Chapter 5
Benchmarks

In order to verify both the heat transport process that is induced by the operation of BHEs, two benchmark comparisons have been carried out. In the first case, the result from analytical Infinite Line Source Model has been used as a standard (Sect. 5.1). In the second case, the numerically simulated outflow temperatures have been compared to observations from an indoor sandbox experiment (Sect. 5.2).

5.1 Borehole Heat Exchangers: Comparison to Line Source Model

Here in this benchmark, the soil temperature evolution induced by a BHE is obtained from three different configurations. They are:

- Using the *infinite line source (ILS)* analytical solution, assuming heat is evenly extracted over the length of a BHE.
- By simulating the HEAT_TRANSPORT process using OpenGeoSys, also assuming heat is evenly extracted by the BHE.
- By simulating the newly developed HEAT_TRANSPORT_BHE process in OpenGeoSys. Although the same thermal load is imposed on the BHE, this new process allows the dynamic development of pipeline and grout temperatures as well.

All three configurations have been established with the same geometry, initial conditions, and material parameters etc., which are listed in Table 5.1. It is known that the analytical line source model will produce inaccurate results of soil temperature in the immediate vicinity of the BHE. Nevertheless, the results should converge at a couple of meters away from the BHE. The result comparison will be presented in Sect. 5.1.4.

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Table 5.1 Parameters used in the line source model comparison

Parameter	Symbol	Value	Unit
Specific thermal load on the BHE	q_b	-5.68	W m^{-1}
Length of the BHE	L_{BHE}	46	m
Thermal load on the BHE	Q	-261.68	W
Soil thermal conductivity	λ_{soil}	1.34	W m^{-1} K^{-1}
Heat capacity of soil	$(\rho c_p)_{soil}$	2×10^6	J m^{-3} K^{-1}
BHE type		$1U$	
Diameter of the BHE	D_{BHE}	15	cm
Diameter of the pipeline	d_{pipe}	3.98	cm
Wall thickness of the pipeline	b_{pipe}	0.36	cm
Distance between the pipelines	w	6.3	cm
Thermal conductivity of pipeline wall	λ_{pipe}	0.39	W m^{-1} K^{-1}
Thermal conductivity of the grout	λ_{grout}	0.73	W m^{-1} K^{-1}
Heat capacity of the grout	$(\rho c_p)_{grout}$	3.8×10^6	J m^{-3} K^{-1}
Thermal conductivity of the refrigerant	$\lambda_{refrigerant}$	0.477	W m^{-1} K^{-1}
Heat capacity of the refrigerant	$(\rho c_p)_{refrigerant}$	$3.838 \cdot 10^6$	J m^{-3} K^{-1}
Viscosity of the refrigerant	$\mu_{refrigerant}$	$3.04 \cdot 10^{-3}$	kg m^{-1} s^{-1}
Flow rate of the refrigerant	$Q_{refrigerant}$	15.087	m^3 d^{-1}

5.1.1 ILS Analytical Solution

When using the infinite line source (ILS) solution (Stauffer et al. 2014), soil temperatures are expressed in difference values in comparison to the undisturbed initial temperature T_0 at a radial distance r_b. And this difference is given by

$$T - T_0 = \frac{q_b}{4\pi\lambda} E_1\left(\frac{r_b^2}{4\alpha t}\right) \tag{5.1}$$

with q_b referring to the heat flow rate per length of BHE, thermal diffusivity $\alpha = \frac{\lambda}{\rho c_p}$ and the exponential integral function E_1.

5.1.2 Numerical Line Source Model

In the numerical line source model, a domain has been constructed, with a single BHE located in the middle of it. Here the numerical process HEAT_TRANSPORT has been simulated. A constant source term of q_b was imposed on a polyline representing the BHE (cf. Fig. 5.1). Here, a constant heat source (a Neumann-type of boundary condition) of $-5.68\,\text{W/m}$ is applied on the polyline “BHE_1”. The following text box shows how the ST file was defined.

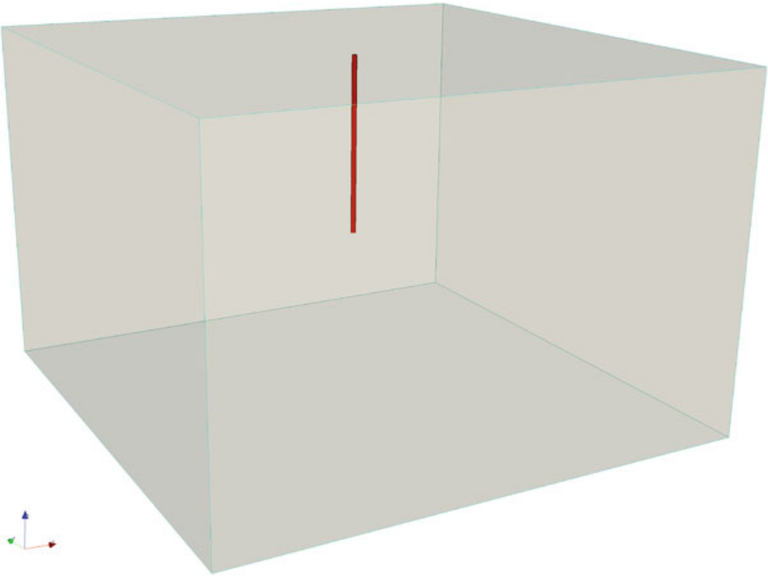

Fig. 5.1 Geometry of the benchmark, with BHE in the centre of the domain, modelled by a line source

Listing 5.1 Source term File (linesource.st)

```
#SOURCE_TERM
 $PCS_TYPE
   HEAT_TRANSPORT
 $PRIMARY_VARIABLE
   TEMPERATURE1
 $GEO_TYPE
   POLYLINE BHE_1
 $DIS_TYPE
   CONSTANT_NEUMANN -5.68
#STOP
```

Other input files of this configuration is summarized in Table 5.2. Interested readers may visit the OpenGeoSys webpage (https://docs.opengeosys.org/books/shallow-geothermal-systems) to download these input files.

5.1.3 Numerical BHE Model

Different from the configuration in Sect. 5.1.2, the numerical BHE model has a different approach to represent the borehole heat exchanger. Here the temperature evolution inside and around the BHE was simulated with a constant power $Q = q_b \cdot L_{BHE}$, and imposed as a boundary condition (cf. Sect. 5.1.4). Such configuration has been reflected in the MMP file (see the text box below). In the MMP file,

Table 5.2 *OGS* input files for the Numerical Line Source model

Object	File	Explanation
GEO	`linesource.gli`	System geometry
MSH	`linesource.msh`	Finite element mesh
PCS	`linesource.pcs`	Process definition
NUM	`linesource.num`	Numerical properties
TIM	`linesource.tim`	Time discretization
IC	`linesource.ic`	Initial conditions
BC	`linesource.bc`	Boundary conditions
ST	`linesource.st`	Source/sink terms
MSP	`linesource.msp`	Solid properties
MMP	`linesource.mmp`	Medium properties
OUT	`linesource.out`	Output configuration

the material group #0 refers to the soil part. Since no groundwater flow process is considered, all values are zero. Material group #1 represents the BHE. Here, all relevant parameters for the BHE model are entered, according to the values given in Table 5.1. What is special here is that, the boundary condition type for the BHEs is set to be "POWER_IN_WATT". This means a fixed thermal load will be imposed on the BHE. The inflow refrigerant temperature will be automatically adjusted to satisfy this thermal load.

Listing 5.2 Medium Properties File (BHE.mmp)

```
#MEDIUM_PROPERTIES
 $GEO_TYPE
  DOMAIN
 $GEOMETRY_DIMENSION
  3
 $GEOMETRY_AREA
  1
 $POROSITY
  1 0.0
 $PERMEABILITY_TENSOR
  ISOTROPIC 0.0
 $HEAT_DISPERSION
  1 0.0 0.0
#MEDIUM_PROPERTIES
 $GEO_TYPE
  POLYLINE BHE_1
 $GEOMETRY_DIMENSION
  1
 $GEOMETRY_AREA
  1
 $BOREHOLE_HEAT_EXCHANGER
  BHE_TYPE
    BHE_TYPE_1U
  BHE_BOUNDARY_TYPE
    POWER_IN_WATT
  BHE_POWER_IN_WATT_VALUE
    -261.28
  BHE_LENGTH
    46
  BHE_DIAMETER
    0.15
```

```
  BHE_REFRIGERANT_FLOW_RATE
    1.746E-04
  BHE_INNER_RADIUS_PIPE
    0.0163
  BHE_OUTER_RADIUS_PIPE
    0.0199
  BHE_PIPE_IN_WALL_THICKNESS
    0.0036
  BHE_PIPE_OUT_WALL_THICKNESS
    0.0036
  BHE_FLUID_TYPE
    0
  BHE_FLUID_LONGITUDIAL_DISPERSION_LENGTH
    0.0
  BHE_GROUT_DENSITY
    2190.0
  BHE_GROUT_POROSITY
    0.0
  BHE_GROUT_HEAT_CAPACITY
    1735.16
  BHE_THERMAL_CONDUCTIVITY_PIPE_WALL
    0.39
  BHE_THERMAL_CONDUCTIVITY_GROUT
    0.73
  BHE_PIPE_DISTANCE
    0.063
#STOP
```

In the BC file, two records have to be made for the inlet temperature at the top of the BHE and the outlet temperature at the bottom of the BHE. These two boundary conditions are required by OGS in order to locate top and bottom nodes of the BHE. Since a power boundary conditions on the BHE has already been defined, the values entered here can be arbitrary, because they will not be considered throughout the simulation.

Listing 5.3 Boundary condition File (BHE.bc)

```
#BOUNDARY_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_IN_1
 $GEO_TYPE
   POINT BHE1_TOP
 $DIS_TYPE
   CONSTANT 1.0
#BOUNDARY_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_OUT_1
 $GEO_TYPE
   POINT BHE1_BOTTOM
 $DIS_TYPE
   CONSTANT 1.0
#STOP
```

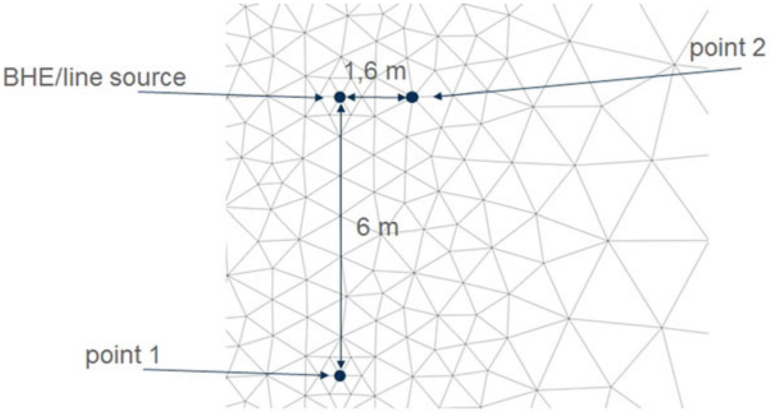

Fig. 5.2 Observation points in line source model

5.1.4 *Results*

Soil temperatures were observed at two locations, one at a distance of $r_1 = 6.0\,\mathrm{m}$ another at $r_2 = 1.6\,\mathrm{m}$ (c.f. Fig. 5.2). Good agreement has been reached between the analytical line source model solution and the numerical results. The comparison of temperature profiles can be found in Figs. 5.3 and 5.4. From these two figures, it can be concluded that the two numerical model configurations produce correct result regarding the soil temperature evolution. This comparison also suggests that the temperature difference along the BHE length is relatively small. It is safe to assume that the thermal load will be evenly distributed along the entire BHE length, and it will not generate observable changes on the soil temperatures.

5.2 Borehole Heat Exchangers: Comparison to Sandbox Experiment

In this benchmark, the Borehole Heat Exchanger (BHE) feature in the OGS software is validated against experimental results obtained by Beier et al. (2011). In their experiment, a Thermal Response Test (TRT) was performed under controlled conditions on a single U-tube borehole heat exchanger placed inside a sand box. Inlet and outlet fluid temperatures were monitored together with temperatures at the borehole wall and at different locations in the sand box.

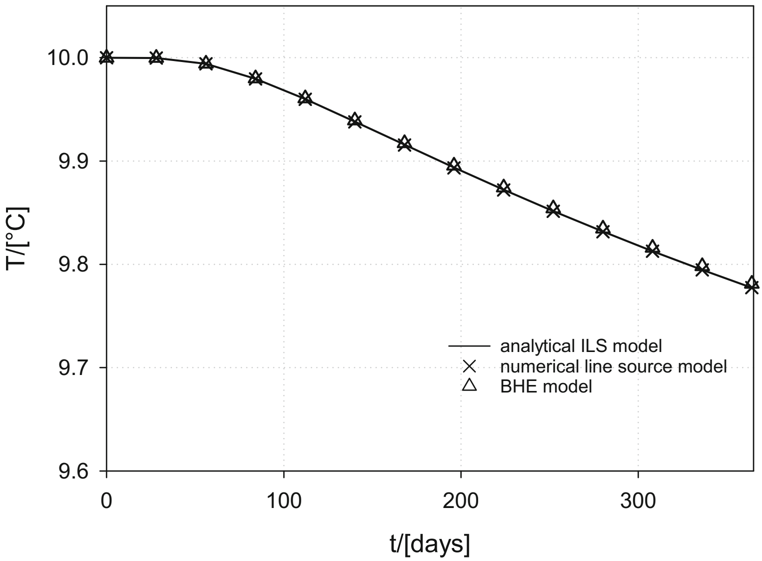

Fig. 5.3 Comparison of soil temperature profile at 6.0 m distance

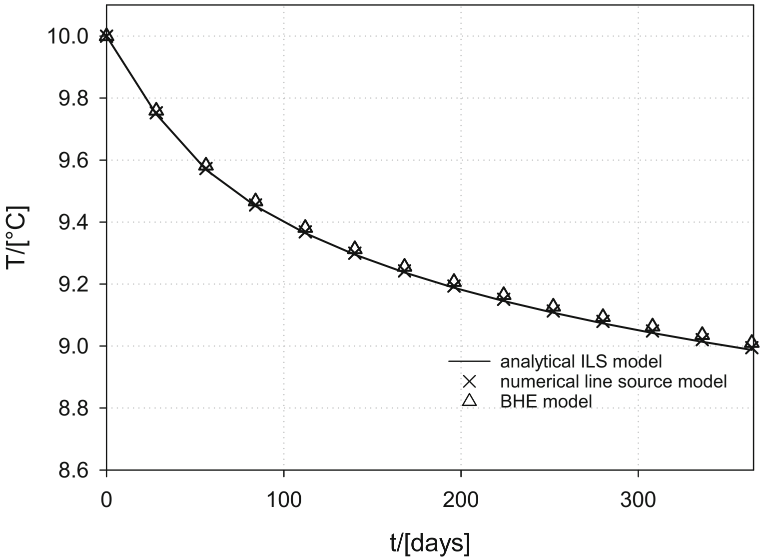

Fig. 5.4 Comparison of soil temperature profile at 1.6 m distance

5.2.1 Model Setup

The model was built according to the experimental configurations. The BHE is represented by line elements which are embedded in a 3D prism mesh representing the sandbox (Fig. 5.5). The length of the box is 18 m with a square cross section of 1.8 m per side. Detailed parameters for the model configuration can be found in Table 5.3.

In Beier's experiment, there was an aluminium pipe acting as the borehole wall. It cannot be represented by the BHE model itself, therefore the borehole diameter was taken as the aluminium pipe's outer diameter of 0.13 m in the numerical model. The grout's thermal conductivity was increased from originally 0.73 W m^{-1} K^{-1} to 0.806 W m^{-1} K^{-1}, in order to include the aluminium pipe's thermal conductivity and its geometry. The BHE is filled with water. Thermal properties and viscosity of water are taken at an average temperature of approx. 36 °C.

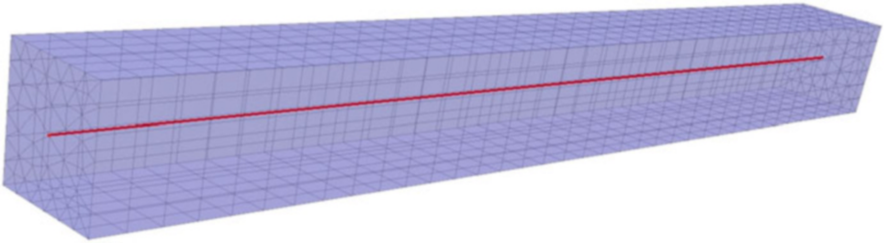

Fig. 5.5 Sandbox model

Table 5.3 Benchmark parameters according to Beier's sandbox experiment (Beier et al. 2011)

Parameter	Symbol	Value	Unit
Soil thermal conductivity	λ_{soil}	2.78	W m^{-1} K^{-1}
Soil heat capacity	$(\rho c_p)_{soil}$	3.2×10^6	J m^{-3} K^{-1}
Diameter of the BHE	D_{BHE}	13	cm
Diameter of the pipeline	d_{pipe}	2.733	cm
Wall thickness of the pipeline	b_{pipe}	0.3035	cm
Distance between pipelines	w	5.3	cm
Pipeline wall thermal conductivity	λ_{pipe}	0.39	W m^{-1} K^{-1}
Grout thermal conductivity	λ_{grout}	0.806	W m^{-1} K^{-1}
Heat capacity of the grout	$(\rho c_p)_{grout}$	3.8×10^6	J m^{-3} K^{-1}

5.2.2 *OGS Input Files*

The OGS input files used in this benchmark is very similar as those in Sect. 5.1. Here only the unique parts are highlighted.

5.2.2.1 Initial and Boundary Conditions

Initial conditions for fluid inlet/outlet temperatures and wall temperature were directly taken from the measurements at $t = 0$. For the initial soil temperature, the mean value of all sensors placed in the sand was taken. As initial grout temperatures, arithmetic mean between wall and fluid inlet/outlet temperature was taken. Detailed initial temperatures can be found in Table 5.4.

Listing 5.4 Initial Condition File (Beier.ic)

```
#INITIAL_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_SOIL
 $GEO_TYPE
   DOMAIN
 $DIS_TYPE
   CONSTANT 22.1
#INITIAL_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_SOIL
 $GEO_TYPE
   POLYLINE BHE_1
 $DIS_TYPE
   CONSTANT 21.95
#INITIAL_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_IN_1
 $GEO_TYPE
   POLYLINE BHE_1
 $DIS_TYPE
   CONSTANT 22.21
```

Table 5.4 Initial conditions of sandbox model

Parameter	Symbol	Value	Unit
BHE inlet temperature	T_{in}	22.21	°C
BHE outlet temperature	T_{out}	21.98	°C
Grout temperature around inlet pipe	T_{grout1}	22.08	°C
Grout temperature around outlet pipe	T_{grout2}	21.97	°C
Soil temperature	T_{soil}	22.10	°C
BHE wall temperature	T_{wall}	21.95	°C

```
#INITIAL_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_OUT_1
 $GEO_TYPE
   POLYLINE BHE_1
 $DIS_TYPE
   CONSTANT 21.98
#INITIAL_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_G_1
 $GEO_TYPE
   POLYLINE BHE_1
 $DIS_TYPE
   CONSTANT 22.08
#INITIAL_CONDITION
 $PCS_TYPE
   HEAT_TRANSPORT_BHE
 $PRIMARY_VARIABLE
   TEMPERATURE_G_2
 $GEO_TYPE
   POLYLINE BHE_1
 $DIS_TYPE
   CONSTANT 21.965
#STOP
```

The boundary conditions are imposed on the BHE as time series of measured inlet fluid temperature and flow rate as demonstrated in Fig. 5.6. Note that the BHE top boundary condition is different (cf. MMP file), as the inlet temperature is imposed here as a time series dataset. A constant value `CONSTANT 1.0` is given in the BC file, which will be multiplied with the corresponding value read from `CURVE 1` in the RFD data file.

Listing 5.5 Boundary Condition File (Beier.bc)

```

#BOUNDARY_CONDITION
$PCS_TYPE
HEAT_TRANSPORT_BHE
$PRIMARY_VARIABLE
TEMPERATURE_IN_1
$GEO_TYPE
POINT POINT9
$DIS_TYPE
CONSTANT 1.0
$TIM_TYPE
CURVE 1
#BOUNDARY_CONDITION
$PCS_TYPE
HEAT_TRANSPORT_BHE
$PRIMARY_VARIABLE
TEMPERATURE_OUT_1
$GEO_TYPE
POINT POINT4
$DIS_TYPE
CONSTANT 1.0
#STOP
```

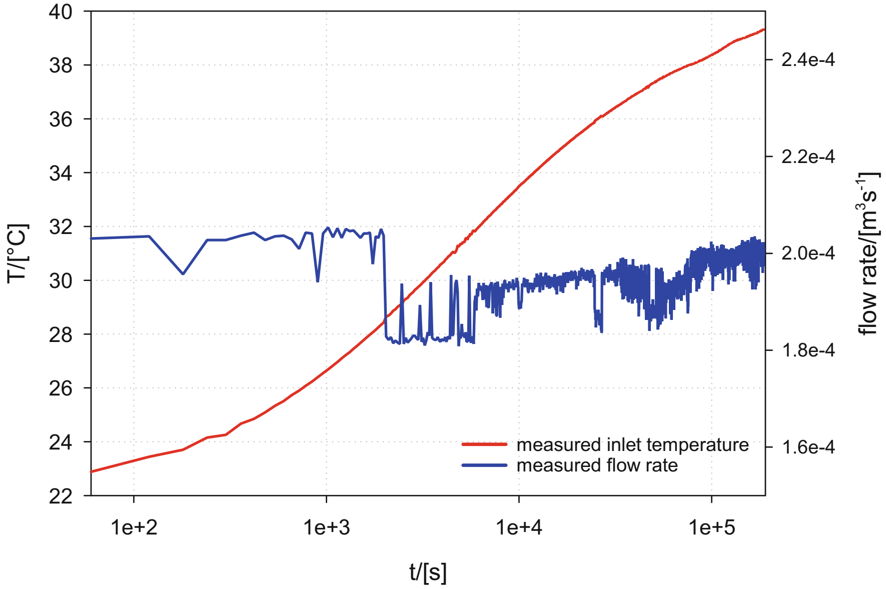

Fig. 5.6 Time series of inlet temperature and flow rate

5.2.2.2 RFD Data File

In this file, time-dependent curves can be defined. In this benchmark, the first curve is the BHE inlet temperature, the second curve is the flow rate.

Listing 5.6 Data File (Beier.rfd)

```
#CURVE
0 22.21111111
60 22.9
120 23.46111111
180 23.72222222
240 24.17222222
300 24.27222222
360 24.68888889
[..]
186180 39.32222222
186240 39.32222222
186300 39.33888889
186360 39.32222222
#CURVE
0 0
60 0.000203129
120 0.000203576
180 0.000195764
[..]
186240 0.000200406
186300 0.000199655
186360 0.000201159
#STOP
```

5.2.2.3 Medium Properties

Please note, that the `BHE_BOUNDARY_TYPE` is different here as the inlet temperature is imposed. Therefore, the “BHE_BOUNDARY_TYPE” is set to “FIXED_INFLOW_TEMP_CURVE”. An index value is also given under the key word “BHE_FLOW_RATE_CURVE_IDX”. Other BHE configurations follow those provided by Beier et al. (2011).

Listing 5.7 Medium Properties File (Beier.mmp)

```
#MEDIUM_PROPERTIES
$GEO_TYPE
DOMAIN
$GEOMETRY_DIMENSION
3
$GEOMETRY_AREA
1
$POROSITY
1 0.0
$PERMEABILITY_TENSOR
ISOTROPIC 0.0
$HEAT_DISPERSION
1 0.0 0.0
#MEDIUM_PROPERTIES
$GEO_TYPE
POLYLINE BHE_1
$GEOMETRY_DIMENSION
1
$GEOMETRY_AREA
1
$BOREHOLE_HEAT_EXCHANGER
BHE_TYPE
 BHE_TYPE_1U
BHE_BOUNDARY_TYPE
 FIXED_INFLOW_TEMP_CURVE
BHE_FLOW_RATE_CURVE_IDX
 2
BHE_LENGTH
 18.0
BHE_DIAMETER
 0.13
BHE_REFRIGERANT_FLOW_RATE
 2.0e-4
BHE_INNER_RADIUS_PIPE
 0.013665
BHE_OUTER_RADIUS_PIPE
 0.0167
BHE_PIPE_IN_WALL_THICKNESS
 0.003035
BHE_PIPE_OUT_WALL_THICKNESS
 0.003035
BHE_FLUID_TYPE
 0
BHE_FLUID_LONGITUDIAL_DISPERSION_LENGTH
 0.0
BHE_GROUT_DENSITY
 2190.0
BHE_GROUT_POROSITY
 0.0
BHE_GROUT_HEAT_CAPACITY
 1735.160
BHE_THERMAL_CONDUCTIVITY_PIPE_WALL
```

```
 0.39
BHE_THERMAL_CONDUCTIVITY_GROUT
 0.806
BHE_PIPE_DISTANCE
 0.053
#STOP
```

5.2.3 Results

The outlet temperature (Fig. 5.7) as well as the borehole wall temperature, soil temperatures at 24 cm and 44 cm distance to the wall (Fig. 5.8) were compared to the experimental results. It can be observed that a good match has been achieved between experimental and simulation results. The largest relative error is about 2.5 % on the wall temperature. Considering the error of measuring temperatures, flow rate and thermal conductivity values are in the same range, it can be concluded that the numerical model is fully validated.

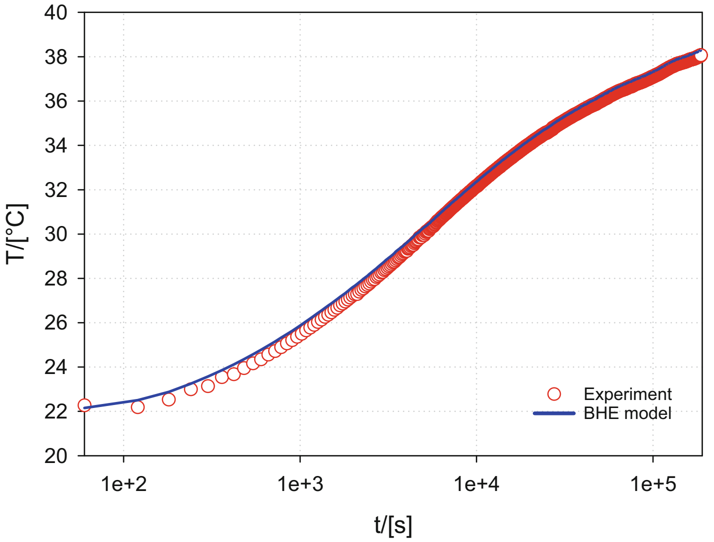

Fig. 5.7 Comparison of simulated and measured outlet temperature profile in the sandbox experiment

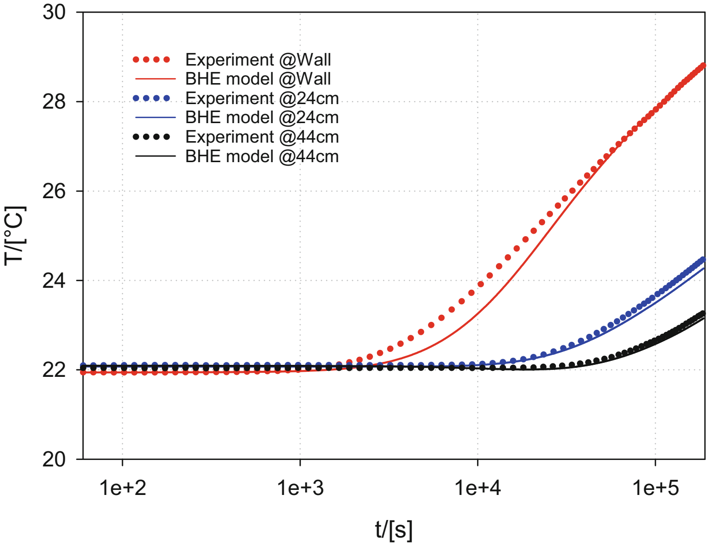

Fig. 5.8 Comparison of modelled and measured wall and soil temperatures