Chapter 6

Field methods

For the design and optimal performance of geothermal systems, various types of parameters such as **economical, technical, design, hydraulic, and thermal parameters**, have to be specified. For example, Blum et al. (2011), who studied the technoeconomic and spatial analysis of more than 1000 vertical ground-source heating pump (GSHP) systems with a heating demand of 11 ± 3 kW in southwestern Germany, concluded that subsurface characteristics are presently inadequately considered for the design of such GSHP systems. In this chapter, we merely discuss the most relevant thermal input parameters for the heat transport in the subsurface and design of geothermal systems using field methods such as **thermal response tests** (TRTs) and **thermal tracer tests** (TTTs). In the governing heat transport equations provided in Chapter 2, thermal diffusivities and hydraulic and thermal conductivities are important for heat transport simulations and design studies of closed and open geothermal systems. Hence, the focus is set on measurement techniques for determining these key hydraulic (K_w) and thermal parameters (λ_m, β_L, β_T). Values can be obtained both in the laboratory and in the field. The latter, being crucial for larger scale geothermal systems, is particularly considered here.

6.1 HYDROGEOLOGICAL FIELD METHODS

For the design of geothermal systems, the knowledge of subsurface characteristics is crucial, even more for open geothermal systems (e.g., Banks 2008). Depending on the type of investigation (e.g., water supply, contaminant, or heat transport), **standard hydrogeological field methods**, such as borehole flowmeter tests, slug tests, hydraulic pumping tests, and dye tracer tests, are typically used (e.g., Molz et al. 1989; Kruseman and De Ridder 1990; Fetter 2001; Schwartz and Zhang 2003). For example, for water supply and also for geothermal investigations of open systems, an integral evaluation of aquifer hydraulic conductivity by hydraulic pump tests is a standard approach. However, for optimal designs of aquifer thermal storage systems (ATES), more detailed knowledge of the spatial distribution of the hydraulic conductivity in the aquifer might be necessary. Hence, other hydraulic methods, such as **hydraulic tomography** and **direct-push methods**, are increasingly applied to describe the spatial distribution of the hydraulic conductivity at higher resolution than standard hydrogeological field methods do (e.g., Brauchler et al. 2003; Butler 2005; Illman et al. 2010; Lessoff et al. 2010). Despite the advantages of these evolving techniques, there are also limitations, the practicability of the hydraulic tomography in the field, and the very local insight obtained by direct-push methods, for example. A detailed discussion on the viability and application windows of these techniques, however, is beyond the scope of this book, and we refer to the study by Bohling and Butler (2010).

6.2 THERMAL RESPONSE TESTS

For the planning and design of large-scale GSHP systems, standard and enhanced **TRTs** are applied. The TRT is primarily used to estimate thermal properties of the subsurface and the heat transfer inside toward the tubes of the BHE. The principle of the TRT is similar to that of the standard hydraulic pumping tests (Raymond et al. 2011a), where an initially undisturbed system is perturbed and its response is subsequently monitored over time. Here, we will first provide an overview of the TRT, showing its development, setup, and application. Furthermore, we review analytical and numerical models for the evaluation of TRT. Finally, an analytical approach is discussed in more detail for the evaluation of groundwater-influenced TRT enabling the estimation of the local hydraulic conductivity.

6.2.1 Development of TRTs

The theoretical basis of TRT was originally developed by Choudhary (1976) and Morgensen (1983). The main idea of the TRT is to circulate a heat carrier fluid, such as water, in a BHE with a constant heating load and to continuously measure the temperature development of the fluid at the inlet and the outlet of the BHE. The first **mobile TRT device** called "TED" was developed in Sweden in 1995–1996 (Gehlin 1998; Figures 6.1 and 6.2). The test was then introduced and also improved in several other countries (e.g., Austin 1998; Austin et al. 2000; Gehlin 2002). In Germany, the first TRT with equipment based on the Swedish device was conducted in 1999 (Sanner et al. 2000). In the Netherlands, the TRT device was built with a reversible heat pump, supplying either warm or cold heat carrier fluid, and consequently could be used in both heating and cooling mode (Witte 2001). Worldwide, various types of such standard TRT equipment with different

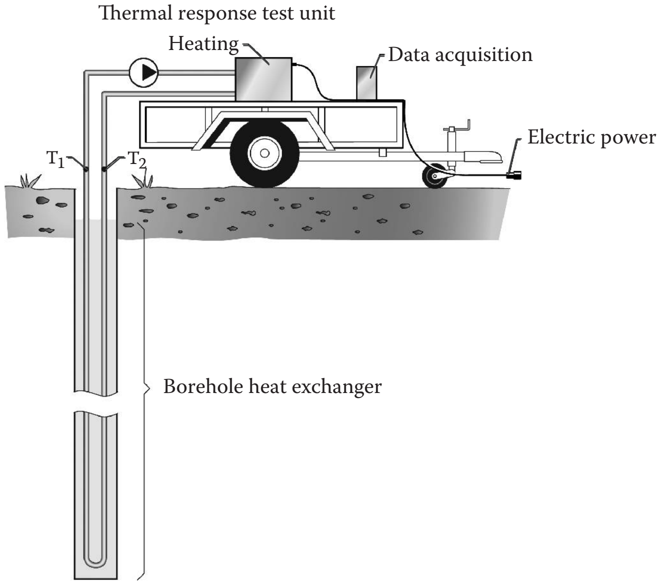

Figure 6.1 Schematic illustration of the setup for a standard TRT. T_{f1}: outlet fluid temperature; T_{f2}: inlet fluid temperature. (Illustrated by Claes-Göran Andersson. From Gehlin, S., Thermal response test method development and evaluation. Ph.D. thesis, Department of Environmental Engineering, Lulea University of Technology, Lulea, 2002.)

Figure 6.2 Mobile TRT device called "TED," which was developed in Sweden. (Photo by Signhild Gehlin. From Gehlin, S., Thermal response test method development and evaluation. Ph.D. thesis, Department of Environmental Engineering, Lulea University of Technology, Lulea, 2002.)

setups for heating and temperature monitoring are used (e.g., Roth et al. 2004; Sanner et al. 2005).

In addition to these standard TRT devices, various different types of so-called **enhanced TRT** were developed by various groups (e.g., Heidinger et al. 2004; Wagner and Rohner 2008; Raymond et al. 2010), where depth-dependent temperature series are measured to estimate depth-specific thermal properties. Heidinger et al. (2004) developed the so-called **enhanced geothermal response test** (EGRT), where both the heating and the temperature measurement, using an optical fiber sensor cable, are integrated in the borehole heat exchanger (BHE). Both systems are installed between the U-tubes of the BHE and the borehole wall inside the backfilling providing depth-specific thermal properties. Similarly, Wagner and Rohner (2008) measure the vertical temperature profile inside the U-tubes using a non-wired temperature probe, while Fuji et al. (2009) use optical fiber sensors. Both methods also provide insight into depth-specific thermal properties. In the following chapters, however, we focus only on the standard TRT.

6.2.2 Setup and application of TRTs

After completion of the borehole drilling, the borehole is typically equipped with a BHE consisting, for example, of double U-shaped polyethylene pipes, which in many countries are subsequently backfilled with a **cement–bentonite suspension**. The latter is left for several days until it is hardened and the released reaction heat has subsided. Before the TRT is started, the undisturbed ground temperature can be determined during an initial circulation phase without heating or cooling. The TRT is initialized by introducing a constant heating or cooling load, typically ranging between 30 and 80 W m^{-1}. The heating load during the test should be kept constant for the standard TRT evaluation. However, this is often challenging (Poppei et al. 2006). Furthermore, **external influences**, such as direct sunlight or seeping rainwater, can influence the apparatus temperature and therefore distort the test results. Hence, external pipes of the TRT devices should be comprehensively insulated (Figure 6.2), and the ambient air temperature should be also measured during the experiment to be able to assess its influence on the fluid temperature.

The total **test duration** can be as short as 12 to 20 h (Smith and Perry 1999), or 30 h recommended by Gehlin and Hellström (2003), and even longer periods of up to 50 h (Austin et al. 2000). Longer test periods, which tend to be more expensive, are desirable to average out diurnal variations. It is difficult to provide a universal recommendation. However, Beier and Smith (2003) provided a graphical method, which can be downloaded in the form of a spreadsheet (http://www.met.okstate.edu/FacultyandStaff/Beier/Beier_res.html), to determine minimum test duration based on subsurface and borehole properties. Based on a numerical model and for ideal conditions during the TRT, Signorelli et al. (2007) concluded that a duration of at least 50 h is required.

The TRT device generally includes a circulation pump connected with the pipes of the BHE and an electrical heater with a stable power supply. The flow rate is controlled to a constant value and monitored with two volumetric flow meters during the entire test duration. During the standard TRT, the following parameters are continuously measured and logged: heat carrier fluid flow rate, inflow and outflow heat carrier fluid temperatures, heat carrier temperature between circulation pump and heater, reference temperature in the trailer, and ambient air temperatures. The typical temperature data consist of curves showing the **ambient temperature and fluid temperature** development for both inlet and outlet over time (Figure 6.3). The data can finally be evaluated to determine subsurface properties, such as the **integral and effective thermal conductivity** λ_m of the subsurface and **thermal borehole resistance** R_{tb} of the BHE.

6.2.3 Evaluation of TRTs

The TRT can be generally evaluated using analytical and numerical models. The standard and also the enhanced TRT are most commonly evaluated using the **Kelvin line source theory**, which assumes an infinite, homogeneous, and isotropic medium and a constant and infinite heat source (Carslaw and Jaeger 1959). In addition, various alternative line source models (Chapter 3), for example, the **moving finite line source model** (Equation 3.60) and **cylindrical source models**, are also applied (Chapter 3.1.4). Besides those, a

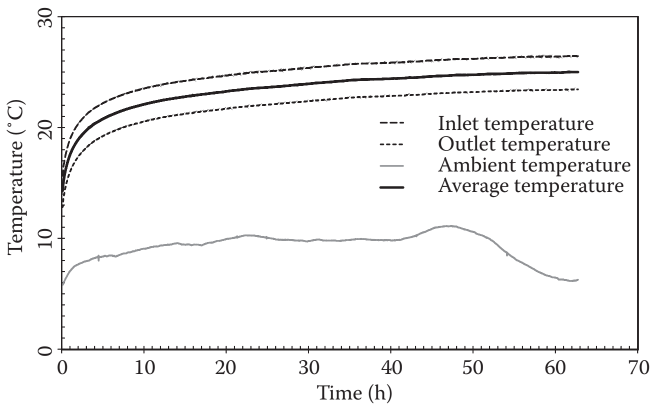

Figure 6.3 Example of the measured inlet and outlet fluid temperatures, the average fluid temperature in the pipes, and the ambient air temperature during a standard TRT in Germany.

variety of **numerical models** (Chapter 4) are also available for the analysis of TRT.

6.2.3.1 Analytical models

The standard TRT is most commonly evaluated using **Kelvin line source theory**. In the basic infinite line source model (Equation 3.10), a constant amount of energy is injected or extracted by conductive heat transport only. The temporal and spatial temperature changes around the line source can be determined and approximated as follows (Gehlin 2002; Signorelli et al. 2007; Wagner et al. 2013):

$$T(r,t)-T_0=\frac{q_{\mathrm{tb}}}{4\pi\lambda_{\mathrm{m}}}\int_{\frac{r^2}{4D_{\mathrm{t}}t}}^{\infty}\frac{e^{-u}}{u}du=-\frac{q_{\mathrm{tb}}}{4\pi\lambda_{\mathrm{m}}}\mathrm{Ei}\left[\frac{r^2}{4D_{\mathrm{t}}t}\right]\approx\frac{q_{\mathrm{tb}}}{4\pi\lambda_{\mathrm{m}}}\left[\ln\left(\frac{4D_{\mathrm{t}}t}{r^2}\right)-\gamma\right] \tag{6.1}$$

where T_0 is the initial or undisturbed temperature, q_{tb} (= J/H) is the heat flow rate per unit length of the borehole (W m^{-1}), λ_{m} is the effective thermal conductivity of the subsurface (W m^{-1} K^{-1}), and γ is the Euler constant (0.5772). If the time criterion $t \geq t_{\mathrm{c}} \geq 5r_{\mathrm{b}}^2D_{\mathrm{t}}^{-1}$ is fulfilled, the maximum error of the logarithmic approximation of the exponential integral is less than 10% (Witte et al. 2002). By increasing the time criterion, the latter can be decreased. For example, if $t_c \geq 20r_{\mathrm{b}}^2D_t^{-1}$, the maximum error is only 2.5% (Wagner and Clauser 2005).

To determine the average heat carrier fluid temperature T_{f}, the thermal borehole resistance R_{tb} between the borehole wall and the circulating heat carrier fluid has to be considered, which is obtained by extension of Equation 6.1:

$$T_{\mathrm{f}}-T_{\mathrm{b}}=q_{\mathrm{tb}}R_{\mathrm{tb}} \tag{6.2}$$

$$\begin{aligned}T_{\mathrm{f}}(t)&=T_{\mathrm{b}}(t)+q_{\mathrm{tb}}R_{\mathrm{tb}}=-\frac{q_{\mathrm{tb}}}{4\pi\lambda_{\mathrm{m}}}\mathrm{Ei}\left[-\frac{r_{\mathrm{b}}^2}{4D_{\mathrm{t}}t}\right]+T_0+R_{\mathrm{tb}}q_{\mathrm{tb}}\\&\approx\frac{q_{\mathrm{tb}}}{4\pi\lambda_{\mathrm{m}}}\ln(t)+q\left[R_{\mathrm{tb}}+\frac{1}{4\pi\lambda_{\mathrm{m}}}\left(\ln\left(\frac{4D_{\mathrm{t}}t}{r_{\mathrm{b}}^2}\right)-\gamma\right)\right]+T_0\end{aligned} \tag{6.3}$$

where T_{b} is the temperature at the borehole wall (°C). To determine the effective thermal properties (λ_{m} and R_{tb}), two different approaches are generally feasible. The recorded TRT data can be either fitted by (1) a **linear**

regression (Gehlin 2002; Signorelli et al. 2007) or (2) a **parameter estimation technique** (Roth et al. 2004). The linear regression is based on the logarithmic approximation of Equation 6.3:

$$T_\mathrm{f} = m \ln(t) + b \tag{6.4}$$

Hence, the slope m of Equation 6.4 is used to determine λ_m, and R_tb is estimated by the intercept with the y-axis b:

$$\lambda_\mathrm{m} = \frac{q_\mathrm{tb}}{4\pi m} = \frac{q_\mathrm{tb}}{4\pi} \cdot \frac{\ln(t_2) - \ln(t_1)}{T_\mathrm{f}(t_2) - T_\mathrm{f}(t_1)} \tag{6.5}$$

$$R_\mathrm{tb} = \frac{(b - T_0)}{q_\mathrm{tb}} - \left(\frac{1}{4\pi\lambda_\mathrm{m}} \left[\ln\left(\frac{4D_\mathrm{t} t}{r_\mathrm{b}^2} \right) - \gamma \right] \right) \tag{6.6}$$

This evaluation procedure was successfully applied in many different settings (Sanner et al. 2005). The main advantage of this variant is its simplicity, and for this reason, it has become the standard procedure. An example

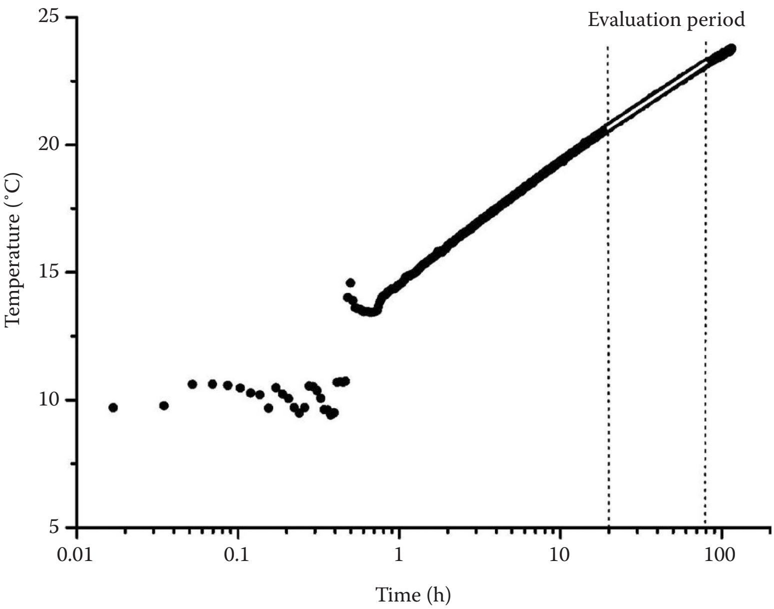

Figure 6.4 Duration time *t* versus average fluid temperature (T_f) of a standard TRT showing the linear regression for a selected evaluation period. (From Menberg, K. et al. *Grundwasser* 18, 103–116, 2013.)

is illustrated in Figure 6.4, showing the linear regression by plotting the time t along the x-axis in natural logarithmic scale (Menberg et al. 2013). Furthermore, an example for the parameter estimation technique is illustrated in Figure 6.5. It shows that depending on the selected procedure, also close-to-optimal solutions can be inspected in addition to the best fit. This example shows that given a certain tolerance for the fitting error, several value pairs of λ_m and R_{tb} are found. In practice, due to measurement errors, a tolerance range is often recommendable, and then the parameter estimation or a simple grid search is preferable to linear regression. However, the TRT may not deliver specific parameter values but rather correlated parameter pairs.

Using the temporal **superposition principle**, Raymond et al. (2011a) developed a TRT evaluation, which can also consider variable heat injection rates and can therefore also analyze the temperature recovery of a TRT by automatic optimization of the parameters using the solver function in Microsoft Excel. The spreadsheet can be downloaded as supporting information from the review paper by Raymond et al. (2011a). An example for the TRT analysis using the superposition principle, which is also discussed in detail in the review paper, is illustrated in Figure 6.6.

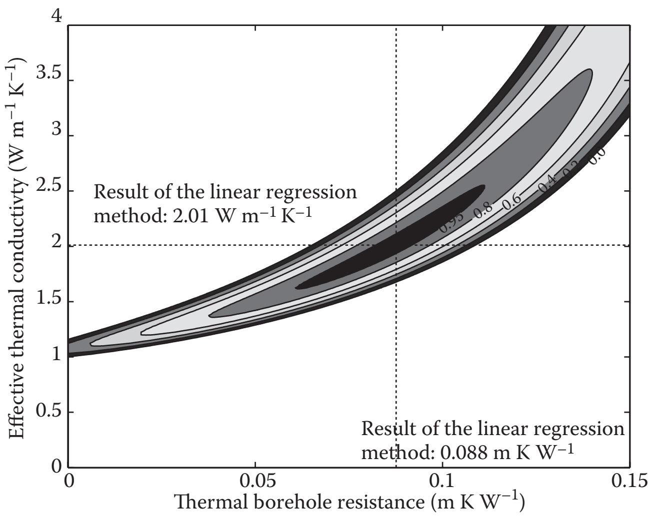

Figure 6.5 **(See color insert.)** Example of the parameter estimation technique for the evaluation of the thermal borehole resistance and the effective thermal conductivities showing the results of the model efficiencies (EF values) according to Loague and Green (1991). The results of the linear regression method are also shown. (From Wagner, V. Analysis of thermal response tests using advanced analytical and high resolution numerical simulations, Diploma thesis, University of Tubingen, Tubingen, Germany, 88 pp. 2010.)

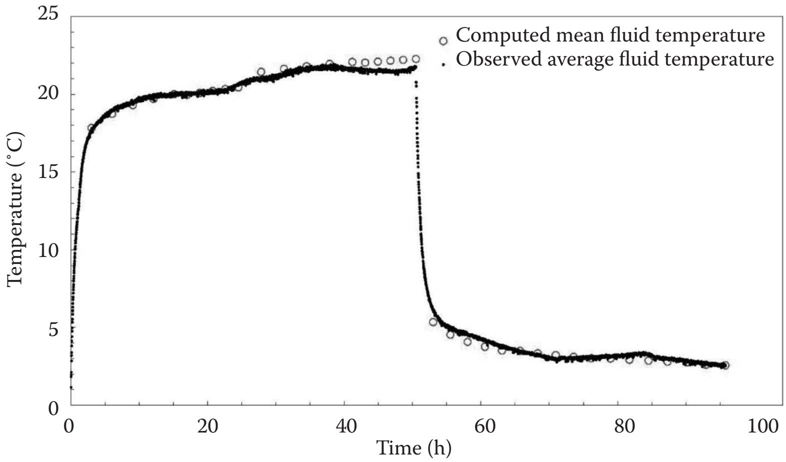

Figure 6.6 TRT data and analysis from the Doyen Mine in Québec (Canada) using the superposition principle and best fit for the entire test duration including the temperature recovery phase. (Modified after Raymond et al. 2011a.)

Due to the many assumptions for standard TRT evaluation using the Kelvin line source model, the **main limitations** arising are as follows:

1. It is impossible to evaluate the **first hours** of a TRT for the characterization of the subsurface. The reason is that the response signal is initially only influenced by the thermal properties of the BHE (Poppei et al. 2006); hence, the resulting values would be dominated by the BHE properties.
2. The assumption of a **constant heat injection** is often difficult to assure in practice. Several studies reported fluctuations for the heat input during the test duration (e.g., Eklöf and Gehlin 1996; Poppei et al. 2006; Witte et al. 2002). To overcome this issue, the TRT analysis suggested by Raymond et al. (2011a), which is able to consider variable heat injection rates, could be used.
3. A limitation of the standard TRT evaluation is the assumption of a **homogeneous undisturbed soil temperature**. For example, the geothermal gradient is not included in the standard TRT analysis (Witte et al. 2002). The influence of the geothermal gradient was comprehensively studied by Wagner et al. (2012) using a numerical model. The study shows that typical geothermal gradients (0°C to 5.2°C per 100 m) result in an underestimation of λ_m and R_{tb} using the Kelvin line source model. The estimation error may even exceed 10% for gradients of 5.2°C per 100 m.

4. The assumption that the studied medium is **homogeneous, isotropic, and infinite** is always doubtful, as BHEs often penetrate several different geological layers with different thermal and hydraulic properties. Raymond et al. (2011a) revealed that geological heterogeneity such as layering can result in an overestimation of λ_m. Alternatively, enhanced TRT or numerical models could be used to study the vertical distribution and heterogeneity of thermal properties (e.g., Raymond and Lamarche 2013).
5. **Horizontal groundwater flow** is also not considered by the conductive line source model. Yet, many studies have demonstrated the influence of increasing groundwater velocities on the estimation of the effective thermal conductivity (e.g., Bardenhagen et al. 2010; Witte et al. 2002). Signorelli et al. (2007) showed a significant influence of horizontal groundwater flow velocities higher than 0.1 m day^{-1} on the results of a TRT.
6. **Vertical groundwater flow** may also influence the results of a TRT. Borehole convection inside a BHE mainly appears in open boreholes, poorly grouted BHEs, or BHEs that are grouted with sand (Sanner et al. 2005).

In addition, a comprehensive **error analysis** of TRT, which was performed by Witte (2013), showed that measurement and theoretical errors such as parameter and model errors are about 5% for the thermal conductivity and 10%–15% for the borehole thermal resistance.

To overcome all restrictions and limitations such as variable heat injection rates, heterogeneities, and groundwater flow, enhanced TRT (e.g., Heidinger et al. 2004), the analytical approach by Wagner et al. (2013), or improved evaluation strategies like the finite and moving line source models (e.g., Molina-Giraldo et al. 2011), the superposition model by Raymond et al. (2011a), or numerical models (e.g., Signorelli et al. 2007) might be applied.

6.2.3.2 Numerical models

Numerical models have become increasingly popular, because they are able to account for spatial and temporal aspects that are typically ignored or not considered by analytical models, such as groundwater flow (Signorelli et al. 2007), specific borehole geometries, and heterogeneities of the hydraulic and thermal properties of the subsurface and the BHE. However, numerical models often need a large amount of data and information to demonstrate their advantage compared to analytical solutions. They are time-consuming and not justified for conventional TRT evaluations and cost-based geothermal projects. Nevertheless, various numerical models have been developed for BHE simulation and applied to TRT interpretation with parameter estimation techniques (e.g., Eskilson 1986; Diersch et al. 2011a,b; Raymond et al. 2011b; Wagner et al. 2012).

Eskilson (1986) developed the **superposition borehole model** (SBM), a FORTRAN-based code that is able to simulate the three-dimensional (3D) temperature field of one or several BHEs. In 1996, the SBM was integrated into the commercial transient energy simulation software package TRNSYS, the combination being called TRNSBM. Witte and van Gelder (2006) combined the latter with a parameter estimation procedure using the generic optimization package GenOpt. In addition, they performed two TRTs with and without controlled horizontal groundwater flow, where groundwater was pumped with a flow rate of 2.9 $m^3\ h^{-1}$ from an extraction well at a distance of 5 m from the studied grouted BHE. Without groundwater flow, λ_m was estimated to be 2.34 $W\ m^{-1}\ K^{-1}$ and with groundwater flow 3.22 $W\ m^{-1}\ K^{-1}$, clearly demonstrating the influence of groundwater flow on the evaluation of λ_m. The simulation performed with TRNSBM showed that even for a small Darcy velocity of <3.5 m per year, the estimated λ_m would be 6% higher in comparison to purely conductive conditions.

Shonder and Beck (1999) developed a **one-dimensional** (1D) **finite difference** (FD) **BHE model**, which is also based on a parameter estimation technique for determining thermal properties from short-period TRT. They simulated the inlet and outlet temperatures and flows using a cylinder source model. They showed that the model is even accurate for short times, and therefore, early-time data from the experiment can be used, which is an advantage compared to the analytical cylinder source method. Gehlin (2002) also developed an explicit 1D FD BHE model, which consists of 18 cells coarsening in the radial direction from the center of the BHE. The first and second cells represent the heat carrier fluid and the grouting material, and the remaining cells represent the subsurface. The results of this 1D numerical model showed slightly higher values for the thermal conductivity and R_{tb} in comparison with the analytical line source model.

A transient **two-dimensional** (2D) **finite volume** (**FV**) **model** of a vertical BHE was developed by Yavuzturk and Spitler (1999). The 2D model also uses a parameter estimation algorithm by varying R_{tb} and thermal conductivities from grout and subsurface. Wagner and Clauser (2005) developed a parameter estimation technique using the **3D FD code** SHEMAT (Chapter 4). With the developed approach, it was also possible to estimate an integral heat capacity of the ground. They showed for the TRT analysis that the average variation of the heat capacity of around 20% may only cause a 2% difference in geothermal energy yield.

Signorelli et al. (2007) used the **3D finite element** (**FE**) **code** FRACTure for the TRT analysis, which was previously successfully applied for the simulation of a deep BHE in Switzerland (Kohl et al. 2002). Other existing FE numerical flow and heat transport codes (see Chapter 4), such as HydroGeoSphere (Raymond et al. 2011b) and FEFLOW (Diersch et al. 2011a), were extended to also simulate BHEs. In FEFLOW, the numerical strategy developed by Al-Khoury et al. (2005) was extended, adopted,

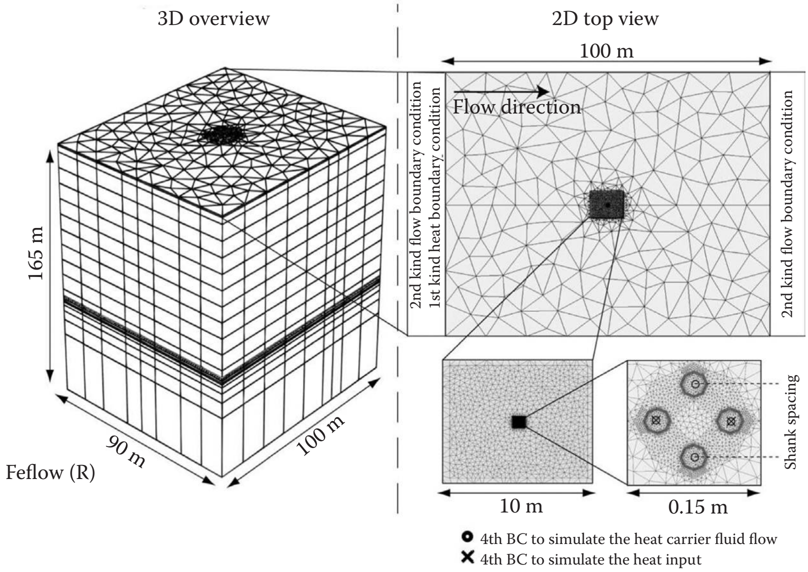

Figure 6.7 Left: 3D overview of the model domain and applied discretization. Right: 2D top view of the model domain and boundary conditions used. (Modified after Wagner, V. et al. *Renewable Energy* 41, 245–253, 2012.)

verified against an analytical solution, and applied for borehole thermal energy storage (BTES) consisting of 80 BHEs (Diersch et al. 2011b). Using FEFLOW (version 6.0), Wagner et al. (2012) studied the effects of (1) the in situ position of the U-shaped pipes of the BHE (shank spacing), (2) different geothermal gradients (i.e., nonuniform initial thermal distributions), and (3) thermal dispersivity (Figure 6.7). The results showed that the shank spacing and typical geothermal gradients have only minor effects (<10%) on the evaluation of λ_m and R_{tb}. However, given a constant groundwater flow velocity, varying thermal dispersivity values can have a significant impact on the evaluation of R_{tb}.

6.3 THERMAL TRACER TEST

When we use heat as a tracer (e.g., Anderson 2005; Saar 2011), we distinguish between long-term and short-term experiments (Wagner et al. 2014). **Long-term injection-storage experiments** are conducted to assess the performance of ATES (e.g., Molz et al. 1978; Sauty et al. 1982a,b; Xue et al. 1990; Palmer et al. 1992; Wu et al. 2008) and are also comprehensively discussed in Chapter 7. Such experiments are typically conducted with large volume injections of hot water (thousands of cubic meters) and with long-term monitoring of aquifer temperature changes (months to years). The main purpose of such large-scale field experiments is to assess the warm water storage capacity and/or recovery efficiencies of ATES. In addition, short-term active **TTTs** are infrequently conducted to derive hydraulic and thermal parameters (e.g., Shook 2001; Ma et al. 2012; Wagner et al. 2014). Here, for short periods, heated or cooled water is injected as a tracer, and then temperature changes are continuously measured in nearby observation and/or extraction wells. In some "heat tracer" experiments, thermal effects are induced by in situ heating of specific devices (e.g., Leaf et al. 2012), and one may categorize these applications as TRT-type variants without mass exchange.

In Table 6.1, selected short-term TTTs are summarized and discussed below with respect to configuration, hydrogeological setting, and test duration (Wagner et al. 2014). Keys and Brown (1978) conducted TTT in Texas, USA, by performing three **recharge tests** with various injection temperatures, water volumes, and rates. The injected water was supplied from a nearby playa lake with diurnal fluctuations of water temperatures between 13°C and 23°C. Up to 46 m away from the recharge well, the water was continuously monitored in five observation wells. The thermal pulses recorded in the wells were analyzed, and the hydraulic conductivity and its distribution were determined using laboratory and field data. Macfarlane et al. (2002) conducted a forced gradient injection test in a fractured porous sandstone aquifer in Kansas, USA. Heated water with 73°C was injected, and the temperature was monitored using distributed optical-fiber temperature sensing (DTS) in a pumped well at a distance of 13.2 m. The groundwater flow velocity derived, using the arrival time of the plume, is 2.7×10^{-5} m s^{-1}, which is 30 times larger than the estimated regional flow velocity. Leaf et al. (2012) performed three **open-well thermal dilution tests** in a fractured porous sandstone aquifer in Wisconsin, USA, using DTS also for the temperature monitoring. However, no flow velocities or hydraulic conductivities could be determined with the tests, which only provided information on the borehole flow regimes.

Vandenbohede et al. (2008a,b, 2009) conducted two single-well **push–pull tests** (PPTs) in a deep aquifer in Belgium. These tests were designed to evaluate the performance of a planned ATES. The obtained data were also exploited to examine the differences between solute and heat transport. They used an injection temperature for both PPT with 11.5°C, which was slightly colder than the ambient aquifer temperature of 15.8°C (Table 6.2). The 2D FD numerical model ReacTrans was adopted to simulate the field tests, in which the simulated solute (chloride) and heat transport were compared. They concluded that the most sensitive parameters are solute longitudinal dispersivity for the solute transport and thermal diffusivity for the heat transport (Vandenbohede et al. 2009). Ma et al. (2012) applied the 3D numerical groundwater flow model MODFLOW and MT3DMS/SEAWAT for studying

Table 6.1 Overview of short-term (<12 days) TTTs reported in literature

Location	*Aquifer type*	*Injected volume* (m^3)	*Injection rate* ($m^3\ h^{-1}$)	*Temperature difference (K)*	*Injection time (h)*	*Duration (days)*	*Observation wells*	*Remarks*	*Reference*
Stewart site, Texas, USA	Unconsolidated porous aquifer	32,832	3283	–2.3 to + 7.7	240	10	5	Natural gradient test; variable injection temperature	Keys and Brown (1978)
Kansas, USA	Porous fractured sandstone aquifer	359.6	2.5	+55	173	7.2	1	Forced gradient test, one production and one observation well	Macfarlane et al. (2002)
Coastal plane, Belgium	Deep fine sand confined porous aquifer	188	3.9	–4.3	48.15	9.2	–	Only short-term push and pull test	Vandenbohede et al. (2008a,b, 2009)
Hanford site, USA	Unconfined and unconsolidated porous aquifer	156	16.3	–7.8	9.75	11.8	28	Parallel solute and TTT	Ma et al. (2012)
Wisconsin, USA	Porous fractured sandstone aquifer	Not specified	0.6–0.8	+2–7	2.6–3	0.2–0.3	–	Three open-well thermal dilution tests; wells intersect several aquifers	Leaf et al. (2012)
Lauswiesen site, Germany	Unconfined shallow porous aquifer	16	1.0	+11	8.0	4	5	Natural gradient test	Wagner et al. (2013)

Source: Wagner et al. Thermal tracer testing in a heterogeneous sedimentary aquifer: Field experiment and numerical simulation. Hydrogeology Journal. 2014.

Table 6.2 Examples of thermal dispersivity values reported in literature obtained by field experiments and synthetic modeling studies

Reference	*Location*	*Method*	*Thermal dispersivity*	*Remarks*
Andrews and Anderson (1979)	Cooling lake of a power plant in Wisconsin (USA)	FE model, trial and error adjustment procedure; seepage from the cooling lake	β_L = 0.1 m (best fit) β_L = 0.025 m	Longitudinal to transverse dispersivity ratio = 4; scale of the 2D model = 200 m
Sauty et al. (1982b)	Bonnaud (Jura, France); confined aquifer with 2.5 m thickness	Large volume injections (up to 1680 m^3); calibrated using two 3D numerical models	β_L = 1 m (best fit)	Thermally influenced radius of about 13 m
Smith and Chapman (1983)	–	Synthetic study of a sedimentary basin (40 km wide and 5 km deep with a 1 km relief)	β_L = 100 m β_T = 10 m	2D FE flow and transport model
Xue et al. (1990)	Shanghai (China)	Single-, double-, and multiple-well experiments using flow rates of about 700 m^3 day^{-1}	β_L = 3.30 m (best fit)	3D FD flow and transport model
Molson et al. (1992)	Borden aquifer (Canada)	Warm water injection (35°C) with volume of about 54 m^3	β_L = 0.1 m β_{Th} = 0.01 m β_{Tv} = 0.005 m	3D FE flow and transport model
Su et al. (2004)	Russian River, California (USA)	Simulations of stream and groundwater temperature profiles for the six wells	β_L = 0.5 m β_T = 0.05 m	2D FD flow and transport model, best fit only with β_L
Ma et al. (2012)	Hanford site, Washington State (USA)	Combined bromide and heat tracer experiment with an injected volume of about 154 m^3	β_L = 1.0 m β_{Th} = 0.1 m β_{Tv} = 0.01 m	3D FD flow and transport model, only β_L was used for calibration
Gelhar et al. (1992)	–	1D radial flow solution 2D numerical model 3D numerical model	β_L = 1.5 m β_L = 1.0 m β_L = 0.76 m	Review of data of field-scale dispersion in aquifers

Note: β_{Th}, transversal horizontal; β_{Tv}, transversal vertical.

heat transport at the MADE site. The comparison between the two heat transport models was used to investigate the influence of variable densities and viscosities (Table 6.2). They demonstrated that when the maximum temperature difference is within 15°C, the assumption of constant fluid density and viscosity has only negligible effects on the simulated temperature distribution (Ma and Zheng 2010). Wagner et al. (2014) conducted a TTT for the characterization of a shallow heterogeneous aquifer close to Tübingen, Germany (Table 6.2). A FEFLOW based 3D model was set up to reproduce the thermal anomaly observed after 8 hours of warm water injection.

These TTTs successfully demonstrated that aquifer structures and/or properties could be comprehensively studied by monitoring groundwater temperatures. Both long- and short-term experiments can particularly be used to estimate **thermal dispersivity** values, which are only sparsely reported in the literature (e.g., Molina-Giraldo et al. 2011). Examples of reported values, which range between 0.1 and 100 m depending on the scale of observation, are provided in Table 6.2.

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