Experimental and numerical study of geothermal rainwater tanks for passive cooling of buildings

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Abstract - This communication presents the study of a new hybrid system composed of a buried rainwater tank thermally activated through a water-to-water heat exchanger. This low-tech solution, not well studied in the literature, performs the passive cooling of buildings and reduces domestic water network consumption (for non-potable uses). Firstly, experimental results retrieved from two at-scale prototypes are presented. Then, numerical studies will be discussed.

Résumé – Cet article vise à présenter un nouveau système hydride composé d'un récupérateur d'eau de pluie enterré dans lequel un échangeur de chaleur eau-eau est ajouté pour permettre une récupération de froid ou de chaleur. Cette solution simple, low-tech, encore peu étudiée dans sa globalité, permet d'assurer un rafraichissement passif des bâtiments ainsi qu'une réduction de la consommation d'eau du réseau pour les usages domestiques non potables. Tout d'abord, des résultats expérimentaux issus de deux prototypes à l'échelle seront présentés pour ensuite aborder les résultats obtenus via des premiers modèles numériques.

Nomenclature

c_p	heat capacity, $J.kg^{-1}.K^{-1}$
D	diameter, m
h_c	convection coefficient, $W.m^{-2}.K^{-1}$
HX	heat exchanger
$\dot{Q}$	heat flux, W
q_m	mass flow, $kg.s^{-1}$
q_v	volume-flow, $m^3.h^{-1}$
RMSE	Root Mean Square Error
T	temperature, K
z	altitude, m
Greek symbols	
λ	thermal conductivity, $W.m^{-1}.K^{-1}$
ρ	density, $kg.m^{-3}$
Subscripts and exponents	
a	air
cv	convection
dcw	district cold water
evap	evaporation
gard	garden
gr	ground
HX,a	air to water heat exchanger
HX,w	water to water heat exchanger
HX,i	heat exchanger inlet
HX, o	heat exchanger outlet
in	to tank inside air
loss,a	wall in contact with the air
loss,w	wall in contact with the water
of	overflow
out	to outside
toil	toilet
rad	radiative
vent	ventilation
w	water

1. Introduction

With climate change, summer comfort and CO2-emission reduction are two increasingly relevant topics. In this project, we are trying to develop a low-tech system using a rainwater tank allowing for the cooling of the supply air of indoor spaces without using refrigerants or with a reduced energy expense.

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The literature review shows a lack of detailed studies of such systems. The exploitation of experimental data was treated by Kaltz [1] and the study by simulation was done by Upshaw [2] or Sodah [3], while Gan [4], considered the tank as a heat source for a heat pump (active system), which is different from our approach. To the best of our knowledge, the modelling of variable free-surface water storage and the related mass and heat transfers involved appears to be poorly documented.

To set up the model, the physical equations from both usual domestic water tanks and atmospheric reservoirs were combined, taking into account heat transfers between air and water. We hence aim here at establishing and validating an equation-based physical model, using the data of two full-scale prototypes in operation since July 2021.

The final goal of this project is to couple the model with a state-of-the-art building energy simulation tool in order to estimate the relevance of the system regarding summer comfort.

This work is organised as follows: first the principle of the system is explained, then the experimental setup and results are described and eventually a first version of numerical model and simulation is presented.

2. Main concept of the Rainergies system

The basis of our solution consists in a new or existing buried rainwater tank, initially used for rainwater collection as non-potable domestic water and the relief of sewage networks. In France, the water resources management legislation locally enforces the water management at parcel level which could democratize the use of such rainwater tanks [5]. A helicoidal water-to-water heat exchanger is placed in the tank in order to take advantage of the heat storage capacity of water as a by-product. Thanks to an air-to-water heat exchanger connected to the ventilation supply duct, the tank delivers cooling energy to the building during summer [6].

In summary, the "Rainergies" system consist in following elements:

- A water tank for rain collection,
- A water/water coil heat exchanger immersed in the rainwater tank,
- A water/air heat exchanger placed after the supply air duct and connected to the immersed coil.

The main feature of this system is to provide cooling to the supply air, using the heat storage capacity of rainwater and of its surrounding ground, without using a refrigerant cooling system. As a by-product, the device can be used for the pre-heating of supply air in winter, as it benefits from the thermal inertia of the ground.

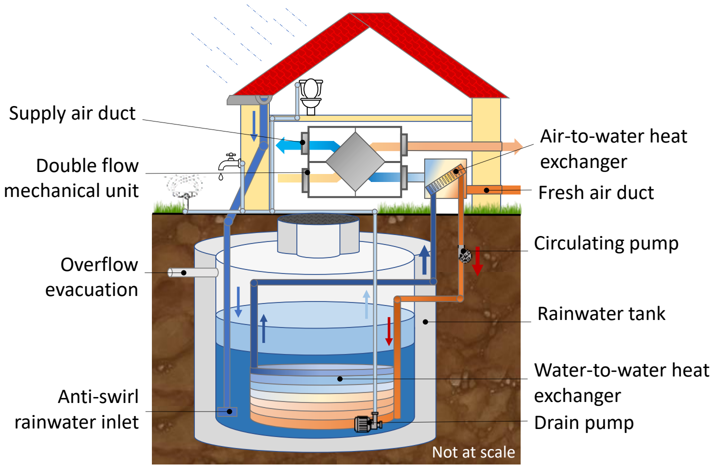

Figure 1 *: Schematic diagram of the Rainergies principle*

3. Experimental Study

3.1. Experimental set-up

Three Rainergies prototypes are installed in different locations in Alsace, France, in a semi-continental climate [7]. For the sake of conciseness, this article focuses on one prototype, located in Haguenau.

It consists of a 11 m^3 tank made of precast concrete with a coppered hundred-meter-long coiled heat exchanger. The surrounding ground is dry sand. A 1 kW cooling heat-exchanger, placed before the double flow mechanical unit, allows the heat transfer from the water loop to the supply air ventilation of a 150 m² family house which dates from the 1930's but has been retrofitted lately to match current standards of the French building energy code.

Another prototype, also installed in a residential house, is very similar. The third system is located under a small office building with a larger tank of 25 m^3 and two immersed coils.

These prototypes will be the topic of a future communication, allowing to compare results with different setups (e.g. the position of the coil in the double flow mechanical ventilation) and ground properties (sandstone and groundwater flow).

3.2. Measurements

Presently, the Haguenau prototype is monitored with more than 25 sensors connected to dataloggers, with a minimum timestep of 10 min. The devices were installed in the summer 2021 and consolidated data is available since early 2022. The main measured data with their sensor references are:

- Water temperature stratification thanks to 5 fixed dataloggers (ref. HOBO MX2203) 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).
- Air temperature and humidity inside the tank (ref. HOBO U23-002A).
- Temperatures at the air-to-water heat exchanger limits (both air: ref. HOBO U23-002A and water: type K thermocouple).
- Meteorological data including rainfall, global solar radiation, air temperature and humidity (ref. Davis Vantage Pro 2).
- Temperature inside the buildings (at air vent and in the room: ref. HOBO UX100-01)

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

3.3. Experimental Results

During summer operation, as observed on Figure 2, the system can decrease the supply temperature of the ventilation up to an encouraging 13°K, keeping indoor temperatures of the monitored houses under 27°C during the 2022 summer French heatwave. The cooling energy between the 14th of May to 1st of September reached 455 kWh (considering an average ventilation flow rate). The average cooling power is 365 W but peaks of 1 kW were observed. Measurements show little variation of the air-to-water heat exchanger efficiency between [0.64 ; 0.88] with an average of 0.82 ± 0.16 which is consistent with the design value.

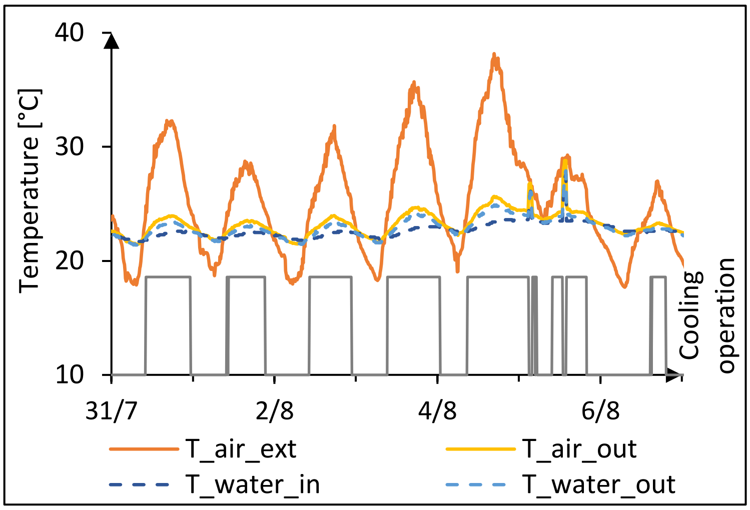

Figure 2 : *Air and water temperature variations in the air-to-water HX, summer operation (2022 - Week 31 - Haguenau)*

In winter, it is also possible to use the energy in the tank for preheating before it passes through the double flow ventilation. This preheating is necessary to protect the ventilation elements from freezing in case of negative outdoor temperatures. It is usually provided by an electrical heater. On the Haguenau prototype, this phenomenon was observed during 120 h over the winter period 2021-2022 (November 1st to March 15th), corresponding to ~39 kWh saved. The power supplied reaches 500W (average of 230W) and the air temperature was maintained above 0°C despite outdoor dry bulb temperatures of -6°C (see Figure).

Thus, the system also allows for energy savings in winter (though in moderate quantities). Noticeably, winter operation allows to cool down the reservoir and its surrounding ground, which is beneficial for summer operation, as it participates to a seasonal energy storage.

One of the difficulties of this project is to assess correctly the input parameters and their influence on the system behaviour. The experimental observation phase of the project can help to highlight and understand these events. For example, during rainfalls the water temperature inside the tank is influenced by the quantity of rain but also its temperature (see Figure – "*T_Xm*" meaning that the temperature sensor is at X m starting from the bottom of the tank) : during rainy events, for similar quantities the water temperature in the tank may drop significantly differently. As this phenomenon is not observed after each rainfall, the hypothesis can be made that the temperature of the rain arriving in the tank is in cause. This parameter is difficult to evaluate, however recording the temperature inside the tank rainwater filter will allow in the future to validate the rain temperature model chosen.

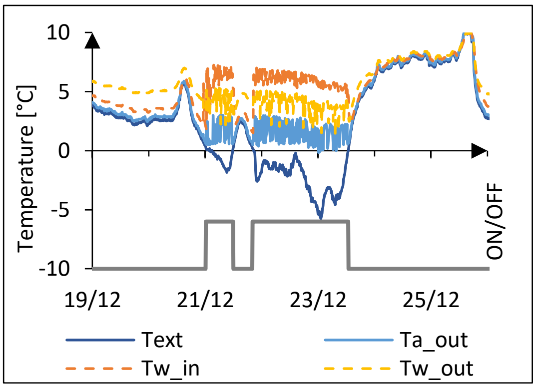

Figure 3*: Air and temperature variations in the air-to-water HX, winter operation (2021 - Week 51 - Haguenau)*

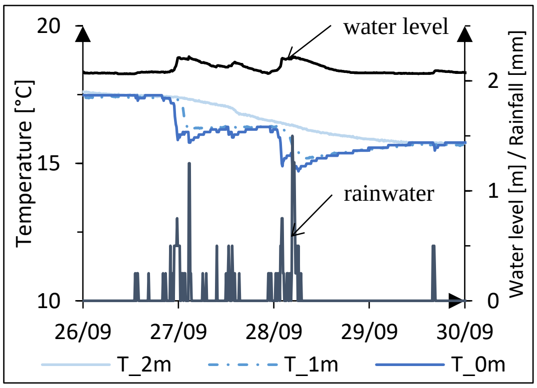

Figure 4*: Water temperature and level in the rainwater tank during rainy event (2022 - Week 39 - Haguenau)*

4. Numerical Modelling

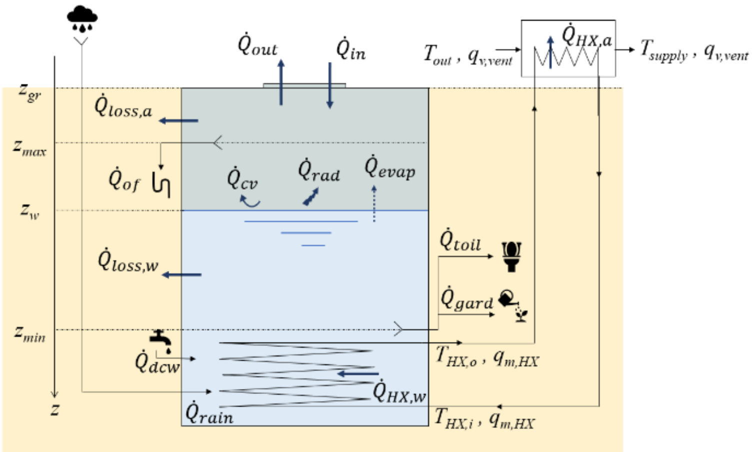

Figure 5*: System thermal balance*

4.1. Tank model

In first approach the tank is modelled with two temperature nodes, the ambient air temperature (T_a) and the water temperature (T_w) associated with their volume V_a and V_w, with the notations described in Figure 5, which also shows the heat fluxes involved in the system thermal balance (see Nomenclature).

$$\rho_w c_{p_w} \frac{dV_w T_w}{dt} = -\dot{Q}_{loss,w} - \dot{Q}_{cv} - \dot{Q}_{rad} - \dot{Q}_{evap} + \dot{Q}_{HX,w} + \dot{Q}_{rain} + \dot{Q}_{dcw} - \dot{Q}_{toil} - \dot{Q}_{gard} - \dot{Q}_{of} \quad (1)$$

$$\rho_a c_{p_a} \frac{dV_a T_a}{dt} = -\dot{Q}_{loss,a} + \dot{Q}_{cv} - \dot{Q}_{out} + \dot{Q}_{in} \quad (2)$$

The inlet and outlet temperatures of the coil are computed through both equations of the air-to-water and water-to-water heat exchanger. As mentioned in the experimental results section, the air-to-water heat exchanger efficiency does not vary much, hence it is assumed constant which is also consistent with the forced convection that takes place in the exchanger. For the first simulations, the same hypothesis has been made for the water-to-water heat exchanger efficiency. The supply air temperature is determined by heat flow egality at the air-to-water heat exchanger.

4.2. Ground model

The ground is assumed to be homogeneous with constant properties not depending on the soil moisture. As the heat transfer is symmetrical according to the z axis, the 2D heat transfer equation in cylindrical coordinates was used:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} \right) \quad (3)$$

The numerical model for the heat equation is a discrete finite volume formulation of Equation (3). Depending on the volume location, thermal properties are adapted. A source term is added on the superficial node to consider the solar radiation. In this first model, the spatial discretisation is constant with 50 cm mesh, but it is intended that following developments integrate a variable space discretisation with local refinements around the tank. The variation of ground moisture content is not taken into account in this first modelling attempt.

4.3. Solving procedure

In order to solve simultaneously for the air, water and ground temperatures, the semi-implicit Crank-Nicolson numerical method was used as described by Walther [8]. It has the advantage of unconditional stability and is of second order in space and time.

5. Model validation

5.1. Simulation hypothesis

Input parameters, such as weather data or geometrical parameters, are extracted from measured prototype data. Glycol water mass flow and air ventilation flow are considered constant respectively at 0.14 $kg.s^{-1}$ according to the design value and 200 m^3/h according to one-off measurement values. Convection coefficients were assessed for steady state and kept constant throughout the simulation.

The ground temperature was assumed constant at a depth of 10 meters below ground level. The outdoor weather data are used as boundary condition for ground surface (temperature, wind and solar flux retrieved from experimental data). The vertical boundaries are adiabatic (symmetry along the z-axis and vertical heat flux at sufficient distance from the tank).

5.2. Numerical Results

The prototype setup was simulated over the summer period (from the 14/05/22 to the 31/08/22), using the boundary conditions described in previous section.

The simulation results obtained are presented on Figure , depicting the simulated versus measured water tank temperature (above) and the supply air temperature (below). This first model exhibits a correct behaviour in terms of dynamics of the phenomenon, although the magnitude of variations can possibly be fine-tuned after the model's improvements/, *e.g.* if the uncertain parameters are fitted (convection coefficients, rain temperature…).

Considering the simplifications made, the numerical results are very encouraging: the dynamics of water and air temperatures are respected and the simulated water-to-water heat exchanger inlet and outlet temperatures and air supply temperature globally match the experimental data.

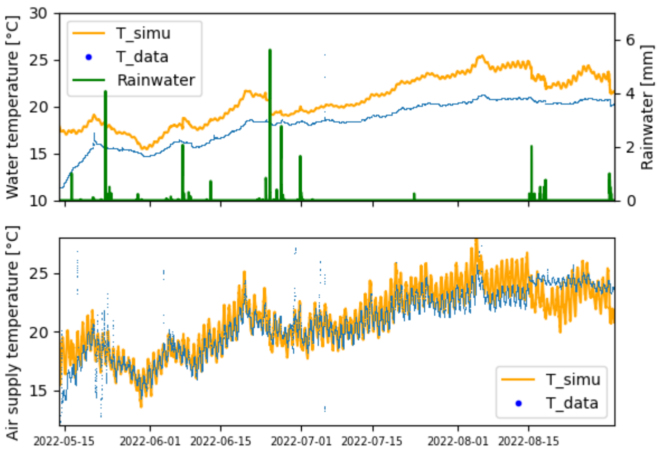

Figure 6*: Experimental and numerical data comparison during summer operation – focus on air supply and water tank temperatures*

	RMSE (°C)
Air tank temp.	1.62
Water tank temp.	2.66
Inlet HX temp.	1.09
Outlet HX temp.	1.19
Supply temp.	1.22

Table 1*: Root mean square error (RMSE)*

In terms of RMSE, the preliminary simulation results obtained are as follow: the highest error is made on the tank temperature prediction (2.77 K) and errors of the order of 1.09 to 1.62 K are made on other temperatures. In order to reduce the discrepancy between model and measurement, a sensitivity analysis of the model to its input parameters was undertaken.

5.3. Sensitivity analysis

In order to identify the influential parameters of the model, with the intention to obtain a better fit between model and measurements, a preliminary sensitivity analysis was conducted. We used Morris' [9] "one-at-a-time" sensitivity analysis method, which provides a ranking of parameters with an acceptable computational expense, given the involved simulation time (*id est* approximately 2 hours computation for 1 month simulated). The principle of Morris' method, nowadays widely used in the building simulation community, consists in computing the average elementary effect of the variation of one parameter at a time, usually for a dozen of repetitions. This was performed using the state-of-the-art SAlib python library.

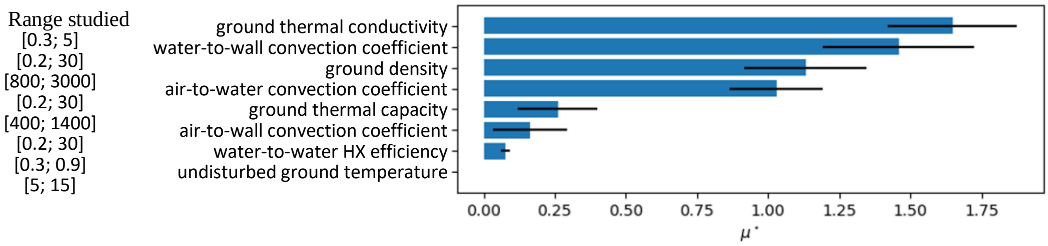

Figure 7*: Elementary effects of Morris's sensitivity analysis on the water tank temperature*

The investigation focusses on ground properties, thermal convection coefficients and the efficiency of the water-to-water heat exchanger. The results obtained on the water tank temperature are presented on Figure 7, where the thermal conductivity of ground, the reservoir wall convective transfer coefficient of water and the density of ground are the three first influent parameters.

The results show that following parameters are particularly influent on the outputs:

- All ground properties are significant on the water temperature output. Therefore, assessing those coefficients will be crucial for future work.
- The convection coefficient between wall and water, which calls into question the hypothesis of its non-variability.

As a sequel, a parametric fit optimisation on the most influent parameters will be undertaken in a future work, with the aim of obtaining a better prediction of the measured temperatures.

6. Discussion

On the experimental side, the primary results exhibit good results with outside air temperature reduction of more than 10 K and cooling power reaching 1 kW. Noticeably, this system does not aim at replacing air conditioning, but it can reduce its use, especially in high-performance buildings. During winter, the prototype can pre-heat the air to protect the installation from frosting, saving the use of an electrical heater.

It is foreseen to conduct data acquisition within shorter timestep to try to better understand short-timed event such as rainfall and its impact on the rainwater tank temperature.

Regarding numerical aspects, ensuing the sensitivity analysis, a parameter fitting procedure will be led in order to minimize the discrepancy between the model and measurements. Moreover, the models need improvement which have already been planned. The rainwater tank needs to integrate the water stratification along with an evaporation model and a better evaluation of air leakage within the tank which can strongly influence both air and water temperature. Thermal convection coefficients and water-to-water heat exchanger efficiency need also a finer calculation, *e.g.* depending on the air or water temperature instead of constant values.

7. Conclusion & Perspectives

With the rise of drought frequency, the applications of rainwater collection may widen, for example with the use of rainwater for domestic applications. This raises several new questions about the quality of the water stored in the tank. The water temperature increase may lead to microbiologic development. This problem is not very common and deserves some investigation. Microbiologic development can also be involved in the development of a biofilm leading to the heat exchanger fouling. At that time, neither visual observation nor performance degradation allow us to pronounce on that issue, which will remain under surveillance.

The applicability of such systems in real configurations, the performance prediction and the determination of design guidelines is obviously one of the objectives of the research conducted here, be it for commercial buildings or housing applications.

Coupling the model with a building energy simulation tool will allow in future works to optimize the controls and test the solution in different conditions (climate, …). It is also planned to explore the use of an adiabatic exchanger that can provide extra cooling power by water evaporation.

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