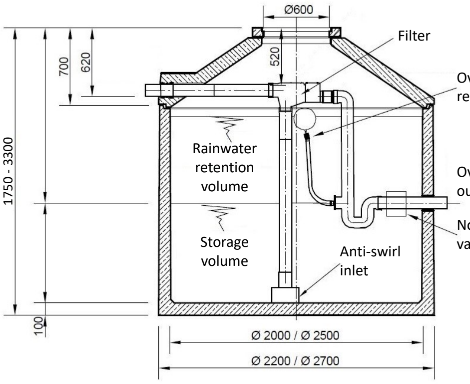

Figure 3 : *Data-sheet for a rainwater retention and storage tank - Source : PLUVIEAU (translated).*

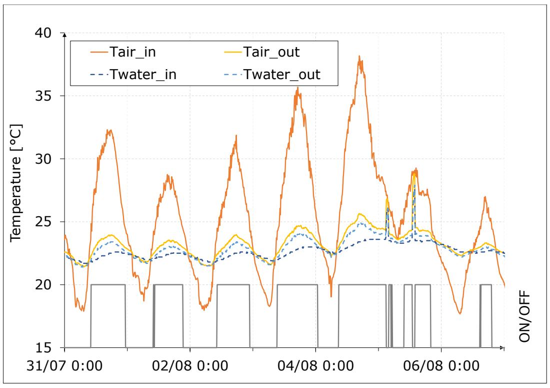

Figure 4 : *Air and Water temperature at the air-to-water HX limits (summer 2022 – Haguenau).*

dity (ref. Davis Vantage Pro 2).

- Temperature inside the buildings (at air vent and in the room : ref. HOBO UX100-01 $\pm 0.2°C$)

The temperatures measured in the system will serve as validation data, with meteorological data as input and/or boundary conditions.

4.2. Experimental results

4.2.1. Supply Air

After two years of monitoring, the experimental results show good operating performances. During the hottest week of the year 2022, when outside temperature reached 38 °C, a temperature drop of temperature of 13 °C was observed (see Fig. 4). This corresponds to a cooling power peak of more than 1 kW. Indoor temperatures were kept under 27 °C during this summer with an appropriate building thermal management (night ventilation and solar shading).

The energy produced during the summers 2022 and 2023 (see Table 1) is calculated assuming an average ventilation flow rate of 240 m^3/h, based on spot measurements taken in the field. The cooling power distribution (Fig. 5) and temperature drops are relatively similar between the two years. There are some small differences between the two summers :

- A two-week delay in starting on the system with a 2022 start date the 15^{th} of May against the 1^{st} of June in 2023,
- A continuous operation in 2022 and 20 days of downtime in 2023 (holidays, week-ends,...)
- A slightly hotter summer in 2022 with an average outside temperature of 22.1 °C and ”only” 21.5 °C in 2023. It should be added that these are the 2^{nd} and 4^{th} hottest summers ever recorded in France [15].

These differences largely explain the lack of about 350 hours of operation in 2023. The cooling production of the system is 476 kWh in 2022 and 344 kWh in 2023. The consumption of the water pump is not measured. Given the size of the network (about 200 m) and a volumetric flow rate of 0.7 m^3/h, the pump datasheet indicates an electrical consumption of 11 W. With this hypothesis, the average COP of the installation is 35.

	H_{op}	ΔT_{max}	$T_{blown_{max}}$	P_{max}	P_{mean}	E_{prod}	E_{cons}
	h	°C	°C	W	W	kWh	kWh
11/05 to 15/09 2022	1250	13.1	25.6	1071	381	476	13.8
01/06 to 03/10 2023	873	13.3	24.5	1085	394	344	9.6

Tableau 1 : *Main production values for the summers of 2022 and 2023*

4.2.2. Water temperatures

In this paragraph we present the results in terms of water temperature. The temperature of the heat sink is an important parameter for passive systems as it is the limiting parameter -*i.e.* in summer/winter mode the temperature of the working fluid can not fall below/exceed this value. It will also be used as a basis for numerical validation in further communication. On Figure 6, one can observe the variation of water temperature during a part of summer 2023 at each level of the tank. Tw_X means the water temperature at X metres from the bottom of the tank. Here are the most important comments :

- The maximum average temperature is similar between the two years : 22.9 °C in 2022 22.3 °C.
  However the minimum temperature was 5.4 °C and 7.1 °C for the winter 2021/2022 and 2022/2023 respectively. This difference is partly due to a harsher winter in 2021/22 and probably also to the operation the 2022 summer that influences the surrounding ground. The model will help to determine this part.
- During summer operation, the water stratification can reach more than 2.4°C/m while in winter it is almost zero.This natural stratification of the tank (the coldest water is at the bottom) improves the performance of the coil, which is precisely positioned at the bottom of the tank. Specifically, the stratification is well defined when the system is not operating with an almost constant temperature gradient over the height of the tank (from 0.4 to 1 °C/m). During operation, 2 types of stratification can be distinguished. When the outside temperature is rather high (*i.e.* high cooling power), a low and narrow thermocline forms. The gradient at the bottom of the tank is large - $\sim$ 2.4 °C/m - whereas none is observed at the top (The three temperatures at the top are the same). At lower heat extraction, the thermocline is wider, with gradient between 1.4°C/0.6°C at the bottom and top, respectively. The temperature at 0.5 m (and to a lesser extent, at 1 m) is influenced by the coil and fluctuates between the temperature at bottom and the top water.

The water stratification will be use as a criterion for the model validation.

5. Performance comparison with other technologies

Based on the previous promising analysis it is legitimate to ask : How does this new system compare with other passive geothermal systems ? In this section, three case studies of four different systems have been selected and compared with the result described above. A comparison with two conventional systems (air-to-water and water-to-water heat pump) is also undertaken. Table 2 summarizes generic values from the literature for each technology. The chosen indicators are :

- The excavated volume, V_{exc}, as a measure of the space required for the system (and more or less investment cost, depending on the drilling/excavation technique) .
- The heat sink temperature range, as this determines the minimal operating temperature of the system (in the summer case study).

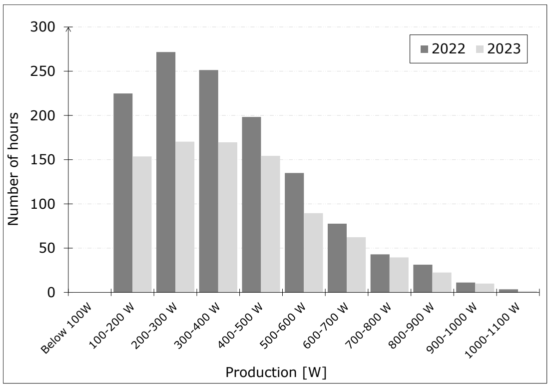

Figure 5 : *Distribution of cooling capacity for the summers 2022 and 2023.*

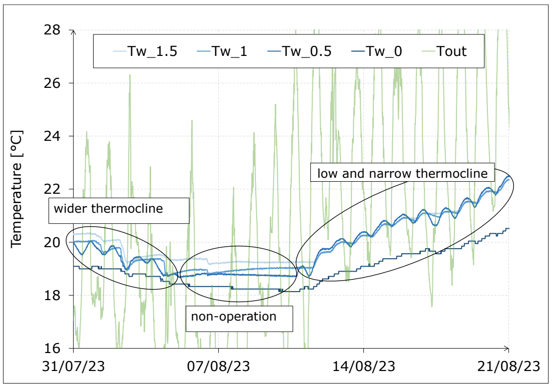

Figure 6 : *Water temperature variations in the tank during summer operation (2023 – Weeks 31 to 33 – Haguenau).*

- The maximal cooling power produced.
- The average COP, COP_{avg}, which is an important indicator for passive systems because the auxiliary consumption can be a limiting factor

The energy produced is not investigated because it is too dependent on the duration of operation and meteorological data.

5.1. An experimental study of climatic well in Strasbourg, Alsace

A thorough study analyses the experimental performance of a climatic well located in Illkirch near Strasbourg in terms of energy and exergy [16]. As this experimental system is well instrumented and close to the Rainergy prototype in Haguenau (only 30 km away) it is a natural choice for a comparison.

The climatic well consists of a polyethylene pipe with a 20 cm-outer diameter. It is buried between 0.7 and 1.2 m underground and has a total length of 29 m. The trench is 1.2 m wide. The volumetric flow rate is about 200 m^3/h which is similar to the Haguenau prototype.

In terms of performance, the EAHE was able to deliver up to 1188 W of cooling power, leading to an air temperature drop of 10 °C (see Figure 7) at an outside air temperature of more than 36 °C. During the studied week, the climatic well produced 63 kWh of cooling energy for an electricity consumption of 4.4 kWh, resulting to an average COP of 14. The performance of this climatic well and the presented geothermal rainwater tank are quite similar, however due to the high convective coefficient between the water and the tank wall, the geothermal rainwater tank system can be more compact with a similar performance. The COP differences are due to lower electricity consumption between the fan (31 W) and the pump (11 W)

5.2. Other technologies

In 2005, Hollmuller et al [17] carried out a study for the Swiss Federal Office of Energy that set up sizing rules for geocooling technologies based on 10 experimental at-scale installations. They investigated the free cooling potential of usual vertical ground heat exchangers (VGHE), EAHE but also geothermal pile foundations (GPF) and horizontal ground heat exchangers (HGHE). The latter was also coupled with an EAHE. The presented GPF and VGHE are large installation with total borehole length exceeding the kilometer. However the maximal linear power and cooling production are similar for the mentioned systems : 40 W/m and 30

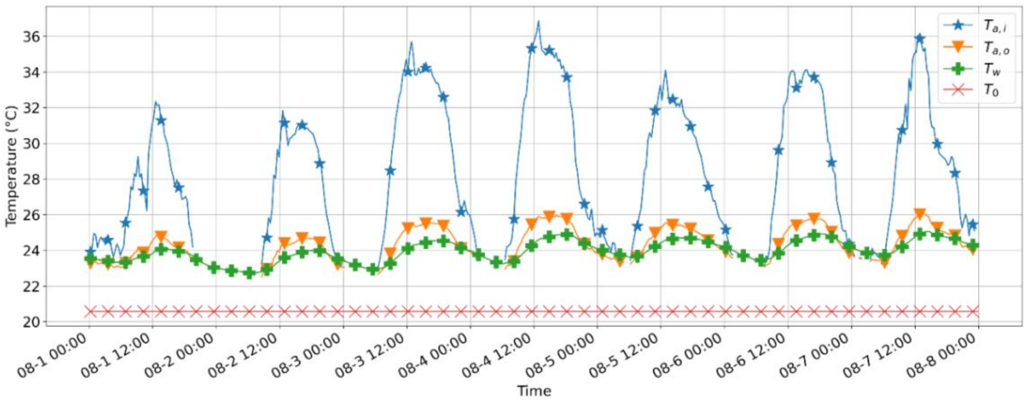

Figure 7 : *Measured temperatures (°C) at the inlet and outlet of EAHE during 2018's hottest week [16]*

kWh/m.an. The data for the chosen indicators are gathered in Table 2.

	Sources	V_{exc}	T_{source}	P_{max}	COP_{avgd}
	-	m^3	°C	kW	-
Geothermal rainwatertank	Rainwater	~ 20	$5-23$	1.1	35
Climatic well - Zeitoun [16]	Ground	33	$2-25$	1.2	14
Vertical Borehole - Hollmuller [17]	Ground	$85-3700$	$2-20$	$8-300$	$12-24$
Geothermal pile foundation - Hollmuller [17]	Ground	31000	$7-17$	313	nc
Horizontal water loop - Hollmuller[1] [17]	Ground	180	16-27	2.6	3
Conventionnal chiller (air-to-water HP)	Air	-	$-20-48$	$5-1000$	$3-4$
Conventionnal chiller (water-to-water HP)	Ground	-	$15-45$	$2-2500$	$4-5$

Tableau 2 : *Comparison of different technologies using geocooling*

Here are some additionnal comments :

— The comparison between the different systems is delicate due to different scales.

— The excavated volume is a good indicator in terms of difficulty of implementation but the needed area is not to neglect especially when it comes to dense urban area (*i.e.* a large volume does not always mean a large area, which is the limiting factor in urban zone).

— The comparision is biased since the geothermal rainwater tank is hybride and fulfills also a water management function.

— Other secondary advantages of passive systems over split air conditioners include : no contribution to urban heat island effect and less noise pollution.

6. Conclusion and perspectives

As climate change accelerates and the frequency of heatwaves increases, so does the need for sober cooling technology. With this in mind, a new concept of geothermal rainwater tank

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[1] Issues pointed by the rapport : influence of the building on the ground leading to high temperature and wrong sizing of the water flow rate in the water loop leading to low COP.

has been presented. This article reviews two years of experimental data and compares the main production parameters to other passive near surface geothermal technologies. The experimental results are very promising and encourage the continuation of the project. The comparison with other passive systems showed that the literature on experimental geocooling studies is not extensive and that geothermal rainwater tanks perform quite well in terms of available cooling power, energy produced and energy consumed, especially considering their compactness. However to match the In further work, a numerical model will be validated thanks to these experimental data and then coupled to a building energy software in order to be able to simulate various configuration (climate, location, size of the tank, ...). Finally, the tank could also be connected to an adiabatic heat exchanger for additional evaporative cooling power. This third function would then compete with the other two - heat and water storage.

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