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

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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, scarcely studied in the literature (variable level of atmospheric water volume), performs the passive cooling of buildings and reduces domestic water network consumption (for non-potable uses). Experimental results retrieved from two at-scale prototypes are presented. Then, the discussion focuses on the numerical model built and its validation thanks to the experimental results. Sensitivity analysis used for model improvement will also be discussed.

Highlights
- Presentation of a low-tech and passive hybrid system using rainwater tank as geothermal probe.
- Scale one prototypes validated the concept and showed promising results (> 1 kW of cooling power)
- Comparison of experiment with a 2D numerical model using finite volumes Crank & Nicolson's method.

Introduction
"It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred." (IPCC.2021). In the light of the March 2023 IPCC’s report, this sentence, introduces the changes that will occur in the next decades. These include the increase of temperatures with more frequent and severe heatwaves, more intense precipitation but also prolonged droughts, biodiversity loss and impact on human health. Urgent action is needed to reduce greenhouse gas emissions and mitigate the impacts of climate change. Adaptation to the future climate is also an important issue and in the building sector this includes improving the summer thermal comfort. Currently, summer comfort is mainly provided by active air conditioning systems which are responsible for greenhouse gas emissions through their electricity consumption and their use of refrigerants. They can also contribute to the urban heat island effect.

This project aims at developing a system that allows passive cooling of buildings, i.e. without the use of refrigerants and with low energy consumption.

The main idea is to use buried rainwater tanks as geothermal probes by immersing a water-to-water heat exchanger (HX). Indeed, water management is also becoming a major issue, with both intense rainfall events and droughts on the increase. This hybrid system could therefore address both water management issues as well as providing cooling for buildings in summer.

The literature review shows a lack of detailed studies of such systems. The exploitation of experimental data from cold and hot water tanks connected to a thermo-active building system has been addressed by Kalz et al. (2010). They demonstrate that a 11 m³ cistern could provide about 1000 kWh of cooling energy over a whole year. Simulation studies have been carried out by Upshaw, Rhodes and Webber (2017) with the study of a non-buried rainwater storage tank. The approach considered the rainwater tank as a means of shifting the electrical peak load of an air conditioning unit. Sodha, Sawhney and Buddhhi (1994) simulate an open system with an aeration loop to enhance evaporative cooling but the calculation is performed only monthly, failing to capture sub-hourly temperature variations. Gan, Riffat and Chong (2007) and Marigo et al. (2021) exposed experimental and numerical studies of a buried water tank coupled to a heat pump, respectively with a plate HX and a coiled HX, which differs from the present work. Regarding Marigo et al. (2021) the ground heat exchanger consists of a helical polyethylene pipe immersed in a concrete water tank. The tank and pipe sizes are very similar to our prototypes; however the water surface remains static (no in or outflow of rainwater). To the best of our knowledge, the modelling of variable free-surface water storage and the associated mass and heat transfer appears to be poorly documented.

This paper aims to bring a more complete study of variable free surface water tank with a numerical model and an experimental validation. It is also expected to validate the use of this type of system as geothermal probe in a passive installation (without the use of a heat pump).

To set up the model, the physical equations from both usual domestic water tanks and atmospheric reservoirs were combined, taking into account heat transfer 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.

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, along with a sensitivity analysis following Morris’ method.

**Main Concept of Raineries Systems**

The basis of our solution consists in a new or existing buried rainwater tank (see Figure 1), 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 tank (Communauté d’Agglomération de Haguenau, 2017). The collected rainwater is mostly used for gardening but also for toilet flushing.

A helicoidal water-to-water heat exchanger in copper 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 heat exchanger connected to the ventilation supply duct, the tank provides cooling energy to the building during summer (Bouvenot, 2021).

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 ground boreholes for geothermal probes or the construction of a Canadian well.

In summary, the so-called “Raineries” system consists in following elements:

- A water tank for rain collection,
- A water/water coil heat exchanger immersed in the rainwater tank (inner fluide is glycol water),
- A water/air heat exchanger placed after the supply air duct and connected to the immersed coil,
- In option : an indirect adiabatic HX

**Experimental Set-up**

Three Raineries prototypes are installed in different locations in Alsace, North-East of France, in a semi-continental climate (SIU, 2021). For the sake of conciseness, this article focuses on one prototype, located in Haguenau.

It consists of a 11 m³ tank (see Figure 2 – diameter: 2.5 m and height: 3 m) made of precast concrete with a copper hundred-meter-long coil heat exchanger (22 mm diameter). Rainwater is collected from the 180 m² roof area via gutters and, after passing through an 800-micron filter, is directed to the bottom of the tank. There is an overflow outlet to the garden in case the maximum water level is exceeded.

The surrounding ground is dry sand. A 1 kW air-to-water cold battery (plate 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 m³ 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).

![Figure 2: Datasheet for a rainwater retention and storage tank – PLUVIEAU (translated).](https://example.com/datasheet.png)

**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 are:

- Water temperature stratification thanks to 5 fixed dataloggers 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.

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• Air temperature and humidity inside the tank.
• Temperatures and humidity at the air-to-water heat exchanger limits (both air and water) so that enthalpy can be derived. This will allow us to deduce the sensitive and latent exchanges.
• Meteorological data including rainfall, global solar radiation using a pyranometer, air temperature and relative humidity with 1 min timestep to record short event like precipitations.
• Temperature inside the buildings (at air vent and in the room).

In addition to continuous monitoring, on-off measurements were recorded during field missions, particularly for airflow rate, water level or water pH.

**Experimental Results**

The results observed in winter operation mode and summer operation are encouraging.

During summer operation, as observed on Figure 3, the system can decrease the supply temperature of the ventilation by up to 13°C, keeping indoor temperatures of the monitored houses under 27°C during the 2022 summer heatwave with outside temperatures close to 40°C.

The cooling energy between the 14th of May and 1st of September reached 455 kWh _i.e._ 3 kW/m² (considering an average ventilation flow rate of 240 m³/h). As shown in Figure 4, the average cooling power is 365 W but peaks of 1 kW have been observed. The 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 in line with the design value of 0.9.

The fact that airflow and waterflow are forced implies forced convection, which also explain the relatively constant value of the heat exchanger efficiency.

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 hours over the winter period 2021-2022 (November 1st to March 15th), corresponding to ~39 kWh saved. The power supplied reaches 500 W (average of 230 W) and the air temperature was maintained above 0°C despite outdoor dry bulb temperatures of -6°C (see Figure 5).

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.

![Figure 3: Air and Water temperature variations at the air-to-water HX limits during summer operation (2022 – Week 31 – Haguenau).](https://doi.org/10.26868/25222708.2023.1540)

![Figure 4: Cooling power produced by and Efficiency of the air-to-water HX during summer operation (2022 – Week 31 – Haguenau).](https://doi.org/10.26868/25222708.2023.1540)

![Figure 5: Air and Water temperature variations at the air-to-water HX limits during winter operation (2021 – Week 31 – Haguenau).](https://doi.org/10.26868/25222708.2023.1540)

![Figure 6: Water stratification and air temperature inside the tank during summer operation (2022 – Week 33 – Haguenau).](https://doi.org/10.26868/25222708.2023.1540)

The experimental study also allows for a better understanding of the behaviour of the system. Thanks to the different datalogger placed in the water tank, we observed that the water stratification (Figure 6) is higher in summer with a temperature difference between the top and bottom of the tank reaching 3°C at its maximum.
“Tw/a Xm” stands for water/air temperature at X m from the bottom of the tank. The water temperature at the bottom is influenced by the water-to-water HX. The air temperature (yellow) is influenced by the outside air temperature (green). At the end of the winter 2022, the bottom tank temperature was at 5°C and at the end of summer 2022 the bottom temperature was slightly above 20°C while the surface temperature was between 22 and 23°C. Experimental data also validated the model’s hypothesis of saturated air inside the tank. During the year 2022, the relative humidity inside the tank reached 100% most of the time and did not fall under 95%.

**Numerical Modelling using finite volumes and Crank-Nicolson’s Scheme**

One of the aims of the project is to build a model of the system that can predict its behaviour, *i.e.* the temperatures inside the tank and at the heat exchangers terminals.

The Figure 7 shows the different heat flows involved in the operation of the system which will be detailed in the following paragraphs.

The model is built on Python using a finite volume approach and consists of two coupled parts:

- The tank and system model (meaning the air and water heat exchangers)
- The soil surrounding the tank

The model will be then validated through the collected experimental data.

The aim of validation, still to be conducted in future works, is obviously to allow for the study of this system under other operating conditions and in particular in future climates (confrontation with droughts and heat waves).

\[
\rho_w c_p w \frac{dV_w T_w}{dt} = -\dot{Q}_{loss,w} - \dot{Q}_{cv} - \dot{Q}_{rad}
- \dot{Q}_{evap} + \dot{Q}_{HX} + \dot{Q}_{rain} + \dot{Q}_{dcw}
\]

\[
\dot{Q}_{HX} - \dot{Q}_{out} + \dot{Q}_{in} \quad (1)
\]

\[
\dot{Q}_{loss,a} = \dot{Q}_{cv} + \dot{Q}_{out} + \dot{Q}_{in} \quad (2)
\]

The different heat flows \(\dot{Q}_k\) are detailed below, starting with the water node thermal balance.

The conduction losses between the water and the ground depending on \(U_{w,gr}\) the heat transfer coefficient, taking into account the convection resistance (between the water and the tank wall), taken in the literature from Incropera (2011) and conduction resistance (depending on wall thickness and concrete thermal conductivity), and \(\overline{T}_{w,gr}\) the weighted mean temperature of the ground adjacent to water:

\[
\dot{Q}_{loss,w} = U_{w,gr} S_w (\overline{T}_{w,gr} - T_w) \quad (3)
\]

The convection heat flux between the air and water with \(h_{c,a-w}\) the convection coefficient depending on air speed \(\overline{u}_w\) inside the tank (assumed constant) (Auer, 1996):

\[
\dot{Q}_{cv} = h_{c,a-w} S_w (T_a - T_w) \quad (4)
\]

The radiative heat flux from the wall to the tank above it with \(U_{r,gr}\) the heat transfer coefficient, taking into account the conduction and the linearized radiative resistance, also taken from Incropera (2007):

\[
\dot{Q}_{rad} = U_{r,gr} S_w (\overline{T}_{a,gr} - T_w) \quad (5)
\]

The evaporative heat flux depending on the vaporization latent heat \(L_v\) and the evaporation mass flow rate computed thanks to Hens’ correlation (2009) involving the vapour pressure difference between the saturated air at the water surface and the air inside the tank:

\[
\dot{Q}_{evap} = -q_{m, evap} L_v \quad (6)
\]

The heat flux extracted from the water by the water-to-water heat exchanger:

\[
\dot{Q}_{HX} = q_{m, HX} c_{pw} (T_{HX, o} - T_{HX, i}) \quad (7)
\]

The rain and district cold water (dcw) heat fluxes due to water intakes are treated as advection fluxes:

\[
\dot{Q}_{rain} = q_{m, rain} c_{pw} T_{rain} \quad (8)
\]

\[
\dot{Q}_{dcw} = q_{m, dcw} c_{pw} T_{dcw} \quad (9)
\]

Likewise, the withdrawals due to toilet flushing (toil), gardening (gard) or overflowing (of) are computed as advection fluxes:

\[
\dot{Q}_{toil} = -q_{m, toil} c_{pw} T_w \quad (10)
\]

\[
\dot{Q}_{gard} = -q_{m, gard} c_{pw} T_w \quad (10)
\]

\[
\dot{Q}_{of} = -q_{m, of} c_{pw} T_w \quad (10)
\]

The heat flux involved in the air node thermal balance are now presented below.

The conduction losses between the air and the ground depending on \(U_{a,gr}\) the heat transfer coefficient, taking into account the convection resistance (between the air and the tank wall) and conduction resistance in the same way as the previously, and \(\overline{T}_{a,gr}\) the weighted mean temperature of the ground adjacent to the air volume:

**Figure 7: Scheme of the system thermal balance.**

**Tank-System Model**

In first approach the tank is modelled with two temperature nodes, the ambient air temperature \(T_a\) and the water temperature \(T_w\), with the notations described in Figure 7. Heat transfer coefficient were calculated at steady states with average water and air temperatures. (1) and (2) describe the thermal balances of the water node and air node, respectively.

\[
\rho_w c_p w \frac{dV_w T_w}{dt} = -\dot{Q}_{loss,w} - \dot{Q}_{cv} - \dot{Q}_{rad}
- \dot{Q}_{evap} + \dot{Q}_{HX} + \dot{Q}_{rain} + \dot{Q}_{dcw}
\]

\[
\dot{Q}_{HX} - \dot{Q}_{out} + \dot{Q}_{in} \quad (1)
\]

\[
\dot{Q}_{loss,a} = \dot{Q}_{cv} + \dot{Q}_{out} + \dot{Q}_{in} \quad (2)
\]

The different heat flows \(\dot{Q}_k\) are detailed below, starting with the water node thermal balance.
\[ Q_{\text{loss,a}} = U_{a,gr} S_a (T_{a,gr} - T_a) \]  

(11)  

The convection flux between air and water, already detailed in (4):

\[ Q_{\text{w}} = h_{c,a-w} S_{w-a} (T_w - T_a) \]  

(12)  

The air leakage (leak) and volume variation airflow (out or in) heat fluxes are also computed as advection fluxes. \( q_{m,\text{in}} \) and \( q_{m,\text{out}} \) only depends on the air volume volume difference over the timestep and \( q_{m,\text{leak}} \) is calculated through an air change rate \( \tau \):

\[ Q_{\text{out}} = -(q_{m,\text{out}} + q_{m,\text{leak}}) T_a \]

\[ Q_{\text{in}} = (q_{m,\text{in}} + q_{m,\text{leak}}) T_{\text{ext}} \]

\[ q_{m,\text{leak}} = \tau V_a \]  

(13)  

The inlet and outlet temperatures of the coil are computed through both expressions of the air-to-water and water-to-water HX efficiencies. 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 and around the exchanger. In this model, the water-to-water HX efficiency is also considered constant. The supply air temperature is determined by the balance of the heat flow at the air-water HX.

**Ground Model**

The ground is assumed to be homogeneous with constant properties, independently 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:

\[ \rho_{gr} c_{gr} \frac{\partial T}{\partial t} = \lambda_{gr} \left( \frac{\partial^2 T}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) \right) \]  

(14)  

The numerical model for the heat equation is a discrete finite volume formulation of Equation (13) (a ground mesh is therefore created). Depending on the volume location, thermal properties are adapted. A source term is added on the superficial node to consider the solar radiation. The variation of ground moisture content is not modelled in this first model.

**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, 2021). It has the advantage of unconditional stability and is of second order in space and time.

**Model Exploitation**

**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 240 m\(^3\).h\(^{-1}\) 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 the ground surface (dry bulb temperature, wind and total solar radiation) with a convection coefficient \( h_{ext} \) assumed constant at 20 W.m\(^{-2}\).K\(^{-1}\). Due to the z-axis symmetry, only half of the tank and ground surrounding are calculated. At a sufficient distance from the tank, temperature fields are parallel and horizontal, meaning there only a vertical heat flux, resulting in adiabatic boundaries for vertical edges of the mesh (see also Figure 10).

The input parameters are summarized below in Table 1.

**Table 1. Input parameters of the presented simulation.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Simulation parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Time step</td>
<td>600 s</td>
</tr>
<tr>
<td>Spatial step through z axis</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Spatial step through radial axis</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Increasing factor through radial axis</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Geometrical dimensions</strong></td>
<td></td>
</tr>
<tr>
<td>Tank diameter &amp; height</td>
<td>2.6 &amp; 3m</td>
</tr>
<tr>
<td>Tank depth</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Ground domain depth</td>
<td>10 m</td>
</tr>
<tr>
<td>Ground domain radius</td>
<td>10 m</td>
</tr>
<tr>
<td><strong>Material properties</strong></td>
<td></td>
</tr>
<tr>
<td>Ground thermal conductivity</td>
<td>1 W.m(^{-3}).K(^{-1})</td>
</tr>
<tr>
<td>Ground heat capacity</td>
<td>1100 J.kg(^{-1}).K(^{-1})</td>
</tr>
<tr>
<td>Ground density</td>
<td>1600 kg.m(^{-3})</td>
</tr>
<tr>
<td><strong>Heat transfer coefficients</strong></td>
<td></td>
</tr>
<tr>
<td>Water-to-water HX efficiency</td>
<td>0.8</td>
</tr>
<tr>
<td>Air-to-water HX efficiency</td>
<td>0.8</td>
</tr>
<tr>
<td>Water to tank wall convection coefficient</td>
<td>200 W.m(^{-2}).K(^{-1})</td>
</tr>
<tr>
<td>Air to tank wall convection coefficient</td>
<td>5 W.m(^{-2}).K(^{-1})</td>
</tr>
<tr>
<td>Air to water surface convection coefficient</td>
<td>3.1 W.m(^{-2}).K(^{-1})</td>
</tr>
</tbody>
</table>

**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 8 and Figure 9. Figure 8 shows the air-to-water heat exchanger temperature variation during the hottest week of summer 2022. Compared to experimental results of the same period presented on Figure 3 (and reported on Figure 8), this first model exhibits a correct behaviour in terms of dynamics of the phenomenon.

**Figure 8: Simulated and experimental Air and Water temperature variations at the air-to-water HX limits (2022 – Week 31 – Haguenau).**
Figure 9 depicts the simulated versus measured water tank temperature (above) and the supply air temperature (below), highlighting that although the magnitude of variations can potentially be fine-tuned by identification of simulation parameters (e.g. heat transfer coefficients, ground properties), the dynamics are well preserved.

A thorough validation of the model is still pending and will be performed by minimizing the root mean square errors (RMSE) for each output defined by:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{N}(T_{\text{simu}} - T_{\text{data}})^2}{N}}
\]  

(15)

We aim at reducing the RMSE to the accuracy of the sensors (± 0.25°C).

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

Figure 9: Experimental and numerical data comparison – Haguenau prototypes – focus: air supply and the water tank temperatures.

Even though the air and water tank temperatures display larger root mean square errors, the errors in the inlet/outlet temperatures of the air-water exchanger, which are used to calculate the performance of the system, remain under one degree (see Table 2 below).

Figure 10 presents the ground temperature variation after the summer operation. It is clearly influenced by the rainwater tank, but the effect seems limited at a radial distance of 5 m. A multiyear computation will be necessary to verify that observation.

Table 2: Root Mean Square Error (RMSE) between numerical and experimental results.

<table>
<thead>
<tr>
<th>Analysed output</th>
<th>RMSE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air tank temperature</td>
<td>1.90</td>
</tr>
<tr>
<td>Water tank temperature</td>
<td>1.10</td>
</tr>
<tr>
<td>Inlet HX temperature</td>
<td>0.84</td>
</tr>
<tr>
<td>Outlet HX temperature</td>
<td>0.83</td>
</tr>
<tr>
<td>Supply temperature</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Figure 10: Temperature fields in the ground during summer operation (8th of August).

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’ “one-at-a-time” sensitivity analysis method (Morris, 1991), taken up by Campolongo, Cariboni and Saltelli (2007), which provides a ranking of parameters with an acceptable computational expense, given the involved simulation time (id est approximately 2 hours computation for 4 months 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 (twenty repetitions in the presented case with eight parameters meaning 20 × (8 + 1) = 180 simulations). This was performed using the state-of-the-art S4Alib python library.

Figure 11: Elementary effects of Morris’s sensitivity analysis on the water tank temperature.

The results obtained on the water tank temperature and air tank temperature are presented on Figure 11.

The investigation focused on ground properties, thermal convection coefficients and the efficiency of the water-to-water heat exchanger. For readability, the parameters are numbered, and the range of variation studied is given in brackets:

- 1: ground thermal conductivity (0.3 – 5) [W.m⁻¹.K⁻¹]
- 2: ground density (800 – 3000) [kg.m⁻³]
- 3: ground thermal capacity (400 – 1400) [J.kg⁻¹.K⁻¹]
- 4: water-to-wall convection coefficient (50 – 350) [W.m⁻².K⁻¹]
- 5: undisturbed ground temperature (5 – 15) [°C]
• 6: air-to-water convection coefficient (0.2 – 30) [W.m\(^{-2}\).K\(^{-1}\)]
• 7: air-to-wall convection coefficient (0.2 – 30) [W.m\(^{-2}\).K\(^{-1}\)]
• 8: water-to-water HX efficiency (0.3 – 0.9) [-]

Similar studies were also conducted on the inlet and outlet heat exchanger temperature and on the supply air temperature. The conductivity of ground, the thermal capacity of the ground and the density of ground are the three first influential parameters. The reservoir wall convective transfer coefficient of water is also influential on the water tank temperature.

The results show that following parameters are particularly influential on the outputs:
• All ground properties are significant on the water temperature output. Therefore, assessing those coefficients will be crucial for future works.
• The convection coefficient between wall and water, which calls for a temperature dependant formulation in the model.

As a sequel, a parametric fit optimisation on the most influential parameters will be undertaken, with the aim of obtaining a better prediction of the measured temperatures and fully validating the model.

**Discussion**

On the experimental side, the primary results exhibit good result 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 frost, 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 lead in order to minimize the discrepancy between the model and measurements. Moreover, the models need further improvements: the rainwater tank should integrate the water stratification along with an evaporation model and a better evaluation of air leakage 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.

It is also planned to assess the overall efficiency of the system taking into account the electricity consumption of the circulating pump. In passive systems study, auxiliary power consumption is often overlooked and can reduce the benefits of the passive heat recovery.

**Conclusion and Perspectives**

A new concept of buried rainwater tank hybridized by immersing a water-to-water heat exchanger to add the new function of geothermal probe was presented. The concept has been tested on two prototypes in real operation. The results are very promising and are an incentive for the continuation of the project and the development of models.

A first modelling of the system has been done in Python and solves the heat balances in discrete finite volume formulation using Crank-Nicolson’s method.

The model needs obvious improvement, in particular by developing a stratified tank model. The ground properties also need to be well assessed and the variations of its properties with moisture will be investigated. The comparison to the experimental data remains encouraging.

With the rise of drought frequency, the applications of rainwater collection may widen, for example with the use of rainwater for laundry. This raises several new questions about the quality of the water stored in the tank. The water temperature increase may lead to microbiologic development, which can make the water unsuitable for certain uses (such as supply for washing machine). It is also possible for a film to be deposited on the heat exchanger leading to fouling and deterioration of its performance, although none were observed during the tests. This problem would be a threat to the operation of the system and deserves a detailed investigation.

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.

In further works, the model will be coupled with a state-of-the-art building energy simulation tool in order to estimate the relevance of the system regarding summer comfort.

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, …). For the time being, a solution mentioned in a recent article of the National Renewable Energy Laboratory (2022) suggests that EnergyPlus, with its Python EMS (Energy Management System) feature, could be adapted for these applications. It is also planned to explore the use of a dew point cooler that can provide extra cooling power by water evaporation.

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**Nomenclature**

\( c_p \) heat capacity, J.kg\(^{-1}\).K\(^{-1}\)
\( h_c \) convection coefficient, W.m\(^{-2}\).K\(^{-1}\)
\( p \) pressure, Pa
\( \dot{Q} \) heat flux, W
$q_a$ mass flow, kg.s$^{-1}$
$q_v$ volume-flow, m$^3$.h$^{-1}$
$S$ Surface, m$^2$
$T$ temperature, K
$U$ heat transfer coefficient, W.m$^{-2}$.K$^{-1}$
$u$ air speed, m.s$^{-1}$
$V$ volume, m$^3$
$z$ altitude, m

Greek symbols
$\beta$ implicit-explicit distribution coefficient (between 0 and 1)
$\lambda$ thermal conductivity, W.m$^{-1}$.K$^{-1}$
$\rho$ density, kg.m$^{-3}$
$\tau$ air change rate, h$^{-1}$

Subscripts and superscripts
$a$ air
$a-w$ air to water
$cv$ convection
dcw district cold water
evap evaporation
$ext$ exterior (outside)
gard garden
$gr$ ground
gw glycol water
$HX.a$ 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
$sat$ saturated
$vap$ vapour
$vent$ ventilation
$w$ water
$+$ next time step

References


