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Adoption of GSHP System at the Residential Micro-Scale: Field Analysis and Energetic Performance

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ABSTRACT

The adoption of the GSHP system (Ground Source Heat Pump), in alternative to the more common ASHP (Air Source Heat Pump), can be energetically more favorable for space conditioning (heating/cooling operations) also at the residential micro scale, given the thermal stability of the primary heat source. The present study analyzes the issue of heat transport in the ground induced by the presence of a shallow horizontal groundwater heat exchanger (GHE) for cooling of a typical house in the Po River Plain (Italy). The analysis is conducted via a finite element model (FEFLOW®) describing the domain heterogeneity through a quasi-three dimensional approach. The flow and thermal field are resolved in transient conditions, determining the temperature at the GHE outlet and the soil temperature distribution. The results allow to formulate some novel considerations for the GSHP system optimization.

1. INTRODUCTION

Geothermal energy has received considerable attention over the recent decades due to increasing energy demands and depletion of non-renewable resources. Different technologies are available for the exploitation of geothermal energy; among those, ground source heat pump (GSHP) systems are being increasingly used for space conditioning (heating/cooling operations) in commercial, industrial and residential buildings in several countries (Austria, Canada Japan, Sweden, Switzerland, United States). In Italy, the use of this technique is not yet widespread, apart from a few specific sites such as Larderello and Ferrara; however there is potential for its adoption (Basta and Minchio, 2008), given also that under Italian legislation the energy generated by geothermic plants is certified as renewable and eligible for Green Certificates.

GSHPs are attractive alternatives to conventional heating and cooling systems, owing to their higher energy utilization efficiency and to recent improvements in heat pump technology (e.g. Chiasson et al., 2000). In addition to energy conservation, they are considered environmentally safe systems, due to connected reduction in emission of the greenhouse gases (Rybach and Eugster, 2002).

Essentially GSHP systems use the earth and/or groundwater as a heat source or sink; the heat rejection/extraction is obtained circulating a heat exchange fluid through an underground piping system. The scheme most commonly adopted nowadays is the ground coupled heat pump system (GCHP), consisting schematically of three closed loops (Chiasson, 1999): i) an air/water (fan-coil circuit) or water/water loop on the load side; ii) a refrigerant loop inside a water-source heat pump; iii) a ground loop in which water or antifreeze solution exchanges heat with the refrigerant and the earth and/or groundwater. In dual-mode systems, the refrigerant loop can work either in heating mode or in cooling mode.

A large body of technical and scientific literature exists on GSHP systems; several studies, starting from the 70s, are concerned with installation in vertical boreholes reaching a depth between 50 and 150 m. Alternatively, the pipes can be installed horizontally in horizontal trenches a few meters below the ground surface; this kind of installation, albeit less favorable in winter due to the lower temperature of the ground at shallow depths, deserves more attention, especially in an urban context, since it does not interfere with deep aquifers and does not risk generating preferential pathways favoring the spreading of contaminants.

The abundant literature concerning vertical, or, to a lesser extent, horizontal installations is often concerned with the simulation of fluid flow and heat transfer in the ground loop and in the surrounding soil, adopting analytical, numerical and experimental techniques to calculate the dimensions and burial depth of the groundwater heat exchanger (GHE). A review of the existing literature is outside the scope of this paper; among the most recent contributions, analytical, numerical and/or experimental results were presented for vertical installations by Diao and Fang (2004), Lee and Lam (2008), Bandyopadhyay et al. (2008), Nam et al. (2008), and Michopoulos and Kyriakis (2009) and for horizontal ones by Inalli and Esen (2004, 2005), Yari and Javani (2007), Coskun et al. (2008), Demir et al. (2009), and Eicker and Vorschultze (2009).

This paper presents an analysis of heat transport in the ground induced by the presence of a shallow horizontal groundwater heat exchanger (hereinafter GHE); the modeling effort, aimed mainly at understanding the thermal response of the soil surrounding the GHE, is motivated by the need to quantify the spatiotemporal extent of temperature modifications induced in the ground surrounding the GHE, and its compliance with existing or proposed environmental regulations. In fact, it is well known that one needs to determine balanced heat fluxes to keep ground temperatures constant over a long time frame.

The study is conducted via the implementation of a unsteady-state three-dimensional numerical finite element method. The code adopted is FEFLOW® (Diersch, 2005); the model allows determining the groundwater flow and temperature fields in saturated/unsaturated porous media, considering both conductive and convective heat transport.

2. SIMULATION MODEL

The analysis is focused on the transient behavior of the ground temperature in GSHP systems for heating or air-conditioning of commercial and/or residential buildings. In these applications, heat rejection or extraction is accomplished via a closed-loop system, which can function in heating or in cooling mode operation. In the first case, an heat exchange fluid (water or antifreeze) absorbs heat from the ground and uses it to heat the house or building, while in cooling mode, heat is absorbed from the conditioned space and transferred to the ground. The GHE used for these system consists usually of one or more plastic pipes buried in the ground. The topic under examination is part of a joint research effort aiming at evaluating the overall performance of various types of GHEs adopted in GSHP systems; ongoing activities include also laboratory and field case analysis. In this paper, for the sake of simplicity, we focus only on the cooling mode and consider a single horizontal GHE embedded in a bentonite backfill; further, heat transfer in and around the inlet and outlet vertical pipes is neglected. Extension to heating mode and a more complex geometry (e.g. multiple GHEs in parallel) should prove straightforward. In the model, the horizontal heat exchanger is represented as a fictitious porous medium with unit porosity and having the hydraulic and thermal properties of water. This approach is in variance with other modeling efforts employing FEFLOW (e.g. Nam et al., 2008), in that the GHE pipe and the surrounding soil are not modeled as two separate systems coupled by a boundary condition, but as a unique system with heterogeneous characteristics.

For the sake of brevity, the mass conservation, momentum conservation, and energy conservation equations valid for the porous medium (a combination of soil particles, liquid water, and gas), which are solved by FEFLOW are not reported here; they can be found in Diersch (2005).

2.1 Model Description

The computational domain geometry and parameters follow from the general layout of the GHE and its construction technology. To embed the horizontal pipe in the ground, first a trench 0.30 m wide and 2.10 m deep is dug in the ground. A 0.14 m bentonite layer is then positioned, followed by a 5 m long plastic pipe, whose cross-section is represented in the model by a 0.02 x 0.02 m square. The bentonite backfill around the pipe is then completed, leading to an overall 0.30 x 0.30 m GHE cross-section. Thus the bentonite-backfilled GHE depth is between 1.80 and 2.10 m from the ground surface, taken to be horizontal in the entire domain; such an installation depth is typical for shallow horizontal GHEs (e.g. Coskun et al., 2008, Eicker and Vorschultze, 2009, Inalli and Esen, 2004). Finally, a water table is present, and its level is set at a depth of 1.5 m.

The overall computational domain has dimensions of 15 x 15 x 6 m (Figure 1). Initially a 100 x 100 x 10 m simulation domain was adopted; preliminary numerical simulations with this scheme demonstrated that such a choice did not lead to significant changes in the results, while increasing drastically the computational times. The domain is subdivided into 20 vertical layers; most of them have a 30 cm thickness, while the bottom two are 60 cm thick, and the three layers representing the bentonite backfilled GHE have thicknesses of 14, 2, and 14 cm respectively. The numerical mesh is finer within and around the construction trench, to represent accurately the difference in the hydraulic and thermal properties of the pipe, the backfill and the surrounding soil. The computational mesh has more than 60.000 nodes and 110.000 elements, whose dimensions vary from 0.2 cm^2 for those representing the pipe, to 600÷800 cm^2 for the outer ones. Obtuse triangular elements amount to 9% of the total; 6% have a maximum angle inferior to 120°. Further mesh refinement did not bring about significant changes in the results, thus confirming the adequateness of the scheme.

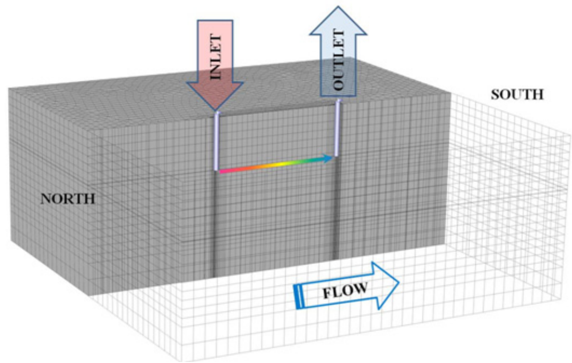

Figure 1: Computational domain

2.1 Materials properties

The hydraulic and thermal properties attributed to the different materials constituting the domain (fluid within the pipe, backfill, and surrounding soil) are summarized in Table 1, while the nomenclature is listed in Table 5. The soil is assumed to be homogeneous, and the thermal properties of all the materials remain constant within the entire range of temperatures investigated. Since the thermal conductivity of the pipe wall material is typically much larger than that of the other materials, its impact can be neglected; this allows attributing the hydraulic and thermal properties of water to the mesh elements representing the pipe, with a porosity equal to unity. The hydraulic and thermal properties adopted for the soil are typical parameters for sandy silts in the eastern Po River Plain in Italy, while the backfill properties are those of bentonitic clay. All properties adopted are within the ranges usually cited in the GSHP literature (Chiasson, 1999).

Table 1: Hydraulic and thermal properties

	Pipe	*Backfill*	*Soil*	*Units*
K	1.0	$1x10^{-12}$	$5x10^{-6}$	m/s
S	1.000	0.002	0.080	-
n	1.00	0.50	0.40	-
$\rho_l c_l$	4.20	4.20	4.20	10^6 J/ (m^2 K)
$\rho_s c_s$	4.20	1.10	2.20	10^6 J/ (m^2 K)
λ_l	0.65	0.65	0.65	J/ (m s K)
λ_s	0.65	3.50	2.50	J/ (m s K)
$\alpha_l^{\ t}$	1.0	5.0	5.0	M
$\alpha_t^{\ t}$	1.0	5.0	0.5	M

2.2 Boundary Conditions

Relevant boundary conditions include hydraulic and thermal conditions at the outer domain boundaries and within the pipe. Hydraulic boundary conditions aim at simulating an underlying natural flux within the aquifer in the north-south direction (parallel to the GHE); to do so, first-order piezometric head boundary conditions of -1.5 and -1.53 m are imposed respectively at the northern and southern boundary; these result in an hydraulic gradient i = 0.002, well within the typical range of hydraulic gradients in this kind of study (Chiasson, 1999; Nam et al., 2008). On the remaining outer boundaries, no-flux conditions are assumed.

Thermal conditions at the upper domain boundary reproduce the soil surface temperature. The latter is assumed to vary during the day with the pattern illustrated in Figure 2, which is fairly typical in the eastern Po River Plain in Italy during the summer season.

In agreement with many real-world cooling applications, the water temperature at the condenser outlet is set to 32°C. The GSHP is operated for 10 h every day from 11:00 AM to 9:00 PM. The flow rate in the GHE loop is chosen in order to have a difference between GHE inlet and outlet water temperatures not inferior to 4°C after prolonged operations, as quite common in GSHP systems. Preliminary simulations with the geometry and materials properties defined above suggested a flow rate of 0.1 m^3/day, corresponding to an average heat dissipation of 3.9 W/m, about half of the value reported by Eicker and Vorschutze (2009) for shallow horizontal GHEs.

2.3 Initial Conditions

The soil initial temperature is obtained via a preliminary modeling of the above system in absence of the GHE. To do so, a simulation is carried out starting from an initial soil temperature set at 17 °C everywhere throughout the domain, and considering as a boundary condition at the ground surface the temperature variation during the day represented in Figure 2. The resulting temperature field within the domain after a three-months simulation time, used afterwards as an initial condition in the main modeling effort, represents the soil temperature at the end of the summer, which clearly constitutes the worst-case hypothesis for GSHP operation.

3. MODEL RESULTS

The model is run for 30 days, obtaining as results the time-varying temperature within the GHE and the soil. Figure 3 shows the variation in time of the water temperature at the GHE outlet. The temperature time series shows saw-toothed oscillations, reflecting the daily operations mode. The daily outlet average temperature, on the other hand, increases with time, reaching an asymptotic limit of 25÷26 °C; the maximum asymptotic value of 28°C is achieved at 9:00 PM, when the system is stopped, while the minimum asymptotic value of 23 °C is achieved at 11:00 AM, when the system is started. The GHE outlet temperature difference between the beginning and the end of daytime operations varies from 6.0 °C at the start of the simulation to about 5.0 °C at its end. The daily heat exchange rate thus varies between 4.8 and 6.3 W/m.

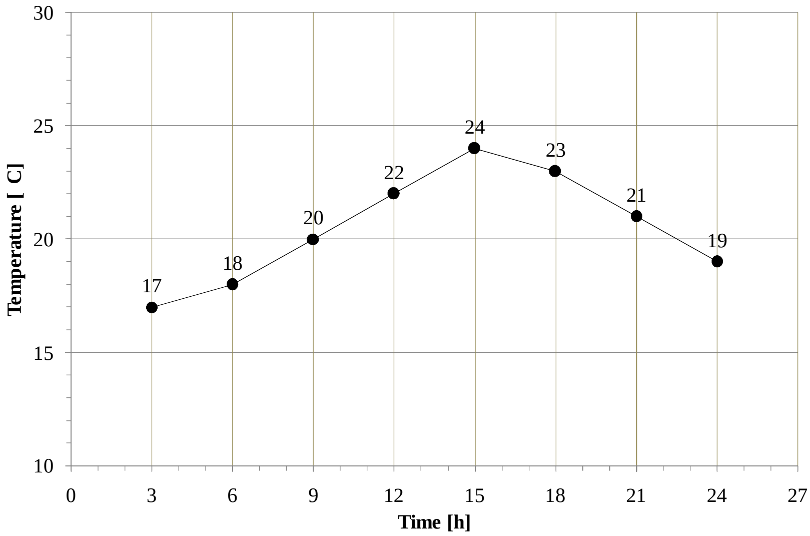

Figure 2: Surface soil temperature during the day

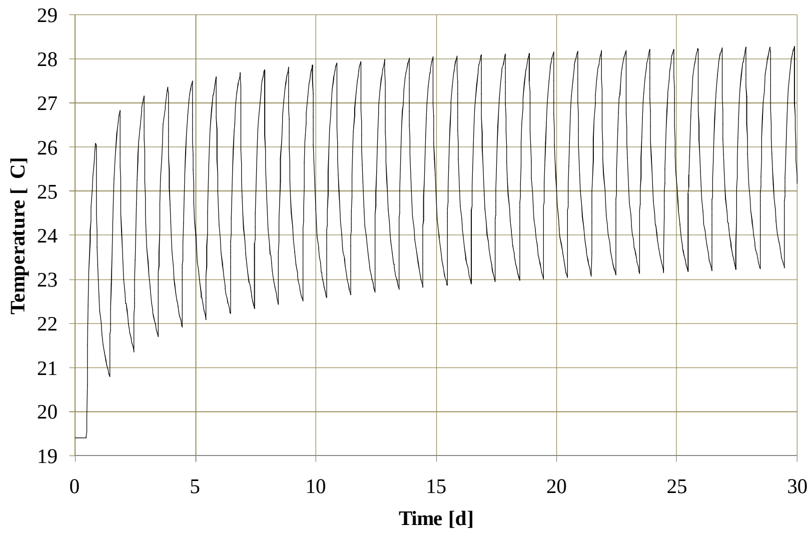

Figure 3: Temperature at the GHE outlet

Figure 4 depicts the domain temperature field after 29.75 days of simulation. Its inspection allows the evaluation of the volume of soil involved in the thermal exchange; at the end of the simulation, the volume of soil whose temperature varies by more than 3°C from the initial condition is nearly cylindrical with a 5.5 m length and a 1.2 m average radius, amounting to an overall volume of about 6 m^3. Considering a 1°C temperature variation, the volume becomes 27 m^3 (6.0 x 2.4 m). Since temperature variations less than a 1°C are nearly negligible, one can conclude that for the given set of parameters the single heat exchangers arranged in parallel can be regarded as isolated from each other when the minimum distance between them exceeds 4.5÷5,0 m, in good agreement with the study of Eicker and Vorschultze (2009).

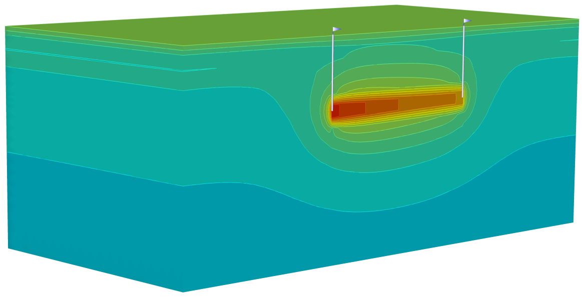

Figure 4: Domain temperature after 29.75 days

Figure 5 illustrates the soil temperature field at the end of the daily cooling operations for day 1, 2, 5, 10 and 30 (rows 1 to 5), along a longitudinal North-South cross section (column 1), and along a transverse cross section taken at a distance from the GHE inlet approximately equal to 1/3 of the pipe length (column 2). The Figure demonstrates the immediate impact within the domain of the first-order boundary condition imposed at the ground surface, in variance with other authors (Nam et al., 2008, Demir et al., 2009) who assign a flux boundary condition. After two days, the effect of the given ground surface temperature interacts with soil heating due to the exchanger, originating a temperature field which is symmetric in the transverse direction. The temperature profiles in the longitudinal direction do not show thermal plumes in the direction of the underlying aquifer flow, indicting that convective heat transfer due to groundwater flow is practically negligible. This qualitative conclusion can be confirmed as follows. Domenico and Schwartz (1990) define the Peclet number (*Pe*) for heat transport in groundwater as:

$$Pe = \frac{\rho_l \cdot c_l \cdot q \cdot L}{\lambda_{eff}} \quad (1)$$

where q, ρ_l, c_l, L, λ_{eff} are volumetric fluid flow rate, density and specific heat capacity of the liquid phase, pipe length, and thermal conductivity of the porous medium, respectively. The latter is given by

$$\lambda_{eff} = n \cdot \lambda_l + (1-n) \cdot \lambda_s \quad (2)$$

with λ_l and λ_s being the thermal conductivities of liquid and solid phase, while

$$q = K \cdot i \quad (3)$$

where K and i are hydraulic conductivity and hydraulic gradient. In the present case, the thermal conductivity varies from 1.825 W/(m K) for sandy silt to 2.075 W/(m K) for the bentonite backfill, with an average value of 1.950 W/(m K). Consequently, inserting the numerical values of the remaining parameters, the Peclet number becomes 0.11 (or 0.24 at most if the effective velocity q/n is used). This shows that conduction prevails over convection, and explains why the isothermals in Figure 5 are scarcely affected by the groundwater flow.

Finally, it is worth examining the nature of the flow in the GHE, by considering the Reynolds number within it; the latter is equal to

$$Re = \frac{\rho_l \cdot v_l \cdot D}{\mu} \approx 116 \quad (4)$$

where v_l, D, μ are water velocity, pipe hydraulic diameter, and water viscosity, respectively. It follows that within the GHE pipe the flow is laminar and heat exchange is conductive in nature.

4. CONCLUSIONS

An analysis of heat transport in the ground induced by the presence of a single shallow horizontal groundwater heat exchanger belonging to the ground loop of a GSHP system has been presented. The study was conducted via the implementation of the unsteady-state three-dimensional numerical finite element method FEFLOW®, modeling the GHE and the surrounding soil as a unique system with heterogeneous material properties; theoretical reasons supporting this schematization were provided. The properties of the materials adopted, the system geometry and operating parameters reflected those of typical field installations, with an eye towards a possible application in the Po River Plain in Italy.

The model runs allowed to reconstruct the time-varying temperature at the outlet of the GHE and within the soil. The temperature profiles respond to the variations in the daily operations mode, while the average soil temperature increases with time, reaching an asymptote after about a month.

Heat transport within the GHE and the soil is conduction-dominated, while convective heat transfer due to groundwater flow is practically negligible.

For the set of parameters adopted, single heat exchangers arranged in parallel can be regarded as isolated from each other when the minimum distance between them exceeds 4.5÷5 m, confirming previous literature findings.

For simplicity, the modeling effort focused exclusively on cooling mode and on a single heat exchangers; future work will include heating applications, the effect of multiple heat exchangers in parallel, and an analysis of soil heterogeneity, which may affect the heat exchange.

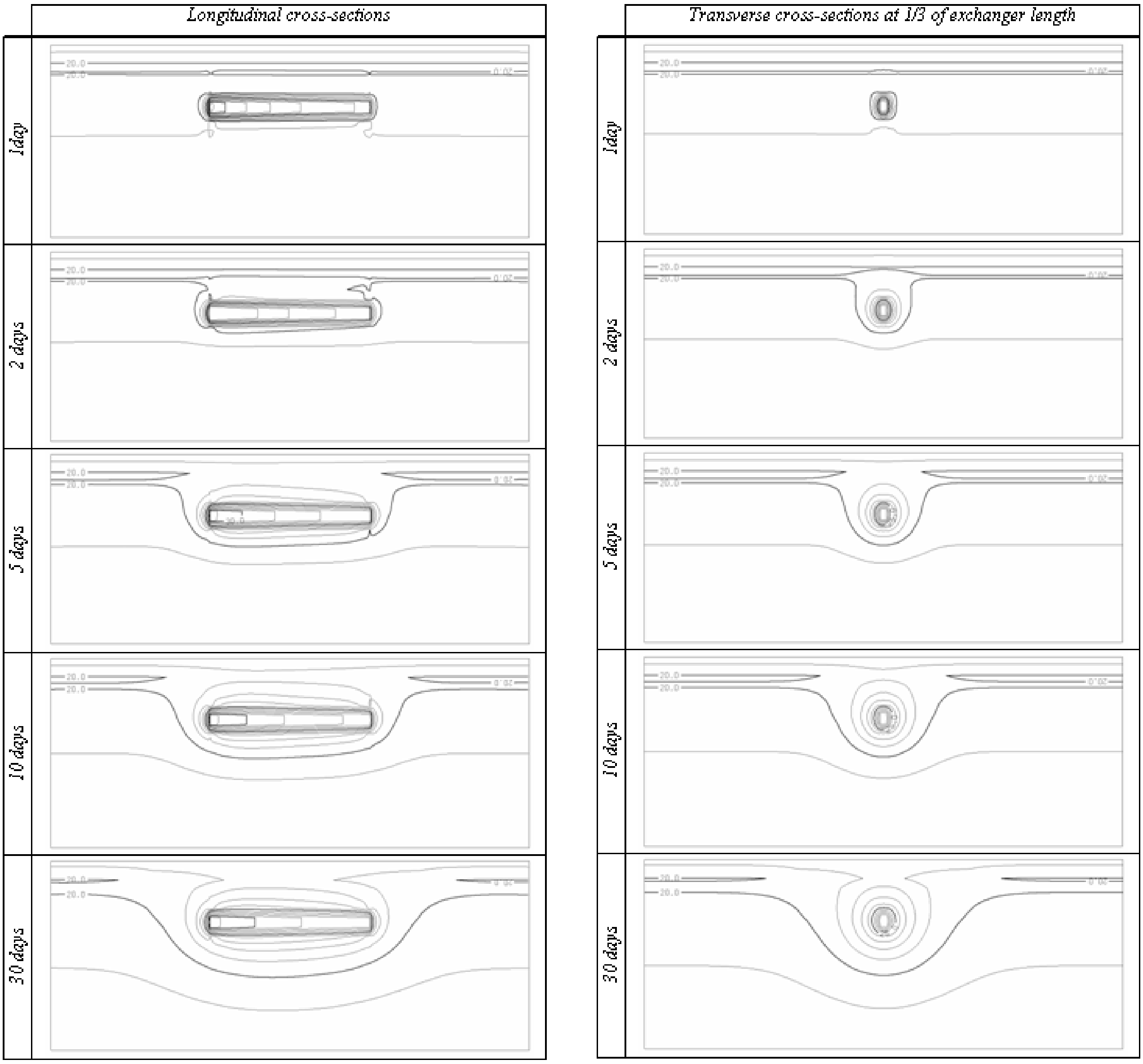

Figure 5: Temperature field within the domain: longitudinal and transverse cross-sections

Table 2: Nomenclature

$\alpha_l^{\,t}$	longitudinal thermal dispersivity, m^2/s
$\alpha_t^{\,t}$	trasversal thermal dispersivity, m^2/s
λ_{eff}	thermal conductivity (saturated porous medium), W/(m K)
λ_l	thermal conductivity (liquid phase), W/(m K)
λ_s	thermal conductivity (solid phase), W/(m K)
ρ_l	density (liquid phase), Kg/m^3
μ	dynamic viscosity (liquid phase), Kg/ (m s)
c_l	specific heat capacity (liquid phase), J/ (Kg K)
i	hydraulic gradient
K	hydraulic conductivity (solid phase)
S	storativity (porous medium)
n	porosity (solid phase)
L	pipe length, m
D	hydraulic diameter
v_l	velocity (liquid phase), m/s
q	Darcian flux

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