ABSTRACT: The use of heat transfer from aquifers to buildings has substantially increased in the last years due to the growing interest in ground-source heat pumps, particularly in groundwater geothermal systems. In this framework, the Catalan Water Agency (CWA) started to develop the basis for a legal regulation of these activities to prevent impacts on groundwater resources. To improve the knowledge about the thermohydrochemical processes involved in these systems, the CWA has implemented an in situ thermal injection pilot test emulating the operation of a scaled real system. From this experiment, the impact produced in the aquifer can be determined and quantified. In such context, the data obtained can be the basis for improving the numerical interpretation which will be of use in the assessment and prediction of future commercial systems, in both (1) the design of the system itself, and (2) the associated impacts of its implementation. Some results of the modelling are presented.

INTRODUCTION

The Ground-source Heat Pump (GHP) systems, the most widespread very low enthalpy geothermal systems (Eugster and Sanner, 2007), can be implemented in two different ways depending on how the energy is exchanged in the ground, i.e., as closed systems or open systems. In open systems, at cooling mode, the heated fluid that flows through a building circuit is groundwater directly extracted from aquifers. After being pumped out, water is re-injected in the same aquifer at a different point from the extraction one and with a different temperature. The heat is transferred to the aquifer by advection and conduction through the materials of the aquifer. In closed systems, the fluid does not come into direct contact with the water inside the heat exchanger and it only heats the ground by conduction. This latter system is of much more widespread use. The GHP systems are coming out as an alternative to conventional systems in Spain and have gained interest recently due to the cheaper deployment and to a better energy efficiency and environmental sustainability.

The growing use of these systems, particularly open loop systems, and their possible placement in strategic aquifers have led the Catalan Water Agency (CWA) to implement an in situ thermal injection pilot test reproducing the operation of a scaled real system in order to study the associated impacts. This paper will show some tasks undertaken in the framework of this project. Major objectives deal with the development and implementation of a heat exchanger linked to a doublet system (production and injection wells). The obtained data will permit evaluate numerical methodologies to predict hydraulic and thermal impacts in the aquifer. Thus, in this paper the numerical reproduction of a real injection test is presented. The selected numerical code, TRANSIN IV (Medina et al., 2001; in advance TRANSIN) a conventional flow and transport numerical code, can be used by means of the analogy between solute and heat transport. Fundamentals of this transport analogy will be previously introduced. Further, by means of a synthetic case, this code will be compared to FEFLOW 5.4 (Diersch, 2002; in advance FEFLOW). This latter will permit heat simulation of both (1) indirect (solute transport analogy) and (2) direct simulations (explicit heat transport). Also, the use of a non linear
boundary condition at the injection well will be tested, with the aim of evaluating the capabilities of an open loop geothermal system at the same site of the in situ experiment. Finally the application of FEFLOW to simulate the real case will be described.

THEORETICAL BASIS

Different heat transport processes take place in porous media (de Marsily, 1986): (1) conduction in the solid matrix, (2) transport by the fluid phase and (3) heat exchange between the two phases depending on the temperature gradient. In practice, a common assumption is the consideration of a unique temperature in the whole porous medium, and the heat transport is characterized by convection similarly to that of the solutes and a phenomenon similar to that of dispersion in porous media.

Considering the mechanisms described, the heat balance of an aquifer can be expressed as the difference between the inputs and outputs of heat at the domain:

$$\rho_{aq} c_{aq} \frac{\partial T}{\partial t} = \nabla (\lambda + aq \rho_w c_w \nabla T) - (q \rho_w c_w \nabla T) + f$$

(1)

where $\rho_{aq}$ and $c_{aq}$ is the specific heat capacity of the aquifer (J/m$^3$/K), $\rho_w c_w$ is the specific heat of the water (J/m$^3$/K), $T$ is the temperature (K), $t$ is the time (s), $\lambda$ is the thermal conductivity of the aquifer (J/s/m/K), $a$ is the dispersivity (m), $q$ is the water flux in porous media (m/s) and $f$ is the heat sink/source (J/m$^3$/s).

So, it can be defined a thermal retardation factor $R$ and a thermal diffusion $D$:

$$R = 1 + \frac{(1 - \phi) \rho_s c_s}{\rho_w c_w}$$

(5)

$$D = aq + \frac{\lambda}{c_w \rho_w}$$

(6)

Then the equation (4) is defined as:

$$\phi R \frac{\partial T}{\partial t} = \nabla (aq + \frac{\lambda}{\rho_w c_w} \nabla T) - (q \nabla T) - f^*$$

(7)

**Analogy between heat and mass transport equations**

Equation (7) can be compared to the mass transport equation:

$$\phi R_s \frac{\partial c}{\partial t} = \nabla ((aq + D_m \nabla c) - (q \nabla c) - f_s)$$

(8)

where $c$ is the solute concentration (mg/L), $D_m$ is the molecular diffusion (m$^2$/s), $R_s$ is the retardation factor and $f_s$ is the solute sink/source (mg/L/s).

So it can be established an analogy between the equations (7) and (8) allowing the treatment of the heat transport as if it were a solute process (Table 1).
<table>
<thead>
<tr>
<th></th>
<th>Solute transport</th>
<th>Heat transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>$\phi$</td>
<td>$\phi$</td>
</tr>
<tr>
<td>Retardation</td>
<td>$1 + \frac{\rho_w k_w}{\phi}$</td>
<td>$(1 - \phi) \frac{\rho_s c_s}{\phi}$</td>
</tr>
<tr>
<td>Diffusion</td>
<td>$D_m$</td>
<td>$\frac{\lambda}{c_w \rho_w \phi}$</td>
</tr>
<tr>
<td>Dispersivity</td>
<td>$a_L - a_T$</td>
<td>$a_L - a_T$</td>
</tr>
</tbody>
</table>

Table 1: Analogy between heat and solute transport processes

APPLICATION TO A REAL CASE

A pilot test was designed to heat the aquifer simulating the implementation of a geothermal system. The system injects heated water into the aquifer in a hypothetical cooling mode in the operation of a geothermal system.

Local hydrogeology
The studied site is situated in Barcelona near the coast. This multilayer aquifer consists of two aquifers; the lower one, which is the focus of the present study, is made up with gravels, sands and clayey silts. The clayey silts behave hydraulically as aquitards. The contact between these lithologies is not clear enough but it appears to be a transition zone (Figure 1).

Figure 1: Schematic geological section oriented NO-SE

The design of the experiment
Specific equipment was designed for the experiments. Briefly, it was integrated by an extraction and an injection well (doublet system) separated by a distance of 20 m and both of 40 m depth. Also, the system includes a heat exchanger, which increases the temperature of the extracted water before re-injecting it. Seven piezometers were build-up to control the head and temperature at the upper and lower aquifers (see Figure 2). Piezometers Pz1, Pz2 and Pz4 were placed at the lower aquifer. Three different experiments were carried out, but only the first one is reported in this paper. This experiment injects a steady flowrate (177.6 m$^3$/d) during 9 days with a temperature increment of 5ºC.

Assumptions, Boundary conditions and Initial conditions
Only the principal aquifer is modelled, since the superficial aquifer is not affected during the experiments. The geological units, considered in the model, have constant thickness along the whole domain: the sand aquifer (10 m width) and the two units of silt that confine the aquifer (6 m and 5.5 m respectively).
Saturated conditions are assumed, with homogeneous and isotropic properties for each material. The density is kept constant.
The natural gradient of the aquifer is not reproduced as it is assumed to be negligible compared with the injection and pump regime.
A drawdown equal to zero is fixed at the principal aquifer at the boundaries of the domain, while constant pumping and injection rates (177.6 m$^3$/d) are fixed at the simulated wells. Top and bottom are considered as no flux boundaries.

An initial uniform temperature throughout the domain 0°C (relative temperatures) is considered, which match with the initial temperature existing before the first experiment (approximately 20 °C).

It is worth mentioning that the heat injection does not take into account the non-linearity associated to the temperature.

A total of 21 days were simulated for this experiment, where the 9 days of injection are included and the rest of days kept the steady flow with no associated injection.

**Domain**

The model area is shown in Figure 2 covering 1 km$^2$. The mesh consists of 25,233 nodes and 46,111 elements, distributed over 12 layers with a total thickness of 21.5 m. The finest elements in the most refined area are 0.2 m wide (around the extraction and injection wells), while the coarsest ones are 110 m wide at the boundaries of the model.

![Figure 2: View of the used numerical mesh: complete mesh (left), detailed area around the wells and piezometers (right). Pz1 and Pz2 were double piezometers, thus means both are opened at shallow and principal aquifers.](image1)

The mesh has been repeatedly refined in order to evaluate the vertical heat transfer through the upper and lower confining units of the studied aquifer.

It is observed that, by using the most refined mesh, the computed error is smaller than the error with a less refined mesh (Table 2). The vertical mesh refinement that minimized the error was the one shown in Figure 3.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Divisions at z</th>
<th>Thickness (m)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silts</td>
<td>1</td>
<td>6</td>
<td>6-7</td>
</tr>
<tr>
<td>Princ. Aq.</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Silts</td>
<td>1</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>Silts</td>
<td>3</td>
<td>2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Princ. Aq.</td>
<td>6</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Silts</td>
<td>3</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Error obtained with different meshes.**

**Results of the experiment**

The experiment was modelled by the analogy solute/heat transport with TRANSIN. The injection temperature function used in the simulation is shown in Figure 4. Instability at the beginning of the injection was explicitly included.
Figure 4: Injection function temperature used for the simulation of the experiment.

The calibration was driven through a trial-and-error approach, which for the sake of conciseness will not be presented in detail. Calibrated parameters are shown in Table 3. In Figure 5, best fits to the measured breakthrough curves using TRANSIN are presented.

Table 3: Parameters calibrated applying the analogy solute/heat transport using TRANSIN.

<table>
<thead>
<tr>
<th>Units</th>
<th>Silts</th>
<th>Principal aq.</th>
<th>Base of silts</th>
<th>channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>6</td>
<td>10</td>
<td>5.5</td>
<td>1 (*)</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>m/d</td>
<td>5E-03</td>
<td>12.6</td>
<td>1E-04</td>
</tr>
<tr>
<td>Specific storage</td>
<td>1/m</td>
<td>1E-04</td>
<td>1E-05</td>
<td>1E-05</td>
</tr>
<tr>
<td>Long. Dispersivity</td>
<td>M</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Transversal dispersivity</td>
<td>M</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Porosity</td>
<td>-</td>
<td>0.3</td>
<td>0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>Diffusion</td>
<td>M²/d</td>
<td>0.094</td>
<td>0.290</td>
<td>0.094</td>
</tr>
<tr>
<td>Retardation coefficient</td>
<td>-</td>
<td>2.89</td>
<td>6</td>
<td>2.89</td>
</tr>
</tbody>
</table>

Figure 5: Breakthrough curves at the observation wells Pz1, Pz2, Pz4, applying the analogy solute/heat transport using TRANSIN.

Pz1 had a different behaviour from the expected one: it increased its temperature very rapidly (in hours). If equation (9) (Custodio y Llamas, 2001) is used to calculate the time that a particle needs to
arrive to the production well in a doublet, for the following values: \( L = 20.4 \text{ m}, \ \phi = 0.15, \ b = 10 \text{ m}, \ \dot{Q} = 177.6 \text{ m}^3/\text{h} \), a total time of 3.7 d is obtained. If a retardation of 5 (common value in literature) is considered the total time is 18 d. So, by approximation for Pz1 (situated between the dipole, exactly a 9.75 m from the injection well) it would be 9 d instead of few hours. So, in order to reproduce the observed measures of Pz1, a set of 1D finite elements were introduced to simulate a preferential flow and transport path in the model. These elements, joined as a channel, with a high hydraulic conductivity, facilitate the arrival of heat at this piezometer (Pz1). The breakthrough curves of Pz2 and Pz4 are more tenuous and they are well reproduced by the model.

\[ t_w = \frac{\pi L \phi b}{3Q} \]  

(9)

From the heat balance of the model it is concluded that 16.1% of the injected heat is captured by the extraction well. The remaining introduced heat is stored in the principal aquifer most (71.1%), while the layers of silt accumulate approximately 6% for each one. As it was expected there are no losses of heat through the boundaries of the domain. It is worth to note the importance of 3D modelling due to heat transport to the upper and lower layers of the principal aquifer is not negligible.

A COMPARISON EXERCISE: SYNTHETIC CASE

Besides adjusting the real case breakthrough curves, a synthetic case was modelled. This synthetic case compares the results obtained using TRANSIN through the solute/heat transport analogy versus mass transport and heat transport modelization using FEFLOW. To achieve this, a simplified conceptual and numerical model comparable to the in situ site experiment was taken into account during a 10-year simulation. Two observation points are included in the model: A, inside the dipole, and B, outside the dipole. Superposition of solute and heat transport solutions from FEFLOW and TRANSIN is shown in Figure 6. The results obtained with the solute and heat transport using FEFLOW are quite comparable. Although the trends of simulated breakthrough curves at both observation points are similar, a 3% mismatch between TRANSIN and FEFLOW at observation point A is observed whereas a 0.5 % mismatch at B.

\[
\begin{align*}
\text{BOUNDARIES} & \quad \text{WELLS} \\
\text{In} & \quad \text{Out} & \quad \text{In} & \quad \text{out} \\
\hline
\text{FLOW (m}^3) & \quad \text{TRANSIN SOLUTE} & +15562 & -15564 & +6.48e+05 & - \\
 & \quad \text{FEFLOW SOLUTE/HEAT} & +16510 & -16508 & +6.48e+05 & - \\
 & \quad \text{TRANSIN SOLUTE} & +9.63e-04 & - & +1.36e+13 & - \\
 & \quad \text{FEFLOW SOLUTE} & +8.33e-01 & -1.48e+01 & +1.36e+13 & - \\
\end{align*}
\]

Figure 6: Estimated breakthrough curves at two observation wells (from left to right, inside and outside the dipole, respectively), using TRANSIN and FEFLOW

The discrepancy observed in the previous figure can be attributed to the difference in the flow balance (Table 4). Note that, as it was expected, the flow balance obtained with FEFLOW using solute and heat was exactly the same.
Table 4: Flow and transport balance obtained in the synthetic case with TRANSIN and FEFLOW

<table>
<thead>
<tr>
<th></th>
<th>FEFLOW HEAT</th>
<th>TRANSIN HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+4.10e+11</td>
<td>-3.14e+11</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>4.14e+11</td>
</tr>
<tr>
<td></td>
<td>+1.36e+13</td>
<td>-1.02e+13</td>
</tr>
</tbody>
</table>

In order to compare the mass balance outputs of TRANSIN and FEFLOW a factor of 4186000 was used to transform solute concentrations into energy units.

Among the FEFLOW capabilities to simulate the feasibility of open loop geothermal systems, within their overall operation time, the use of non-linear boundary conditions is programmed as an IFM module. A further simulation along a 10-year interval was run, testing the SimpleOpenLoop IFM module developed by DHI-WASY GmbH. This module permitted to improve the injection with a non-linear boundary condition applying a time-varying temperature difference between the pumping well and the injection well. It is important to remark that without this non-linear boundary condition, the impact of an open loop geothermal system would be underestimated. In this case, a constant $\Delta T=5^\circ C$ at the injection well would imply a maximum increment of 5$^\circ C$ in the aquifer (solid line, Figure 7). Otherwise, applying the open loop module, a total increment of 11.5 $^\circ C$ is achieved at the end of the simulation (dashed line, Figure 6).

![Figure 7: Estimated breakthrough curves at the observation points A and B using FEFLOW with and without the SimpleOpenLoop module.](image)

A correspondence with the simulated open loop system can be observed at the in situ experiment showed from the 6th day of injection, as the measured temperature at Pz1 starts to rise with a steeper slope (Figure 5).

**REAL CASE SIMULATED WITH FEFLOW**

As mentioned before, an estimation of the breakthrough curves using FEFLOW was carried out. Figure 8 illustrates the reproduction of the same experiment with FEFLOW with the parameterization showed in Table 3. Curves can be considered quite comparable with the ones showed at Figure 5. Fitting differences can be imputed to the channel implementation, as well as, some flow mass balance discrepancies, as shown previously with the synthetic case simulations.
As shown in the data the breakthrough curve at Pz1 presents a temperature rising (at approximately 10 days of experiment) that can be attributed to the arrival of the heated plume at the production well. Taking benefit of the IFM module implemented in FEFLOW a 5-years simulation was performed (Figure 8). The modelling illustrates that an increment of 1.7°C is achieved at the production well at the end of the simulation, reaching approximately 0.5°C in only 50 days. The heat plume can be considered steady at 1 year of simulation. It is worth noticing that a hypothetical geothermal implementation of a doublet system (only for a cooling mode) in this aquifer can be considered as non feasible, as the operation and efficiency of the system should be compromised.

CONCLUSIONS

An in situ experiment emulating an open loop geothermal system was performed. The experiment can be framed as an initiative of the Catalan Water Agency to develop the basis for a legal regulation of geothermal activities, particularly open systems, in order to prevent impacts on groundwater resources.

The paper illustrates the applicability of finite element codes in the design and prediction of impacts of the systems’ operation.

An analogy between solute and heat transport was used to reproduce the data collected in the heat injection experiment. Comparative simulations between both codes demonstrate their capabilities in heat modelling. Some numerical singularities can be considered key aspects: Among these can be highlighted (1) the vertical heat transferences, that will need an appropriate vertical mesh refinement for an accurate solution; and (2) the non-linearity in the heat injection in the operation of fixed thermal increments. This latter can be of utmost relevance in the long-term viability of groundwater geothermal systems, as can permit not underestimate the associated heat plumes.
REFERENCES


