Renewable Energy 77 (2015) 86–93

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Modelling thermal recycling occurring in groundwater heat pumps (GWHPs)

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ARTICLE INFO

Article history:
Received 23 April 2014
Accepted 1 December 2014
Available online

Keywords:
Ground water heat pump
Groundwater
Geothermal
Thermal recycling
Thermal breakthrough
Potential flow theory

ABSTRACT

The performance of a Ground Water Heat Pump (GWHP) is often impaired by the thermal recycling between the injection and the extraction well(s), and hence this phenomenon should be evaluated in the design of open loop geothermal plants. The numerical flow and heat transport simulation of a GWHP requires an expensive characterization of the aquifer to obtain reliable input data, which is usually not affordable for small installations. To provide a simple, fast and inexpensive tool for preliminary and sensitivity analyses, an open-source numerical code was developed, which solves the hydraulic and thermal transport problem of a well doublet in the presence of a subsurface flow. The code, called TRS (Thermal Recycling Simulator), is based on a finite-difference approximation of the potential flow theory. The method was validated through the comparison with flow and heat transport simulations with FEFLOW. Subsequently, TRS was run with different values of the aquifer and plant parameters. The correlation observed between some characteristic non-dimensional quantities permitted an empirical correlation to be developed, that describes the time evolution of the extracted water temperature. An example is given for the use of the numerical code and the formula in the dimensioning of an open loop geothermal plant.

1. Introduction

Geothermal Heat Pump (GHP) installations are spreading fast all over the world, with a total installed power of 33 GW [1]. Half of the world's shallow geothermal energy production takes place in Europe, with a positive occupational and environmental impact, as 7000 people are employed in this sector [2] and a reduction of 5.5 Mton CO_2 per year is achieved by using GHPs instead of more carbon-intensive technical solutions [3]. GHPs are divided into closed loop or Ground Coupled Heat Pumps (GCHPs), where a heat carrier fluid circulates in a pipe circuit buried in the ground, and open loop or Groundwater Heat Pumps (GWHPs), where the thermal exchange takes place directly on the extracted groundwater, which is then usually re-injected into the same aquifer [4]. While closed loop systems (i.e. Borehole Heat Exchangers, energy piles, earth coils) are based mainly on conductive heat exchange with the surrounding ground and, to a lesser extent, advection and dispersion [5–7], the thermal exchange for GWHPs is mostly advective [8]. Since water is usually reinjected after the heat exchange with the evaporator/condenser, a plume of chilled/warmed groundwater around the injection well is generated, which can return to the abstraction well with a gradual worsening of the performance of the system. This phenomenon was firstly observed in the Thirties in Long Island (New York), as re-injection was prescribed to avoid the depletion of the shallow coastal aquifer [9], and it was then either called thermal breakthrough, short-circuit, feedback, recycling etc., usually without any clear distinction. Recently, however, Milnes and Perrochet [10] defined thermal feedback as occurring when the value of the injection temperature is imposed, and thermal recycling when a temperature difference between abstraction and injection is set (Fig. 1).

According to this classification, thermal feedback has been studied for a long time, since Gringarten and Sauty [11] developed a formula for the calculation of the temperature variation in the abstraction well through time. Instead, thermal recycling has only been studied more recently, since its formulation is more complicated from the mathematical point of view. However, the time it takes for reinjected water to reach the extraction well, which is hereby called thermal breakthrough time (t_{tb}), does not vary

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http://dx.doi.org/10.1016/j.renene.2014.12.003
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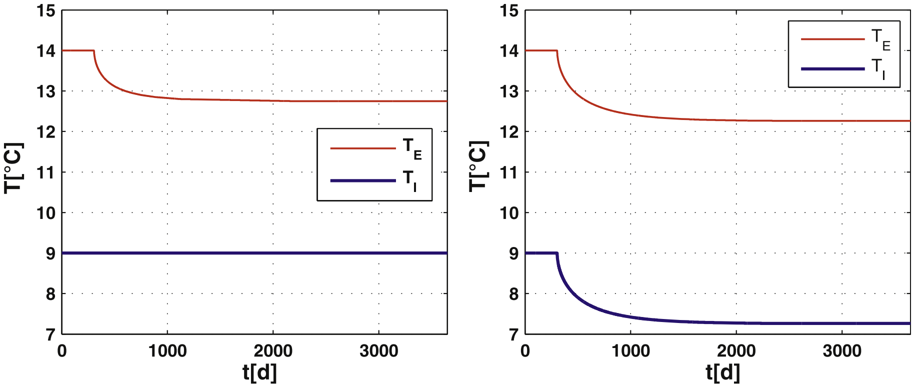

Fig. 1. Difference between thermal feedback (on the left) and thermal recycling (on the right).

depending on the injection temperature. Lippmann and Tsang [12] calculated its value for three different hydrogeological setups: no groundwater flow, regional flow from the injection to the abstraction well and regional flow from the abstraction to the injection well.

While thermal breakthrough inevitably occurs in the first two cases, in the third case it is not observed if:

$$X = \frac{2Q_w}{\pi bkJL} < 1 \tag{1}$$

where Q is the flow rate exchanged by the wells [m^3 s^{-1}], b is the aquifer thickness [m], k is the hydraulic conductivity of the aquifer [ms^{-1}], J is the hydraulic gradient [-] and L is the distance between the wells [m].

This equation is only valid for groundwater flow aligned with the well doublet, and the parameter X is the measure of how strong will the thermal breakthrough be. The minimum value of L required to cope with the criterion of Eq. (1) is too large for most GWHP well doublets, but the breakthrough time t_{tb} could be longer than the duration of a heating or cooling season, thus avoiding the occurrence of this phenomenon. In addition, the thermal recycling can develop over long time scales and/or at a low rate, permitting the plant operation to be continued with a slight reduction of COP (Coefficient Of Performance) or of the EER (Energy Efficiency Ratio). For these reasons, the main focus of the design of an open loop geothermal heat pump is not determining whether the thermal breakthrough is theoretically possible or not, but whether the impact of thermal recycling is sustainable during the heating/cooling seasons and through years. For this task, transient numerical modelling would be the optimal solution, both with programs able at modelling coupled flow and heat transport, like FEFLOW™ [13–16], or flow and solute transport, like MODFLOW, applying the similarity between solute and heat transport [17–19]. In fact, these programs can simulate complicated hydrogeological setups and well arrangements, variable thermal loads, variable flow rates, and optimize the arrangement of the wells and the flow rate patterns. On the other hand, a thorough characterization of the aquifer, which would be necessary for an appropriate use of these softwares, is not affordable for small GWHPs and hence it is usually not performed. In these cases, it is advisable to use simplified models analyzing a broad range of conditions, rather than using sophisticated models with arbitrarily imposed input data. Poppei et al. [20] developed a software called GED (Groundwater Energy Design) which calculates the spatial distribution of groundwater temperatures around a GWHP with simplified models, but not the time evolution of the extracted and injected water temperatures. The analytical formulae reported in Stauffer et al. [21] can be used to calculate the thermal alteration in the extraction well if the injection temperature is known *a priori* (thermal feedback). No simplified methods were found in the literature to simulate the thermal recycling.

A numerical code was therefore developed, starting from the modelling framework of the potential flow theory described by Strack [22] and Luo and Kitanidis [23] that can be adopted for the calculation of velocities and pathlines of a geothermal well doublet. The use of particle tracking (PT) for the design of a GWHP was also proposed by Ferguson [24], who calculated the thermal feedback with a finite-difference flow and solute transport numerical models (MODFLOW with MODPATH) to simulate the thermal feedback with well schemes more complex than a doublet. These articles above provided the conceptual basis for the thermal recycling modelling carried out in this study, where the potential flow theory was used to implement the TRS (Thermal Recycling Simulator) numerical code, able to determine the time series of the extracted water temperature in a GWHP. The adopted numerical method was validated through finite-element simulations developed under FEFLOW™, achieving a good agreement between computed water temperatures, in a wide range of parameter values (well distance, flow rate, hydraulic conductivity etc.) that can be met in real installations. Subsequently, TRS has been used for a larger number of simulations, in order to understand how the thermal recycling evolves depending on these quantities. The time series of the abstraction well temperature have been analyzed, deriving an empirical correlation that can be used to assess the feasibility of a GWHP setup. Finally, an example of the use of the formula and of TRS is given in this paper, comparing their results with those obtained with FEFLOW™.

2. Derivation of the numerical code

The thermal recycling in a GWHP is caused by the hydraulic recirculation from the injection to the extraction well(s), and hence it is necessary to study the path and the travel times of water injected into the aquifer, discretizing it into fractions and assessing which ones will flow downstream and which ones will be captured by the pumping well(s) located upstream. The potential flow theory of Strack [22] can be effectively applied for this purpose, provided that some simplifying assumptions are made (homogeneous aquifer properties distributions, constant flow rate etc.). In this way, the superposition principle can be applied in the modelling of two wells, one with a positive (extracted) flow rate Q_w and one with a negative (injected) flow rate $-RF \cdot Q_w$ (with $RF \le 1$ being the fraction of the extracted flow rate which is reinjected), and a homogeneous groundwater flow $\overline{Q}_{gw}$ with a generic orientation ϑ. Partial reinjection is quite uncommon, and therefore the analyses conducted in this study are focused on the case of a full reinjection ($RF = 1$), which is the usual solution adopted in these plants. Nevertheless, the program is also capable of dealing with partial reinjection, which will be considered in the mathematical derivation presented in this chapter.

The complex potential of a well doublet in the presence of a regional flow can be formalized as follows [23]:

$$\Omega(z) = \frac{Q_w}{2\pi}\log(z - z_E) - \frac{RF\cdot Q_w}{2\pi}\log(z - z_I) - \overline{Q}_{gw}z \tag{2}$$

$$Q_{gw} = kJbe^{i\vartheta} \tag{3}$$

where Q_w is the extraction well flow rate [$m^3\ s^{-1}$], z_E and z_I are the planar positions of the extraction and the injection wells [m] expressed as complex numbers ($z = x + iy$), $\overline{Q}_{gw}$ is the complex conjugate of the groundwater flow vector [$m^2\ s^{-1}$], k is the hydraulic conductivity of the aquifer [ms^{-1}], J is the modulus of the hydraulic gradient in the aquifer [-], b is the thickness of the aquifer [m] and ϑ is the direction angle of the groundwater flow (measured counter-clockwise with respect to the conjunction between the extraction and the injection well).

The vector of the effective velocity field is a function of the spatial derivate of the complex potential, which in turns depends on the planar position z:

$$v_e(z) = -\frac{1}{b\cdot n_e}\frac{d\Omega}{dz} = \frac{1}{b\cdot n_e}\cdot\left[\frac{Q_w}{2\pi}\left(\frac{RF}{z - z_I} - \frac{1}{z - z_E}\right) + \overline{Q}_{gw}\right] \tag{4}$$

The spatial distribution of groundwater effective velocities permits particles to be tracked backward or forward from a generic starting point, by means of finite difference schemes. Since the saturated aquifer thickness b is considered as homogeneous and constant, Eq. (4) is valid, strictly speaking, only for confined aquifers: nevertheless, the influence of the variation of the saturated thickness on groundwater velocities in unconfined aquifers is not appraisable when computing particle travel times.

A forward particle tracking procedure was implemented in a MATLAB™ numerical code called TRS (Thermal Recycling Simulator), in order to draw the pathlines and calculate the travel times of particles starting from the injection well. Considering a uniform radial distribution of the flow rate, the injection well pipe wall can be subdivided into N sectors with equally spaced particles, each one separated by an angle of $2\pi/N$ radians and representative of $1/N$ of the total flow rate circulated. Through the calculation of the pathlines, it is possible to ascertain how many of them will reach the extraction well and, by sorting the particle travel times, the time series of the recycled flow rate fraction $RR(t)$ can be derived.

The PT procedure explained so far only takes into account the hydraulic particle travel times, neglecting the fact that the heat exchange between the injected water and the aquifer results in a slower propagation of the thermal alteration with respect to groundwater. Since the transport equations of solute and heat have a similar form, the thermal retardation factor [25] can be defined, which is the ratio between hydraulic and thermal particle effective velocities:

$$R_{th} = 1 + \frac{(1 - n_e)\rho_s c_s}{n_e \rho_w c_w} \geq 1 \tag{5}$$

$$v_{e-th}(z) = \frac{v_e(z)}{R_{th}} \tag{6}$$

Depending on the velocity flow field described by Eqs. (4) and (6), a maximum number of particles $n_{max} \leq N$ can return to the extraction well, each one after a time $t_P(i)$ which is computed by TRS.

The maximum flow rate fraction which is recycled between the wells is:

$$RR_{max} = \frac{n_{max}}{N} \tag{7}$$

At the time $t \geq t_P(n)$, n particles have reached the extraction well, and the water temperature is therefore:

$$T_E(t) = (1 - RR_{max})\cdot T_0 + \left(RR_{max} - \frac{n}{N}\right)\cdot T_0 + \sum_{i=1}^{n}\frac{1}{N}T_I(t - t_P(i)) \tag{8}$$

The three terms of Eq. (8) respectively represent the following flow rate fractions:

- a constant fraction which is always extracted from upstream, and therefore it is not thermally altered;
- the variable thermally unaltered flow rate fraction, which diminishes through time reaching a value of zero as the asymptote RR_{max} is reached and n_{max} particles on a total of N have returned to the abstraction well;
- the flow rate fraction which comes from the injection well, which is composed of $n(t)$ particles, each one started at a time $t - t_P(i)$ with a different injection temperature:

$$T_I(t - t_P(i)) = T_E(t - t_P(i)) + \Delta T \tag{9}$$

where ΔT is the constant temperature difference between the injection and the extraction wells.

The TRS code is available at the website of Groundwater Engineering research group of Politecnico di Torino: http://areeweb.polito.it/ricerca/groundwater/software/TRS.html.

Further details about the implementation of this mathematical model in TRS are reported in the supporting information, while the conceptual steps of the procedure described in this chapter are summarized in Fig. 2.

3. Validation of the thermal recycling simulator

The method previously described was validated through simulations with the 3D numerical flow and heat transport modelling program FEFLOW™ [14]. This software includes a special package (OpenLoop IFM plugin [27]) for simulating a well doublet with a prescribed (constant or variable) temperature difference. The parameter values and the numerical settings adopted in the simulations for the verify of TRS are summarized on Table 1. A very large rectangular mesh (5 × 3 km) was built around the well doublet to avoid boundary effects. The aquifer was set as unconfined, and the hydraulic gradient was imposed with appropriate boundary conditions at each slice. A very low thermal conductivity ($\lambda_s = 0.01\ Wm^{-1}\ K^{-1}$) was assigned to the solid matrix of the aquifer, with the aim of reproducing the simplifying assumption of purely advective heat transport. An assessment of the error introduced by neglecting the heat conduction and dispersion is included in the supporting information, proving that this leads to an overestimation of the thermal alteration of the extracted water. A total number of 13 simulations was run, with different aquifer parameters, well distances and flow rates, in order to cover a wide range of case studies. The non-dimensional parameter X, which represents the strength of the thermal recycling, varies between 1.27 (very weak) and 63.66 (very strong). A graphical comparison of the results of FEFLOW™ and TRS is reported in Fig. 3, while further

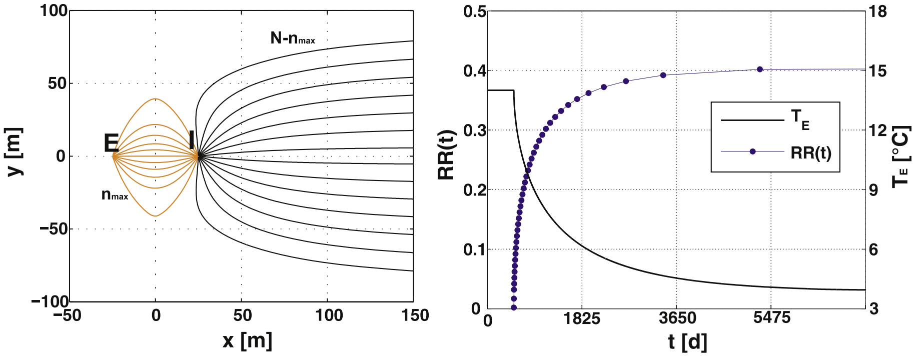

Fig. 2. Graphical synthesis of the procedure implemented in TRS. On the left, the particle tracking is shown, with $n_{\max}$ particles being recycled between the wells and $N-n_{\max}$ particles flowing downstream from the injection well. On the right, the recycled fraction $RR(t)$ is plotted with the ordinate on the left (dotted blue line), while the extracted water temperature is plotted with the ordinate on the right (black line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

analyses of the agreement between the results of these tools are reported in the supporting information. The thermal recycling is reproduced accurately by TRS for small and medium values of X (i.e. less than 10), which are the most likely in GWHP plants, while a worse agreement is obtained for large values (larger than 10), which are however not met in reality.

The streamlines calculated with TRS according to the potential flow field were compared with the ones calculated by FEFLOW™, and a good agreement is observed between them (Fig. 4).

Two other quantities can be examined to check the correctness of the mathematical model: the thermal breakthrough time t_{tb}, which is the shortest particle travel time, and the maximum recirculated flow rate fraction $RR_{\max}$. Both these quantities are described by explicit analytical formulae reported in Milnes and Perrochet [10]:

$$t_{tb} = R_{th}\cdot\frac{n_e L}{kJ}\cdot\left(\frac{X}{\sqrt{X-1}}\tan^{-1}\left(\frac{1}{\sqrt{X-1}}\right)-1\right) \tag{10}$$

$$RR_{\max} = \frac{2}{\pi}\left(\tan^{-1}\left(\sqrt{X-1}\right)-\frac{\sqrt{X-1}}{X}\right) \tag{11}$$

The scatterplots of the values of t_{tb} and RR_{max} calculated analytically and numerically for a large set of simulations are

Table 1
Summary of the model settings adopted in the simulation with FEFLOW for the validation of the TRS numerical code.

Quantity	Symbol	Value	Unit
Domain length	–	5000	m
Domain width	–	3000	m
Thickness of the domain	–	120	m
Thickness of the aquifer	b	15 ÷ 100	m
(default value)		20	m
Effective porosity	n_e	0.02 ÷ 0.2	–
(default value)		0.2	–
Total porosity (equal to the effective porosity)	n	0.02 ÷ 0.2	–
(default value)		0.2	–
Isotropic hydraulic conductivity of the aquifer layers	K	$10^{-4} \div 10^{-3}$	m/s
(default value)		10^{-4}	m/s
Isotropic hydraulic conductivity of the other layers	K	10^{-8}	m/s
Longitudinal dispersivity	α_L	0.1	m
Transverse dispersivity	α_T	0.01	m
Well doublet discharge	Q_w	0.01	m^3/s
Volumetric heat capacity of solid	$(\rho c)_s$	0.63 ÷ 12.6	MJ/(m^3K)
(default value)		2.52	
Volumetric heat capacity of water	$(\rho c)_w$	4.2	MJ/(m^3K)
Thermal conductivity of solid	λ_s	0.01	W/(mK)
Thermal conductivity of water	λ_w	0.01	W/(mK)
Boundary conditions (thermal) on all slices	T	14	°C
Initial conditions (thermal) on all slices	T_0	14	°C
Boundary conditions (hydraulic) on all slices (western side)	–	225	m
Boundary conditions (hydraulic) on all slices (eastern side)	–	175 ÷ 220	m
(default value)	–	200	m
Hydraulic gradient imposed	J	0.001 ÷ 0.005	–
(default value)		0.005	–
Problem class	–	Saturated	–
Aquifer type	–	Unconfined	–
Unconfined aquifer option	–	Free and movable	–
Error tolerance	–	5×10^{-4}	–
Upwinding scheme	–	No upwind (Galerkin FEM)	–
Number of elements of the 3D mesh	–	288,333	–
Number of nodes of the 3D mesh	–	151,060	–
Number of slices of the 3D mesh	–	28	–
Number of layers of the 3D mesh	–	27	–

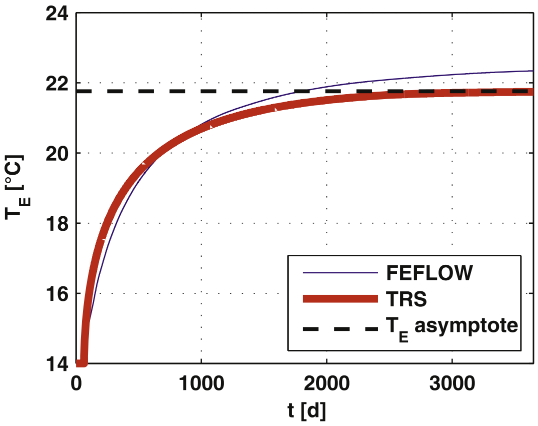

Fig. 3. Example of a graphical comparison of extracted water temperatures calculated by the FEFLOW™ model and by TRS. Further similar plots are reported in the. supporting information.

reported in Figs. 5 and 6 respectively, showing a good alignment. TRS also correctly simulates the asymptotical maximum thermal alteration reached in the case of thermal recycling, which is also described by an analytical formula [9]:

$$T_E(\infty) - T_0 = \frac{RR_{\max}}{1 - RR_{\max}}\Delta T \tag{12}$$

4. Derivation of an empirical relationship for thermal recycling

Thermal recycling can occur in the well doublets where the parameter X exceeds the value of 1, as stated in Eq. (1). The following properties influence the significance of this phenomenon and the time scales for its occurrence: the flow rate, the well distance, the hydraulic conductivity and the gradient, the flow direction and the aquifer thickness.

A similarity in the time scales can also be found among different setups, because well doublets characterized by a long thermal breakthrough time (t_{tb}) reach the asymptotical maximum thermal alteration after a long time. This was originally observed by Clyde

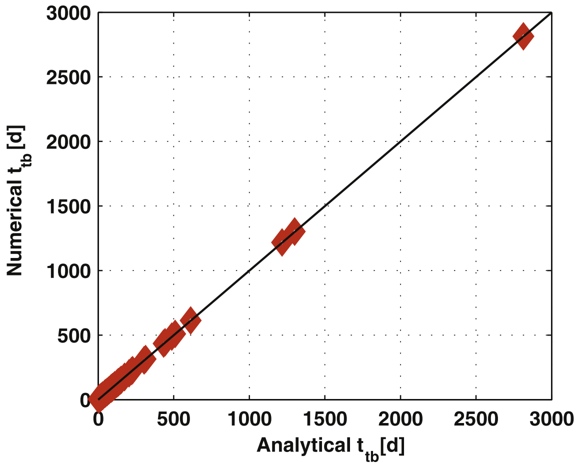

Fig. 5. Scatterplot of thermal breakthrough times t_{tb} according to Milnes and Perrochet [10] (on the abscissa) versus the ones resulting from TRS (on the ordinate).

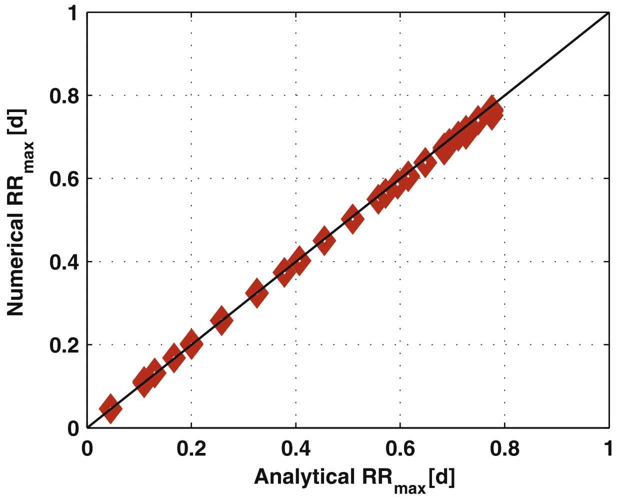

Fig. 6. Scatterplot of the recycled flow rate ratio $RR_{\max}$ according to Milnes and Perrochet [10] (on the abscissa) versus the ones resulting from TRS (on the ordinate).

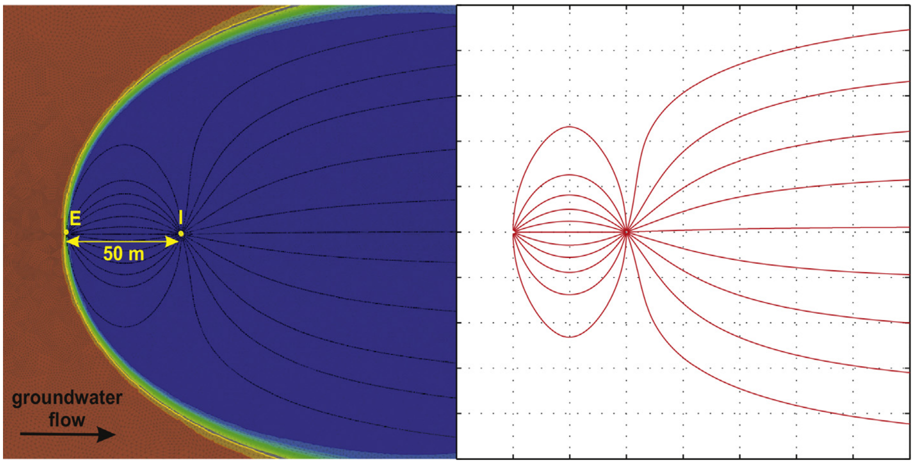

Fig. 4. Comparison between particle tracking in the FEFLOW™ model (on the left) and with the finite-difference potential flow theory implemented in TRS (on the right).

and Madabhushi [28] for the thermal feedback in a well doublet in the absence of groundwater flow. In this case, the variation of the extracted water temperature is a function of the ratio between the time t and the breakthrough time t_{tb}:

$$\frac{T_E(t)-T_I}{T_0-T_I}=0.34\cdot\exp\left(-0.0023\frac{t}{t_{tb}}\right)+0.34\cdot\exp\left(-0.109\frac{t}{t_{tb}}\right)+1.37\cdot\exp\left(-1.33\frac{t}{t_{tb}}\right)\quad \text{for } t>t_{tb} \tag{13}$$

The temperature plots represented in Fig. 3 and in the supporting information demonstrate that the pattern of thermal recycling in the presence of groundwater flow resembles an asymptotical exponential more closely than a sum of exponentials. A more suitable structure of the formula was therefore chosen:

$$T_E(t)-T_0=\Delta T\cdot\frac{RR_{\max}}{1-RR_{\max}}\cdot\left[1-\exp\left(m\cdot\frac{t}{t_{tb}}\right)\right]\quad \text{for } t>t_{tb} \tag{14}$$

In order to estimate the coefficient $m < 0$ of Eq. (14), a total number of 62 simulations with TRS was run, covering a wide range of the X parameter (from 1.27 to 63.67). The ranges of values for each parameter adopted in this study are reported in Table 2, and further data on these simulations are available in the supporting information. Two criteria were adopted for the choice of typical settings to be simulated:

- a better fit should be found for small and medium values of X, since larger ones are typical of an unsustainable thermal exploitation of the aquifer. For this purpose, a larger number of simulations were run with a small X (i.e. less than 10);
- for the same (or similar) value of X, different hydrogeological and well doublet parameters were adopted (e.g. a large well distance and a small hydraulic conductivity vs a small well distance and a large hydraulic conductivity), in order to verify if the coefficient m also depends on parameters other than X.

The fitting of the coefficient m of the asymptotic exponential function on Eq. (14) was performed by comparing the times at which 90% of the asymptotic maximum temperature change occurred (t_{90}). In particular, the ratio between t_{90} and the thermal breakthrough time t_{tb} can be approximated by a polynomial function of X(Fig. 7):

$$\frac{t_{90}}{t_{tb}}=0.0372X^2+1.7136X-1.7508 \tag{15}$$

The interval function of the extracted water temperature was then calculated:

$$\frac{T_E(t)-T_0}{\Delta T}=H(t-t_{tb})\cdot\frac{RR_{\max}}{1-RR_{\max}}\cdot\left[1-\exp\left(\frac{\log(0.1)}{0.0372X^2+1.7136X-1.7508}\cdot\frac{t}{t_{tb}}\right)\right] \tag{16}$$

where the parameters t_{tb} and RR_{max} are calculated respectively with the formulae reported in Eqs. (10) and (11), and $H(t-t_{tb})$ is the Heaviside function.

Table 2
Parameter values adopted for the simulations with the TRS code, in order to fit the parameters of Eq. (14).

Parameter	Symbol	Values
Hydraulic conductivity	k	$10^{-5} \div 10^{-3}$ m s^{-1}
Hydraulic gradient	J	0.001 ÷ 0.02
Aquifer thickness	b	5 ÷ 50 m
Well distance	L	10 ÷ 200 m
Flow rate	Q_w	0.001 ÷ 0.05 m^3 s^{-1}

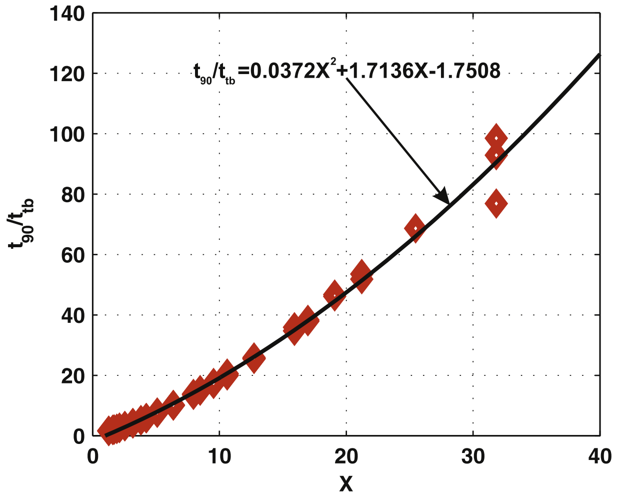

Fig. 7. Plots of the ratio between t_{90} and the thermal breakthrough time t_{bt} against the non-dimensional parameter X.

5. Example of the applications of the models for thermal recycling

The mathematical methods provided in this paper (TRS and the formula reported in Eq. (16)) can be used in the preliminary dimensioning of a GWHP. An example is shown in this chapter, comparing the results of these methods with the output of numerical flow and heat transport simulations with FEFLOW™. The results commented hereby are reported in Table 3. A small block of flats equipped with a GWHP needs a maximum cooling power of

Table 3
Application of the TRS numerical code and of the practical formula for thermal recycling: results with different plant setups.

L [m]	ϑ [°]	X	Quantity	Analyical formulae	TRS	FEFLOW™
100	0°	2.36	t_{tb}[d]	228.274[a]	228.278	243.000
			$RR_{\max}$	0.234[b]	0.232	n.a.
			$T_I(\infty)$ [°C]	17.916[c]	17.906[c]	17.759[e]
			$T_I(t=120d)$ [°C]	17.000[d]	17.000	17.000
40	0°	5.89	t_{tb}[d]	27.510[a]	27.504	26.000
			$RR_{\max}$	0.491[b]	0.484	n.a.
			$T_I(\infty)$ [°C]	19.892[c]	19.814[c]	19.943[e]
			$T_I(t=120d)$ [°C]	18.871[d]	19.043	18.624
40	45°	–	t_{tb}[d]	n.a.	26.474	24.000
			RR_{max}	n.a.	0.512	n.a.
			$T_I(\infty)$ [°C]	n.a.	20.150[c]	20.326[e]
			$T_I(t=120d)$ [°C]	n.a.	19.254	18.693

[a] Calculated with Eq. (10).
[b] Calculated with Eq. (11).
[c] Calculated with Eq. (12).
[d] Calculated with Eq. (16).
[e] Calculated after 10,950 days (30 years).

210 kW during the cooling season (which lasts 120 days). A flow rate of 16.666 l/s with a temperature difference of 3 °C are therefore set. The aquifer is 30 m thick, with a hydraulic conductivity of 3×10^{-4} m/s and a hydraulic gradient of 5×10^{-3}. Given a thermal capacity of the solid matrix $(\rho c)_s = 2.5\ MJ/m^3\ K$, a thermal capacity of water $(\rho c)_w = 4.2\ MJ/m^3\ K$ and an effective porosity $n_e = 0.2$, the thermal retardation factor according to Eq. (5) is $R_{th} = 3.4$. The undisturbed aquifer temperature is 14 °C and the upper limit temperature imposed by the environmental authority is 20 °C. A preliminary evaluation of the feasibility of the plant is requested.

According to Eq. (1), the minimum distance between wells to avoid thermal breakthrough would be equal to 236 m, provided that they are aligned with the groundwater flow direction. Since this is a very large value and it is not compatible with the extension of the property, a value of $L = 100\ m$ is set. As reported in Table 3, this choice would result in a thermal breakthrough time t_{tb} which is longer than the cooling season, and the extracted water temperature will not experience any variation. Nevertheless, such a large distance implies a noticeable increment of the cost of installation, and a reduction of this value would be highly desirable. By setting $L = 40\ m$, a shorter breakthrough time is obtained and the asymptotical thermal alteration $T_I(\infty)$ in the injection well would be very close to the limit imposed by the authority. However, a smaller variation occurs at the end of the cooling season $T_I(t = 120d)$, that can also be calculated with the empirical relationship reported in Eq. (16), and hence this configuration can also be considered as sustainable. A slightly larger thermal alteration occurs if the groundwater flow is not aligned with the well doublet (e.g. Ref. $\vartheta = 45°$), which can be calculated both with FEFLOW™ and TRS with an acceptable agreement between results, but not with Eq. (16).

In general, an acceptable agreement is achieved between calculation results with different methods, confirming the robustness of the models presented in this paper. As for the thermal breakthrough time, a slight difference is observed between the value calculated by FEFLOW™ and those obtained with TRS and the empirical formula.

Besides the results, the calculation times on a 30 years simulation on the same computer (Pentium i7 4771 @3.50 GHz with 12 GB DDR3 of RAM memory) are respectively of some 8 h for FEFLOW™ and 10 s for TRS.

6. Conclusions

Ground Water Heat Pumps are a very convenient technology for the heating and cooling of residential, commercial and industrial buildings, in particular for large plants, where the cost of the well drilling and hydrogeological surveys have a minor incidence on the total expense. In addition, noticeable CO_2 savings can be achieved, since the heat pump operates at a very high COP. Usually groundwater is injected after the thermal exchange to avoid the depletion of the aquifer, but this may cause a thermal feedback (if groundwater is reinjected at a fixed temperature) or thermal recycling (if a fixed temperature difference between production and injection well is set). Thermal feedback has already been studied, through the development of numerical models and practical formulae which estimate the time series of extracted water temperature (the injection temperature is known *a priori*). A practical tool for the study of thermal recycling in the presence of a regional groundwater flow has not yet been developed, which was the objective of this work. A forward finite difference particle tracking procedure, based on potential flow theory, was implemented in a MATLAB™ numerical code called TRS (Thermal Recycling Simulator), in order to calculate the time series of the extracted and injected water temperature in a GWHP with a constant flow rate and temperature difference. Although the code manages to model a partial reinjection and an arbitrarily oriented regional flow, the analysis focused on well doublets aligned with groundwater flow with full reinjection of abstracted water, since this is a standard GWHP setting.

The modelling approach was validated through flow and heat transport simulations carried out with FEFLOW™, the results of which were set as a benchmark. A good agreement was observed for the most important outputs (water temperature time series, pathlines, thermal breakthrough times), except for plants characterized by a very strong thermal recycling, which would however be unsustainable in practice. A practical formula for estimating the time evolution of groundwater temperature was then deduced, that would further speed up the calculation times, while achieving a good agreement both with the TRS code and with the finite-element numerical simulations.

The implemented mathematical models can be used for the design of small GWHPs with conservative parameter values, for the feasibility assessment of larger plants, or for mapping the suitability for GWHP installations on large areas, thus fostering the diffusion of open loop shallow geothermal installations.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.renene.2014.12.003. The TRS model can be downloaded from http://areeweb.polito.it/ricerca/groundwater/software/TRS.html.

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Glossary

Acronyms

COP: Coefficient of Performance
EER: Energy Efficiency Ratio
GCHP: Ground Coupled Heat Pump
GED: Groundwater Energy Design
GWHP: Ground Water Heat Pump
PT: Particle Tracking
TRS: Thermal Recycling Simulator

Symbols (Greek letters)

ΔT: Temperature difference between injected and extracted water K, °C
ϑ: Groundwater flow angle (measured counter-clockwise with respect to the conjunction of the extraction and the injection well) rad
ρ_s: Density of the solid matrix of the aquifer kg m^{-3}
ρ_w: Density of groundwater kg m^{-3}
Ω: Complex potential m^3 s^{-1}

Symbols (Latin letters)

b: Saturated thickness of the aquifer m
c_s: Specific heat of the solid matrix of the aquifer J m^{-3} K^{-1}
c_w: Specific heat of groundwater J m^{-3} K^{-1}
J: Hydraulic gradient of the aquifer
k: Hydraulic conductivity of the aquifer ms^{-1}
L: Distance between the extraction and the injection well m
m: Angular coefficient in the empirical correlation of extracted water temperature vs time
n: Number of injected particles that have already reached the extraction well at a certain time
N: Total number of injected particles
n_e: Effective porosity
n_{max}: Maximum number of injected particles that reach the extraction well
Q_w: Well flow rate m^3 s^{-1}
Q_{gw}: Groundwater flow rate vector m^2 s^{-1}
R_{th}: Thermal retardation factor
r_w: Well radius m
RF: Reinjected flow rate fraction
$RR(t)$: Fraction of the injected flow rate that returns to the extraction well -
RR_{max}: Maximum fraction of the injected thermally altered water flow rate that returns to the extraction well -
t: Time s
t_{90}: Time for which 90% of the maximum thermal alteration in the extraction well is reached s
t_P: Recycled particle travel time s
t_{tb}: Thermal breakthrough time s
T_0: Undisturbed groundwater temperature K, °C
$T_E(t)$: Extracted water temperature K, °C
$T_I(t)$: Injected water temperature K, °C
v_e: Groundwater effective velocity ms^{-1}
v_{e-th}: Effective velocity of the thermal alteration in groundwater ms^{-1}
X: Non-dimensional thermal breakthrough parameter
z: Planar position expressed as a complex number m
z_E: Planar position of the extraction well m
z_I: Planar position of the injection well m