TRS: a numerical code for the assessment of thermal recycling in Ground Water Heat Pumps

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ABSTRACT

The use of Ground Water Heat Pumps (GWHPs) for the heating and cooling of buildings has been increasing in recent years due to the sustainability and economic convenience of this technology. One of the most critical design issues of these systems is the formation of a thermal plume downstream the reinjection well, which can be captured by the abstraction well, thus impairing the energy efficiency of the system. Some analytical models have been already developed to simulate this phenomenon, but they require an imposed injection well temperature, which should be know a priori. With this assumption, the thermal power exchanged with groundwater diminishes with time, due to the thermal alteration of the extracted water. A numerical code called TRS (Thermal Recycling Simulator) was therefore developed to consider a constant temperature difference between the injection and the abstraction well, and hence a constant thermal load, which is a more realistic modelling assumption for GWHPs. The code is based on the potential flow theory and it has been validated against coupled flow and heat transport simulations with FEFLOW. TRS is freely available at www.polito.it/groundwater/software/TRS.html and works in MATLAB environment. An empirical formula, which describes the time evolution of the extracted water temperature, has also been derived from a series of simulations with TRS. The developed mathematical tools can be used to assess the long-term sustainability of a certain plant setup, to perform sensitivity analyses and for large-scale assessments of the thermal exchange capacity of aquifers.

1. INTRODUCTION

Ground Source Heat Pumps (GSHPs) are a sustainable HVAC technology which is expanding at a fast rate in Europe (Antics et al., 2013), thus contributing to the achievement of the energy targets set by the Europe 2020 strategy for smart, sustainable and inclusive growth (European Commission, 2010). GSHPs are divided into two main categories (Casasso and Sethi, 2013; Florides and Kalogirou, 2007):

- closed-loop plants (Borehole Heat Exchangers, geothermal piles, ground collectors), exchanging heat with the ground through the circulation of a heat carrier fluid into a pipe loop, mainly by heat conduction (Casasso and Sethi, 2014a; Casasso and Sethi, 2014b);

- open-loop plants (Ground Water Heat Pumps, GWHPs), exchanging heat with groundwater, mainly by advection and dispersion (Lo Russo et al., 2012).

Closed-loop plants are more diffused than open-loop plants: however, for large sizes, GWHPs are more convenient due to scale economies in the drilling of wells and BHEs. For this reason, the use of GWHPs for large buildings has become very popular in recent years (Beretta et al., 2014; Lo Russo and Civita, 2009; Piemonte and Porro, 2013). The design of open-loop geothermal heat pumps should assess both the external (i.e., the thermal plume developed downstream the injection well) and the internal sustainability (i.e., the hydraulic and thermal short-circuit between the injection and the abstraction well(s)). Lo Russo et al. (2014) recently studied the main factors affecting the size of the Thermally Affected Zone (TAZ), i.e. a certain isotherm of thermal alteration (e.g., 1°C). They concluded that groundwater velocity, thermal capacity and, to a lesser extent, thermal dispersivity are the most influential parameters. Poppei et al. (2006) developed the software Groundwater Energy Designer (GED) to assess the extent of the thermal plume and its evolution in the long term. Hydraulic and thermal short-circuit in a GWHP was observed for the first time by Brashears (1941) in Long Island, New York. Milnes and Perrochet (2013) classified thermal short-circuit into two different phenomena: thermal feedback, which occurs when the injection temperature is imposed (and hence known *a priori*), and thermal recycling, which occurs when a temperature difference is imposed. In addition, they introduced the expression "thermal breakthrough" to identify the time when the temperature of abstracted water is first altered. This definition is valid both for thermal recycling and feedback. According to this classification, thermal feedback has been studied for a long time (Clyde and Madabhushi, 1983; Gringarten and Sauty, 1975; Lippmann and Tsang, 1980), while thermal recycling is still little known. Ferguson (2006) used particle tracking on MODFLOW to assess the time evolution of thermal feedback in a GWHP. The potential flow theory (Strack, 1988) proved to be an effective method for the hydraulic modelling of well doublets, as reported in Luo and Kitanidis (2004) and in Milnes and Perrochet (2013).

The aforementioned studies are the base for the development of the tools presented in this paper. The potential flow theory was used to develop the numerical code TRS (Thermal Recycling Simulator), based on a finite-difference particle tracking of reinjected water in a well doublet. A detailed description of the adopted mathematical method is reported in Casasso and Sethi (2015), and it is synthesised in this paper. TRS was validated against a set of simulations on FEFLOW (Diersch, 2014), and then used to derive an empirical correlation which describes the time evolution of the thermal alteration at the abstraction wells.

2. METHODOLOGY

Water flow in a well doublet can be simulated with the potential flow theory (Strack, 1988) if the following conditions are met:

- the aquifer's properties (hydraulic conductivity k, saturated thickness b, hydraulic gradient J, and flow direction ϑ) are constant and homogeneous;

- the flow rate Q_w is constant.

With these assumptions, the potential of a well doublet in the presence of a regional groundwater flow is expressed by:

$$\Omega(z) = \frac{Q_w}{2\pi} \cdot log\frac{z - z_E}{z - z_I} - kJb \cdot \exp(i\vartheta) \quad [1]$$

Where $z = x + iy$ is the complex number that identifies the coordinate in the x,y plane, z_E and z_I are the position of the extraction and injection wells, and $kJb \cdot \exp(i\vartheta)$ is the vector of the regional groundwater flow.

From the potential field, the groundwater velocity flow field is expressed by:

$$v_e(z) = -\frac{1}{b \cdot n_e} \cdot \frac{d\Omega}{dz} \quad [2]$$

The groundwater velocity field described by equation [2] is used for forward particle tracking from the reinjection well. The injected flow rate is divided into N particles seeded from the well pipe, positioned at an angular distance of $\frac{2\pi}{N}$ radiants. Each particle therefore represents $\frac{1}{N}$ of the total injected flow rate.

The thermal exchange between groundwater and the solid matrix of the aquifer induces the retardation of heat transport with respect to groundwater flow, which is expressed by the thermal retardation factor R_{th} (de Marsily, 1986):

$$R_{th} = 1 + \frac{(1 - n_e)\rho_s c_s}{n_e \rho_w c_w} \geq 1 \quad [3]$$

$$v_{e-th}(z) = \frac{v_e(z)}{R_{th}} \quad [4]$$

The particle tracking permits to ascertain which fraction of the injected flow rate will flow downstream and which fraction will reach the upstream abstraction well, thus leading to the thermal alteration of the extracted water. The time-varying abstracted water temperature $T_E(t)$ is the flow-weighted average of different components:

- the flow rate fraction from upstream at the unaltered temperature T_0;

- the flow rate recycled from the injection well, which is composed of $n(t)$ particles, each one started at a different time $t - t_P(i)$ and hence with a different temperature:

$$T_I\big(t - t_P(i)\big) = T_E\big(t - t_P(i)\big) + \Delta T \quad [5]$$

where $t_P(i)$ is the particle arrival time calculated with the particle tracking implemented in TRS. The code is available at the website of the Groundwater Engineering research group of Politecnico di Torino (http://goo.gl/AdjCp6). Further details on the development of TRS are reported in Casasso and Sethi (2015).

3. VALIDATION

The mathematical method implemented in TRS was validated against a set of numerical simulations with FEFLOW (Diersch, 2014), a 3D finite-element flow and heat transport modelling software which includes a specific plug-in for GWHPs (DHI-WASY, 2014). A good superposition was observed for both $T_E(t)$ and water particle pathlines (Fig.1).

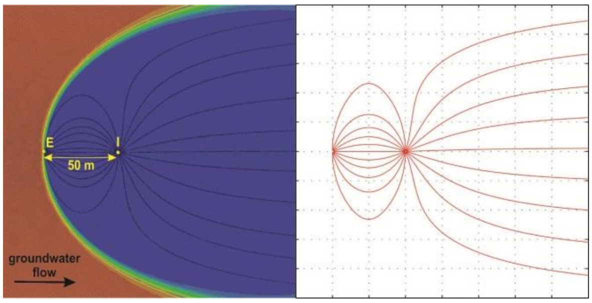

Figure 1: Comparison between particle tracking in FEFLOW (on the left) and in TRS (on the right).

Although the TRS code is able at handling arbitrarily oriented well doublets, a number of simulations was run with doublets aligned with groundwater flow, in order to check the fitting of four quantities which have been defined with analytical formulae in Banks (2009) and in Milnes and Perrochet (2013).

Hydraulic short-circuit in a well doublet occurs as the capture zone of the abstraction well and the release zone of the injection well are overlapping. Milnes and Perrochet (2013) identified the non-dimensional parameter to describe hydraulic short-circuit:

$$X = \frac{2Q_w}{\pi bkJL}$$

[6]

Hydraulic short-circuit occurs for values of X higher than 1 and, in such case, thermal breakthrough time is defined by:

$$t_{tb} = \frac{R_{th}n_e L}{kJ} \cdot \left[\frac{X}{\sqrt{X-1}}\tan^{-1}\left(\frac{1}{\sqrt{X-1}}\right) - 1\right]$$

[7]

In addition, the maximum fraction of recycled flow rate is:

$$RR_{max} = \frac{2}{\pi}\left[\tan^{-1}(\sqrt{X-1}) - \frac{\sqrt{X-1}}{X}\right]$$

[8]

which allows the maximum variation of T_E to be calculated with:

$$T_E(\infty) - T_0 = \frac{RR_{max}}{1 - RR_{max}} \cdot \Delta T$$

[9]

A good agreement between the results of TRS and FEFLOW was observed for the quantities described by equations [6-9].

4. EMPIRICAL FORMULA

Simulations run with FEFLOW and TRS highlighted a correlation between the thermal breakthrough time and the time scale over which thermal recycling develops, reaching the asymptotical value described by equation [9]. This correlation was already observed by Clyde and Madabhushi (1983), who developed an analytical formula for describing the temperature change in case of thermal feedback, i.e. for an imposed injection temperature. For thermal recycling, the trend of the alteration of the extracted water temperature is well described by an asymptotical correlation:

$$\frac{T_E(t > t_{tb}) - T_0}{T_E(\infty) - T_0} = 1 - exp\left(1 - m\frac{t}{t_{tb}}\right)$$

[10]

where m is a coefficient which has to be calibrated with the simulation results. The ratio between t_{90} (time at which 90% of the maximum temperature variation is observed, see equation [9]) and the thermal breakthrough time t_{tb} is closely correlated with the non-dimensional parameter X (equation [6]), as shown in Fig.2.

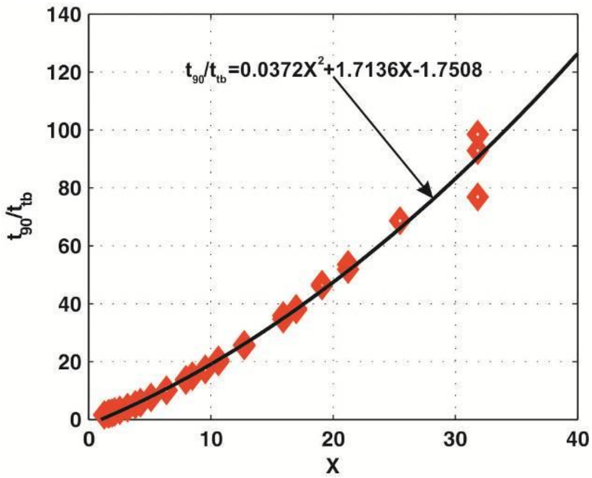

Figure 2: Correlation between the non-dimensional hydraulic short-circuit parameter X and the ratio t_{90}/t_{tb}.

The following empirical formula is derived:

$$\frac{T_E(t>t_{tb})-T_0}{T_E(\infty)-T_0} = 1 - exp\left(-\frac{2.3}{0.0372X^2+1.7136X-1.7508} \cdot \frac{t}{t_{tb}}\right)$$

[10]

where $T_E(\infty) - T_0$ is the asymptotical value described by equation [9]. Fig.3 reports a comparison between the results of a GWHP simulation with FEFLOW, TRS and equation [10]. A perfect agreement is observed between TRS and the empirical formula, and an acceptable agreement is observed with the results of FEFLOW.

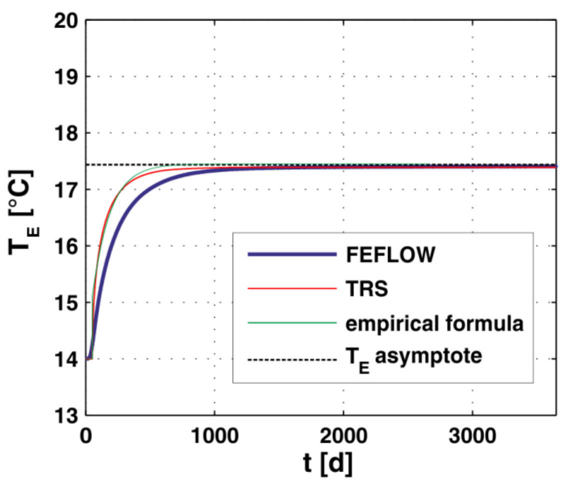

Figure 3: Comparison between the thermal alteration calculated with FEFLOW, TRS and the empirical formula reported in equation [10].

5. CONCLUSIONS

Thermal recycling is a common issue in GWHPs, and should be assessed in the design phase to ensure the long-term sustainability of these plants. However, numerical modelling of such phenomenon is expensive and time-consuming. For small plants, this can result in an unsustainable additional cost, while for larger plants a preliminary assessment would be highly desirable. Under a series of assumptions (homogeneous aquifer properties, constant operating parameters) it is possible to simulate the flow and the heat transport in a well doublet with the potential flow theory. The TRS code is a finite-difference implementation of the potential flow theory applied to track particles forward from the injection well, thus permitting to assess the time evolution of thermal recycling in the abstraction well. An empirical formula was also derived from the results of simulations performed with TRS, which is valid for well doublets aligned with the groundwater flow direction, while TRS simulates arbitrarily oriented well doublets. Together, these free and fast tools can be used for the design of GWHPs, thus reducing the initial investment costs related to their design. However, the most severe conditions of utilization should be considered, since it is not possible to take into account the variation of thermal power during the heating or cooling season.

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