SWC 2019

Seasonal Accumulation of Solar Energy in Aquifer for Thermal Conditioning

Summary

The present work aims to analyze the accumulation of thermal energy in aquifers, using the summer to season to heat water by solar collector and inject hot water into the aquifer, and using it for building heating during cold season. The first approach to model the behavior of the aquifer is made by analytical model and then an experimental arrangement is designed and built. The thermal and hydraulic parameters of the aquifer must be known in order to apply accurately analytical and numerical models. In the site of study, the behavior of the aquifer to an injection of hot water, heated by solar collectors is studied. These measures are used to compare, and as inputs to analytical and numerical models.

Key-words: UTES, ATES, energy storage, geothermal energy, solar energy

1. Introduction

As the energy demand increases, the conservation and efficient use of energy becomes crucial. Throughout the world, applications of the thermal energy storage system (TES) have proven to be economic and ecological solutions to energy problems and more and more attention has been paid to their use, [Paksy et al. (2004), Dincer and Rosen (2007)]. According to Cruickshank (2009), thermal systems are typically two to four times more efficient than photovoltaic (PV) systems. On the other hand, home heating and water heating are responsible for a large part of the energy needs of residential buildings: around 80% in Canada [NRCan (2011)] and 82% in Europe [Linder and Bahr (2007)]. Therefore, there is great potential in the use of solar thermal technologies to convert solar radiation into sensible heat.

When energy storage is carried out in an aquifer environment it is called (ATES) or "open" systems, where groundwater is extracted or injected into the aquifer through the use of wells to carry thermal energy in and out of the aquifer [Novo et al. (2010)]. Typically, the configuration of the system consists of using two wells to separate the extraction and injection of water, for its storage in the aquifer and its subsequent use in cooling and/or heating processes. These systems have been used successfully and are in operation in Sweden, Germany, the Netherlands, Belgium and other European countries. In Uruguay there are no experiences of this type, so there is potential for development and application of these widely used technologies.

2. Project description

The accumulation of thermal energy in aquifers (ATES) is based on the use of the heat capacity of water and solid media to accumulate heat and cold. The heat transfer occurs with the extraction of water from the aquifer through one well and re-injecting it in another at a modified temperature.

For the prediction of the thermal behavior of an aquifer accumulation installation, hydrogeological and thermal measurements on site and also modeling must be carried out [Paksy et al. (2004)].

An essential part of an ATES project is the characterization of the aquifer that will act as a medium for the storage of thermal energy. It is necessary to determine properties such as porosity, hydraulic, thermal transmissivity, etc. It is equally important to understand and know the hydraulic behavior of the aquifer in terms of magnitude and direction of the hydraulic gradient, the existence of preferential flow zones, etc.

This project aims at developing and using numerical models for the performance prediction and design of ATES systems, as well as designing and conducting experimental tests for their validation. Moreover, the use of the models in the evaluation of applicability in Uruguay of such systems is proposed, mainly for seasonal accumulation of solar energy, to be used for thermal conditioning of buildings.

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3. Experimental setup

The experimental facility is located above the Raigón aquifer in the town of Colonia Wilson, San José, Uruguay. Raigón is a sedimentary aquifer, composed mainly of sand and gravel, with an area of approximately 2300 km^2. In the zone where the experimental essay is installed, the aquifer behaves as free surface and is highly productive, with specific flows of the order of 15m^3/h/m. The transmissivity of the medium is in the order of 200m^2/day, the saturated thickness is approximately 15m and the Darcy velocity of the underground flow in the area is 0.013m/day. Figure 1 shows a map of the area.

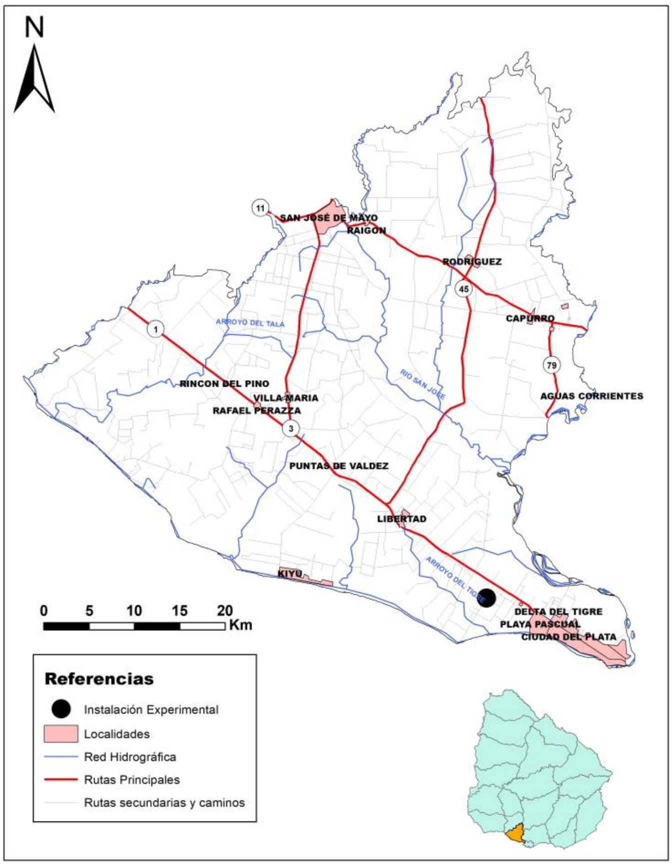

Fig. 1. Location of the experimental facility over Raigón aquifer.

The experiment consists in extracting water from one zone of the aquifer, passing it through a set of solar collectors in order to increase its temperature, and injecting it back into another zone of the aquifer, in the summer season. Inlet and outlet temperatures of the solar collectors, temperatures at different points of the heated aquifer, fluid flow, piezometric level and solar radiation are measured.

In winter, the inverse process is performed, with the aim to measure the temperature of the heated water and the amount of recoverable thermal energy.

Figure 2 shows schematically the experimental set up.

The extraction well is located far enough from the injection zone to avoid recirculation effects. Based on the characteristics of the aquifer, the extension of the land available for the implementation of the experiment and the operating flow, the extraction well was located 70 m from the injection well. Figure 3 shows a map in which the location of the wells and solar collectors is indicated.

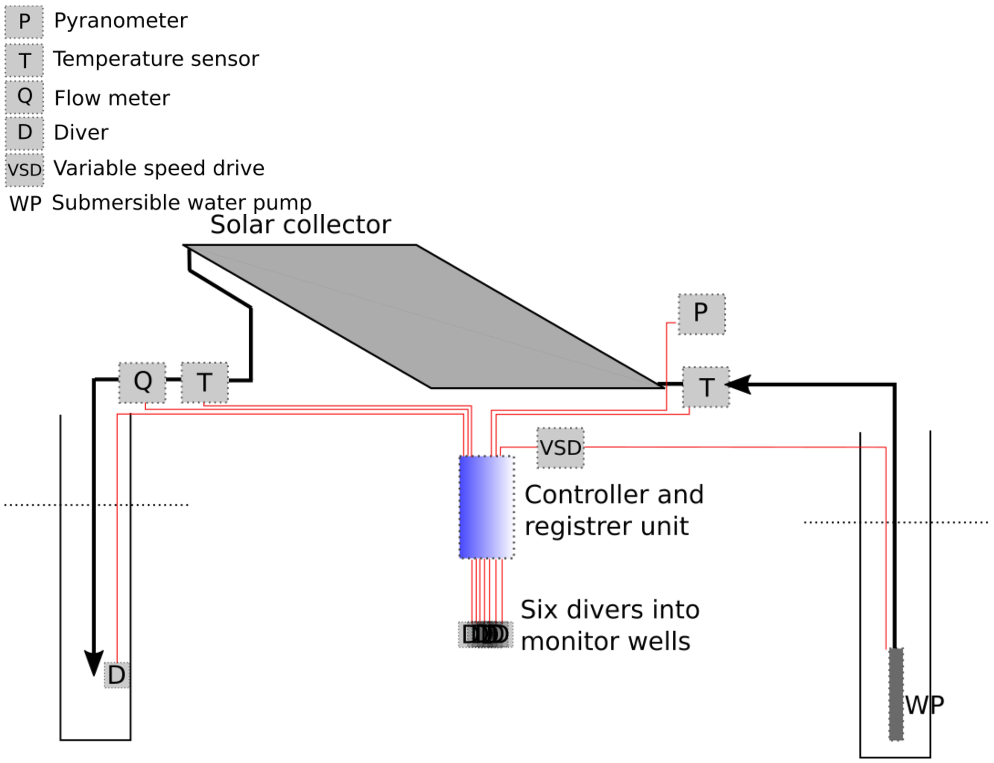

Fig. 2. Schematic of experimental array.

Divers are used to sense the temperature of the water and the height of the aquifer. One is placed in the injection well, and other six are placed in the monitor wells around the injection, specifically perforated to make these measurements. A pyranometer and flow meter complete the measurement instrumental. The system is monitored and controlled with a telemetry system, which allows seeing the measurements in real time, keeping the measurement history and modifying the control logic that operates on the system. The control logic takes temperatures and radiation as inputs and commands the variable speed drive (VSD) to actuate on the submersible water pump.

The system operates at a nominal flow rate of $1m^3/h$, passing through $35m^2$ of uncovered plastic solar collectors, to achieve a temperature of approximately 40ºC at the outlet when the solar radiation is around 1000 W/m^2 in a summer day. With the variation of solar radiation and ambient temperature, the flow rate is adjusted in order to assure that the temperature of the injected hot water is inside an acceptable range around the set point (40ºC).

Fig. 3. Installation overview and component scheme

All recorded data allow analyzing the behavior of the aquifer against the injection of hot water, and later, during the winter season, the thermal behavior of the aquifer when extracting the accumulated hot water for use in heating. Moreover, the injected and extracted energy can be calculated, and with these, the efficiency of the thermal storage.

4. Analytical model

Stauffer et al. (2014), analyses several models for the thermal use of underground water systems. Applying the moving source theory to a two-dimensional model that considers advection and conduction, yields the analytical solution for the response of a constant line source of infinite length along the vertical direction with a continuous heat flow rate $q_{tb} = J/H$ per unit length of the borehole (injection well). This is called MILS model and can be used to compute the variation in temperature in a plane perpendicular to the infinite line of energy injection/extraction for a given time, t. This model is used to represent temperature variations in a 2D cut of the aquifer, without considering the top and bottom edge effects. The model results in the following equation:

$$T(x,y,t) = T_0 + \frac{q_{tb}}{4\pi C_m \sqrt{D_{t,L} D_{t,T}}} \int_0^t exp\left[\frac{-[x-u_t\cdot(t-t')]^2}{4D_{t,L}\cdot(t-t')} - \frac{y^2}{4D_{t,T}\cdot(t-t')}\right] \times \frac{dt'}{(t-t')} \qquad \text{(eq. 1)}$$

where $D_{t,L}$ and $D_{t,T}$ are the longitudinal and transversal thermal diffusivity coefficients, respectively, which include thermal dispersion effects (β_L and β_T) and the thermal velocity of the acuifer u_t.

$$D_{t,L} = D_t + \beta_L u_t \qquad \text{(eq. 2)}$$

$$D_{t,T} = D_T + \beta_T u_t \qquad \text{(eq. 3)}$$

The thermal velocity of the aquifer is defined from the discharge vector of the aquifer (mean aquifer velocity or Darcy velocity, q) and the ratio between the volumetric thermal capacity of the water and the aquifer (C_w and C_m).

$$u_t = qC_w/C_m \qquad \text{(eq. 4)}$$

In this work, this model is used to predict the thermal behavior of a plane section of the aquifer, when hot water coming from solar water heaters is injected. The results are used to design the experimental array that is built in the Raigón aquifer.

For the hot water to be injected, a maximum of 40ºC is stablished to ensure that the aquifer will not suffer unwanted environmental effects. Then, several configurations with different flows are simulated using this analytical model and the response of the aquifer is observed. With the hot water flow and its temperature, the heat rate injected is calculated and used as an input (*J*) in the model.

The model returns the temperature increments in the extension of the aquifer. This is used for selecting the position of the boreholes to be perforated for temperature monitoring. Fig. 4 shows a map of the temperature increments of the aquifer for an injection flow rate of 1m^3/h with a temperature of 40ºC. It is observed that after three months of injection, the aquifer can be considered to reach steady state, and the temperature ceases to rise. Furthermore, temperature increments of around 10ºC at a distance of one or two meters from the injection well are obtained. This temperature rise is well suited to be measured with the available instruments (Divers), and perforating monitor wells separated around two meters from the injection well is feasible.

Figure 2 shows the temperature increment map for a 2D slice of the aquifer, where the natural flow is from west to east.

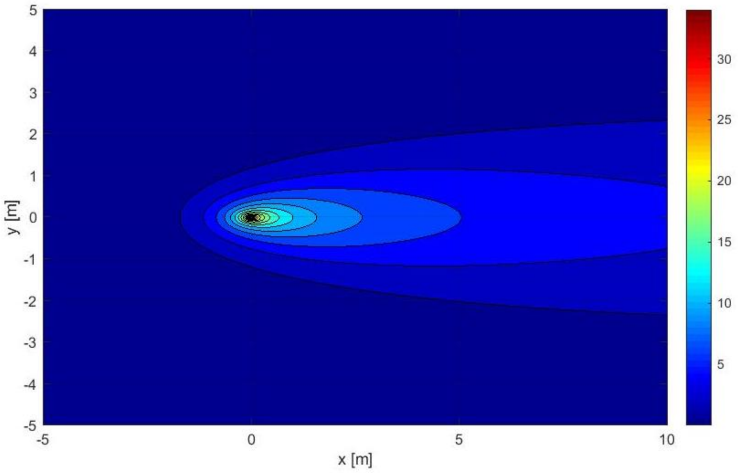

Fig. 4 Temperature increase 2D profile of the aquifer.

5. Results and discussion

The experimental arrangement is currently being adjusted and improved. It has been operative for a part of the summer season in Uruguay, and an increase in the temperature of the aquifer has been observed. In some of the measured points, a temperature increases up to 5ºC is observed. The temperature in the injection well is very sensitive to the flow rates and temperatures injected at each moment.

Figure 5 shows the behavior of temperatures in one day of operation. It is observed that at the beginning of the day the temperatures oscillate, which is due to the behavior of the system at starts up. When the pump is turned on, the system seeks that the outlet temperature, *tempOut*, rise to an acceptable minimum value by lower its flow rate. If at minimum flow rate, this temperature is not reached, the system stops to start again after a set period of time.

The difference between *tempIn* and *tempOut* is the result of solar energy captured by the solar collectors. Then, the temperature in the injection well is represented by *t3* in Fig. 5. It is observed how it responds almost immediately to the injected water, and when the system stops, it slowly decreases indicating that the energy disperses, heating the aquifer in the surrounding area. The temperatures of the monitoring wells are between 20 and 22ºC. The unaltered temperature of the Raigón aquifer is 17ºC.

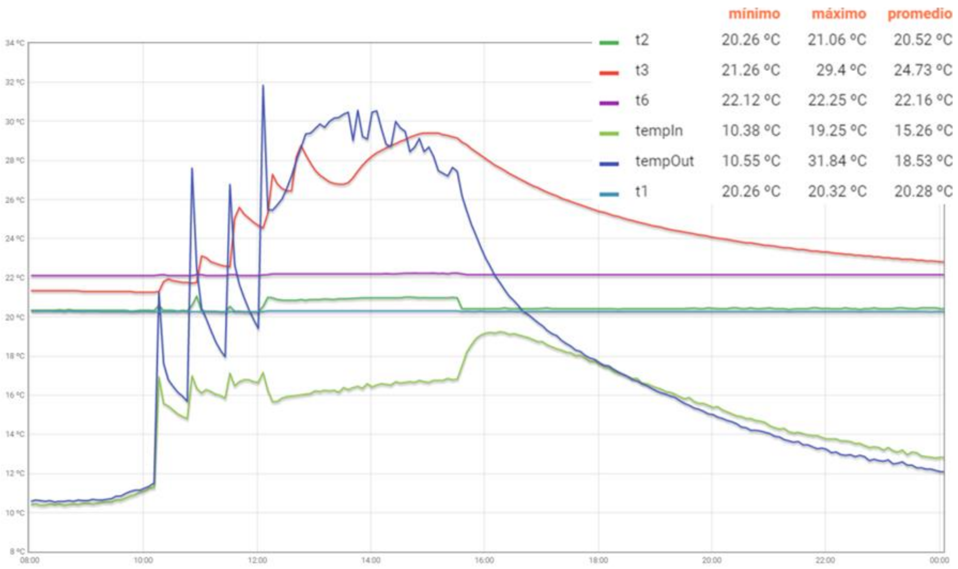

Fig. 2. Temperature measurements for a day of operation.

The data presented in Figure 5 correspond to a day in May (mid-autumn), where, using the measured flow values, a total energy of 16.4 kWh was injected, and a solar collector efficiency of 18% is reached. It is expected that the energy injected on a summer day will far exceed the calculated for this autumn day. Moreover, the efficiency of the collectors increases significantly when the ambient temperature is higher. An efficiency of 58% was measured in a summer day.

To project the operation of the system during the summer season, we consider the radiation data presented in figure 6, obtained directly from the “Laboratorio de Energía Solar” in Uruguay (LES). These radiation data in the place of interest arise from the work [Alonso-Suárez, 2014], where the methodology is detailed.

Radiation in the month of May is two to three times less than radiation in summer. With this, it is projected that the energy to be injected through the system will be close to 100 kWh per day in the hot season. Assuming a storage efficiency of 50%, and the same amount of days of heating in winter as of injection in summer, 50 kWh of heat per day could be obtained from this setup, which would mean around 6-7 kW during 8 hours of operation.

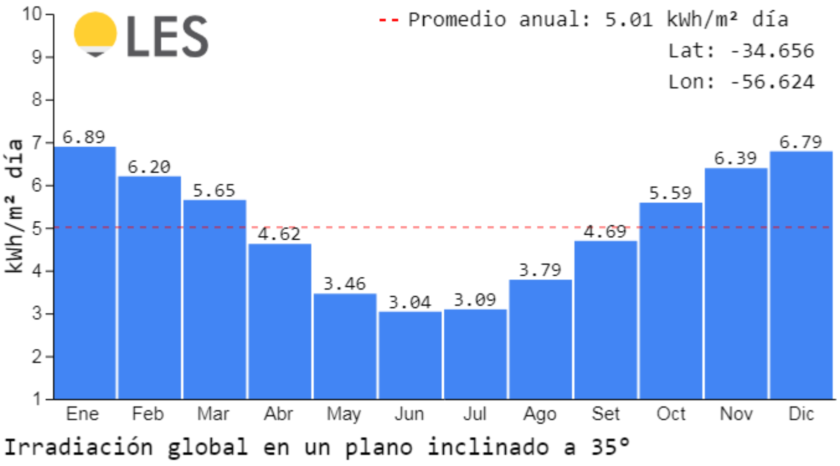

Fig. 3. Mean dayly radiation for each month at the site of the experimental facility (LES, 2019).

The system worked intermittently in the summer period, because it was still in the period of set-up and adjustments. The arrangement is neither conventional from hydraulic point of view, nor from its electrical installation and data-logging system, which resulted in the occurrence of several unforeseen problems, and delays with respect to the initial schedule. To effectively determine the operation and accumulation capacity during the summer period, the system must be operated in the next season in order to achieve a complete evaluation of the system. Afterwards, in the winter season, water must be extracted from the hot zone of the aquifer to finally determine the accumulation capacity and the performance of the seasonal accumulation of solar energy in the aquifer.

6. Further work

Since the installation has been made fully operational, a full summer season test has not been completed yet. It is necessary to achieve an injection of hot water throughout the whole season to assess sufficient temperature increases in the aquifer.

In parallel, we are working with the use of numerical models to simulate the behavior of the system, with the intention to use the experimental measurements for comparison and calibration. Aquifer relevant properties are being determined both by experimentation and the use of analytical correlations.

Once an injection summer cycle is completed, an extraction cycle will be carried out in winter, in order to quantify the energy that can be extracted and determine the efficiency and viability of the system.

7. Acknowledgements

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