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Implementation and validation of a Ground Source Heat Pump model in MATLAB

Master's Thesis in Sustainable Energy Systems

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Abstract

The aim of the project is the implementation of a simple Ground-Source Heat Pump (GSHP) system model in MATLAB. The program is able to run multi-year simulations for a given building hourly load profile, with an hourly time step. The GSHP system, including borehole heat exchanger geometry, borehole field configuration, circulating fluid properties, heat pump selection, can be set up to simulate typical installations. The system model itself consists of an analytical borehole heat exchanger model and of a water-to-water heat pump model based on catalog data. Both components are coupled through a set of equations solved iteratively within a time step, with a robust and efficient MATLAB built-in solver. A procedure aggregation of hourly building load values is also implemented.

The implemented GSHP system model is compared with an equivalent reference model in TRNSYS. It has been developed for validation purposes and a control strategy has been included in order to obtain two models with a similar operation. Both models give average Coefficient of Performance (COP) and average fluid temperature with a difference of less than 2%.

The MATLAB environment has been chosen as a universal and widely spread tool among engineers. The code is meant to be simple and easy to use.

Keywords : ground source heat pump, ground-coupled, ground heat exchanger, borehole thermal energy storage, water-to-water heat pump, free cooling, short-term, long-term, step response, superposition, load aggregation, thermal response test, MATLAB, TRNSYS, GenOpt, simulation, optimization, control

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Contents

Nomenclature	v
List of figures	vii
List of tables	ix
1 Introduction	1
1.1 Topic	1
1.2 Context	1
1.3 Building Services Engineering	1
1.4 Aim	2
1.5 Outline	2
2 Background	3
2.1 System simulation models	3
2.1.1 Building simulation programs	3
2.1.2 Stand-alone programs	4
2.1.3 Summary	5
2.2 Component models	5
2.2.1 Borehole heat exchanger	5
2.2.2 Heat pump	11
3 Methodology	13
3.1 Implementation	13
3.1.1 Parameter estimation method	13
3.1.2 Borehole heat exchanger simulations	17
3.1.3 Ground Source Heat Pump system simulations	21
3.2 Checking and comparison	24

4	Results	27
4.1	Parameters estimation from TRT	27
4.2	GSHP simulation	28
4.3	Model validation	31
5	Conclusion	35
5.1	Summary and conclusions	35
5.2	Future work	36
	References	37
	Bibliography	39
A	Implementation	41
A.1	Main program	41
A.2	Load-aggregation	45
A.3	Heat pump	50
A.4	$I_e(s)$ coefficients	51
B	TRNSYS input file	55
C	TRT test report	71
C.1	Test description	71
C.2	Aim	71
	C.2.1 Personal	71
	C.2.2 Supervisor	71
C.3	Measurements	72
	C.3.1 Temperature (logged each 5 minutes)	72
	C.3.2 Flow (logged each 5 minutes)	72
	C.3.3 Power (logged each 5 minutes)	72
	C.3.4 Pressure (checked at start-up)	72
C.4	Duration	72
C.5	Notes	72
C.6	Results	73

Nomenclature

(l,p)	lumped cell indices
$\bar{k}_{l,p}$	weighting factor for cell (l,p)
$\bar{Q}_{l,p}^{(n)}$	past aggregated load at time step n [W]
\dot{m}	mass flow rate [kg/s]
ϵ	error between modeled fluid temperature and experimental fluid temperature [K]
ϵ_a	error between the mean fluid temperature computed with and without load aggregation [K]
λ_g	grout thermal conductivity [W/(mK)]
λ_s	soil thermal conductivity [W/(mK)]
a_g	grout thermal diffusivity [m ² /s]
a_s	soil thermal diffusivity [m ² /s]
AT	Accumulator Tank
B	borehole spacing [m]
BHE	Borehole Heat Exchanger
C_p	fluid heat capacity per unit length [J/(mK)]
c_p	fluid heat capacity [J/(kgK)]
c_{ps}	soil heat capacity [J/(kgK)]
COP	Coefficient of Performance
EH	Electrical Heater

<i>GHE</i>	Ground Heat Exchanger
<i>GSHP</i>	Ground Source Heat Pump
<i>H</i>	borehole active depth [<i>m</i>]
<i>HP</i>	Heat Pump
<i>HVAC</i>	Heating Ventilation and Air-Conditioning
<i>I_e</i>	shape coefficients defined in 2.2.1
<i>N_b</i>	number of boreholes
<i>P_l</i>	number of cells on level <i>l</i>
<i>Q₃₅</i>	heating capacity at $T_{w2} = 35^{\circ}\text{C}$ [<i>W</i>]
<i>Q₅₀</i>	heating capacity at $T_{w2} = 50^{\circ}\text{C}$ [<i>W</i>]
<i>Q_{ground}</i>	ground heat load [<i>W</i>]
<i>q_{inj}</i>	rate of injection heat transfer per unit length [<i>W/m</i>]
<i>Q_{load,rated}</i>	heating capacity at rated conditions [<i>W</i>]
<i>Q_{load}</i>	heating capacity or heating demand [<i>W</i>]
<i>Q_{step}</i>	heat injection step [<i>W</i>]
<i>q_{step}</i>	heat injection step per unit length [<i>W/m</i>]
<i>R_b</i>	borehole thermal resistance [<i>mK/W</i>]
<i>r_b</i>	borehole radius [<i>m</i>]
<i>r_p</i>	equivalent pipe radius [<i>m</i>]
<i>SSE</i>	Sum of the Squared Errors [<i>K</i> ²]
<i>T_f</i>	mean fluid temperature [$^{\circ}\text{C}$]
<i>T_r</i>	mean fluid temperature from radial solution [$^{\circ}\text{C}$]
<i>T_{amb,exp}</i>	experimental ambient temperature [$^{\circ}\text{C}$]
<i>T_{b1}</i>	source-side entering fluid temperature [$^{\circ}\text{C}$]
<i>T_{b2}</i>	source-side leaving fluid temperature [$^{\circ}\text{C}$]
<i>T_{f,a}</i>	mean fluid temperature, with load aggregation [$^{\circ}\text{C}$]
<i>T_{f,exp}</i>	experimental mean fluid temperature [$^{\circ}\text{C}$]

T_{ils}	mean fluid temperature from infinite line-source solution [$^{\circ}C$]
$T_{in,exp}$	experimental inlet fluid temperature [$^{\circ}C$]
T_{in}	inlet fluid temperature [$^{\circ}C$]
T_{ls}	mean fluid temperature from finite line-source solution [$^{\circ}C$]
$T_{out,exp}$	experimental outlet fluid temperature [$^{\circ}C$]
T_{out}	outlet fluid temperature [$^{\circ}C$]
T_{step}	fluid temperature step response [$^{\circ}C$]
T_{w1}	load-side entering fluid temperature [$^{\circ}C$]
T_{w2}	load-side leaving fluid temperature [$^{\circ}C$]
$W_{el,rated}$	electrical power input at rated conditions [W]
W_{el}	electrical power input [W]

List of Figures

2.1	9-borehole square configuration (Claesson & Javed, 2011)	6
2.2	3-borehole line configuration (Claesson & Javed, 2011)	7
2.3	Geometry and thermal properties of the borehole in the short-term analytical solution (Claesson & Javed, 2011)	7
2.4	Radial heat transfer problem as a thermal network in the Laplace domain (Claesson & Javed, 2011)	8
2.5	2-borehole heat exchanger nomenclature in the DST model (TESS, 2012a)	10
2.6	Reversible water-to-water heat pump (TESS, 2012b)	12
3.1	The TRT setup used at the laboratory of Building Services Engineering, Chalmers with a borehole system and a electrical heater (EH1)(Javed & Fahlén, 2010)	15
3.2	Parameter estimation method using TRNSYS and GENOPT	16
3.3	Step response of 1 borehole, from analytical and finite line-source solutions	18
3.4	Combined step response of 1 and 9 boreholes	18
3.5	Weighting functions for 1, 3 and 9 boreholes (Claesson & Javed, 2011) . .	20
3.6	GSHP model flow chart	22
3.7	GSHP model in TRNSYS	23
3.8	Checking and comparison process	24
4.1	Heat load profile for an annual GSHP simulation (Javed, 2012)	29
4.2	Fluid temperature for an annual GSHP simulation	29
4.3	COP for the 2 first months of an annual GSHP simulation	30
4.4	Source-side entering fluid temperature for the 2 first months of an annual GSHP simulation	30
4.5	Load-aggregation scheme accuracy	31
C.1	Power and mean fluid temperature from TRT	73

List of Tables

2.1	Summary of the existing GSHP simulation models features	5
4.1	Parameter estimation method results, with the analytical model in MATLAB and the DST model in TRNSYS	27
4.2	Parameters for GSHP system simulation in MATLAB	28
4.3	Parameters of a GSHP system heating mode simulation in MATLAB	32
4.4	Main differences between the MATLAB and the reference model in TRNSYS	33
4.5	Comparison of the COP and the fluid temperature between MATLAB and TRNSYS	33

1

Introduction

1.1 Topic

Ground source heat pumps (GSHP) are electrically-driven systems providing heating, cooling and hot water to residential and commercial buildings. Borehole heat exchangers harness the rather constant underground temperature. The circulating fluid delivers (extracts) heat to (from) the building through a heat pump (chiller if needed, directly otherwise). Both components interact with each other, hence the complete system is often referred as a ground-coupled heat pump system. From a Swedish perspective, where heating needs are dominant due to climatic conditions, systems are designed accordingly: a heat pump in heating mode and no chiller in cooling mode, namely free-cooling.

1.2 Context

Ground source heat pumps have sustained a constant growth over the past decade as they offer both economical and environmental benefits (compared to a system powered by fossil fuels) in a wide range of buildings, from a retrofit to a new installation. First, as electricity only is used to run the system, there are no emissions on-site. Second, energy savings, lower maintenance costs and - in some cases - incentives from governments quickly offset the higher initial cost. The investment is recouped within a few years. Still, research is very active and aims at improving current designs, from a component and from a system point of view.

1.3 Building Services Engineering

Ground source heat pump system is one of the research area of the division. The research on GSHP systems is carried out within the division (researchers, PhD thesis, Master

thesis), with other divisions (e.g. Department of Civil and Environmental Engineering) and with external stakeholders such as research institutes (e.g. SP) and companies.

A new heating, ventilation, air-conditioning (HVAC) laboratory has been recently built (Javed & Fahlén, 2010). Among other things, it features a GSHP system aimed to run experiments in a wide range of conditions. It consists of a borehole thermal energy storage system (BTES) including 9 vertical boreholes in a square configuration, heat pumps, storage tanks and heat exchangers. The test facility can be used to test, develop and optimize control strategies and to test, validate and calibrates both component and system models (Javed & Fahlén, 2010) (see section 2).

1.4 Aim

The aim of this project is the implementation and the validation of a simple Ground-Source Heat Pump system model in MATLAB. The program must be able to run multi-year simulations for a given building hourly load profile. Computational efficiency and accuracy are the two main criteria. The GSHP system, including the borehole heat exchanger geometry, borehole field configuration, circulating fluid properties, heat pump selection can be set up to simulate typical installations. The system model itself consists of an analytical borehole heat exchanger model and of a water-to-water heat pump model based on catalog data. Both components are coupled through a set of equations solved iteratively within a time step. A procedure for load aggregation is also implemented, allowing the user to enhance computational time without significant drop in accuracy.

From a research perspective, the major contribution is the implementation of a recently developed analytical borehole heat transfer model (Javed & Claesson, 2011) in a GSHP simulation program in MATLAB. The MATLAB environment has been chosen because it is a universal and widely spread tool among engineers. The code is designed to be simple and easy to use for any engineer or consultant dealing with GSHP issues. TRNSYS is used as a reference software to validate the results.

1.5 Outline

The project was carried out from March 2012 to June 2012 at Building Services Engineering, Chalmers. It is defined as a 20-ECTS-credits project of Master level. The report is divided into the following sections. First, existing component and system models are discussed and explained in the *Background* section. It provides the reader with enough basics to understand the work presented here and to figure out to what extent the study contributes to the topic. Second, the GSHP model developed in MATLAB as well as the TRNSYS reference model are detailed, in the *Methodology* section. Third, results from GSHP annual simulations are presented in *Results* section. At the end, conclusions are drawn and a discussion about the work and its future developments is held.

2

Background

This section is mainly based on existing models from published scientific papers. Models directly used in the project are explained whereas the others are only mentioned. For more details, please refer to the reference papers in the bibliography.

2.1 System simulation models

Here is a quick review (Yang, 2012) of the main GSHP simulation models.

2.1.1 Building simulation programs

These building simulation programs have Ground Heat Exchanger (GHE) models implemented in them.

TRNSYS

TRNSYS (17.1 is the current version) is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. It is used by engineers and researchers around the world to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems (wind, solar, photovoltaic, hydrogen systems), etc. One of the key factors in TRNSYS' success over the last 35 years is its open, modular structure. The source code of the kernel as well as the component models is delivered to the end users. This simplifies extending existing models to make them fit the user's specific needs. The DLL-based architecture allows users and third-party developers to easily add custom component models, using all common programming languages (C, C++, PASCAL, FORTRAN, etc.). In addition, TRNSYS can be easily connected to many other applications, for pre- or postprocessing or through interactive calls during the simulation (SEL, 2009).

Over the past two decades, TRNSYS has been widely used in the research and in the industry as a reliable building energy simulation software (Zogou & Stamatelos, 2007). It is also one of the listed simulation programs in the recent European standards on solar thermal system (ENV-12977-2). The building component, known as "Type 56", is compliant with ANSI/ASHRAE (respectively American National Standards Institute and American Society of Heating, Refrigerating and Air Conditioning Engineers) Standard 140-2001 (ANSI/ASHRAE, 2001) and meet the level of details of the European directive on the energy performance of building. Of greater interest in the scope of this project is the fact that there are systematic studies validating the software results against experiments and other software (Neymark, 2002).

TRNSYS, with additional TESS HVAC libraries, is able to perform simulations of a GSHP system consisting of borehole heat exchangers (numerical model), heat pumps, storage tanks, heat exchangers and control equipment. Loads are calculated either by simulating a given building with a given demand (Type 56) or by reading them as input data (calculated by an external software beforehand).

Please read section 2.2.1 and 2.2.2 to know more about, respectively, the borehole heat exchanger and heat pump models.

HVACSIM+, Energy Plus and eQuest

HVACSIM+ (20 is the current version), Energy Plus (7.1.0 is the current version) and eQuest (3.64 is the current version) will be described together as they are all simulation software able to perform hourly and sub-hourly simulations of borehole heat exchangers, using pre-computed Eskilson's g-functions for times ranging from days to hundreds of years. For shorter time steps, the model is extended with a one-dimensional (radial) finite volume model (Spitler & Xu, 2006), which gives acceptable accuracy as long as the material properties inside the borehole were carefully matched to the actual borehole resistance (HVACSIM+, essentially the same approach for Energy Plus) or with a line-source analytical solution (eQuest) as described in section 2.2.1. Please refer to (Fisher *et al.*, 2006) for more details about the water-source heat pump model. HVACSIM+ and Energy Plus required a high level of computer literacy whereas eQuest is said to be more user-friendly.

2.1.2 Stand-alone programs

GLHEPRO

The professional Ground Loop Heat Exchanger design software (GLHEPRO, V 4.0.9 is the current version) (Spitler, 2000) is a tool for design (borehole depth, number of boreholes) of vertical ground loop heat exchanger used in geothermal heat pump systems. It calculates monthly and peak values of the entering fluid temperature to the heat pump (of interest as the heat pump performance is highly dependent on it), of the power consumed by the compressor and of the heat extraction rate per unit length of borehole.

The borehole response is obtained from pre-computed Eskilson's g-functions (Eskilson, 1987) stored in a database and spanning a reasonable range of common configurations. The heat pump model is based on manufacturer catalog data. The coupling between the ground and the heat pump is solved within a time step. The software features a Graphical User Interface (GUI). Please read section 2.2.1 and 2.2.2 to know more about, respectively, the borehole heat exchanger and heat pump models.

EED

Earth Energy Designer (EED, 3.16 is the current version) is a PC-program for vertical borehole heat exchanger design (Blomberg *et al.*, 2008). Basically, it follows the same philosophy as GLHEPRO, introduced in section 2.1.2. However, there is a major difference. The Coefficient of Performance (COP) of the heat pump is assumed constant. Subsequently, there is coupling to solve at each time step.

2.1.3 Summary

Table 2.1 sums up the main features presented in section 2.1.

Table 2.1: Summary of the existing GSHP simulation models features

	TRNSYS	GLHEPRO	EED	HVACSIM+, Energy Plus	eQuest
BHE	Numerical	Pre-computed numerical	Pre-computed numerical	Pre-computed numerical + numerical for short-term	Pre-computed numerical + analytical at short term
HP	Catalog data	Catalog data	Fixed COP	*	**
Coupling	Yes	Yes	No	Yes	Yes
Time step	Sub-hourly	Monthly + peak values	Monthly + peak values	Sub-hourly	Sub-hourly
GUI	Yes	Yes	Yes	No	Yes
Expertise required	Yes	No	No	Yes	No ***

* Please refer to (Fisher *et al.*, 2006)

** Please refer to (Fisher *et al.*, 2006)

*** according to the software webpage

2.2 Component models

2.2.1 Borehole heat exchanger

In this project, only vertical U-tube borehole heat exchangers are considered. Typically, they consist of:

- circulating fluid (e.g. water with an anti-freeze solution such as ethanol or glycol) with turbulent flow

- a U-tube (e.g. made of polyethylene). Spacing between the upwards and downwards pipes (namely "shank spacing") can either be controlled, like in the US systems, or let free to move along the borehole depth like in Swedish systems.
- the grout region, of which filling (e.g. grout, thermally enhanced grout, groundwater) depends mainly on the surrounding ground composition
- the surrounding ground (e.g. composed of clay, sand, loam, rock, ...)

Borehole heat exchangers are either made of a single borehole or a configuration of several boreholes, depending on the design capacity. In the latter case, there are two options:

- a close, compact (e.g. square, rectangular) configuration designed to store heat in the ground (to extract in winter heat rejected in summer). See figure 2.1.
- an open, dissipative (e.g. line, L-shaped, U-shaped, ...) configuration designed for cooling -dominant (or heating-dominant) applications. See figure 2.2.

See figure 2.5 for a simple drawing of a 2-borehole heat exchanger. Note that the so-called "storage volume" is part of the ground (read section 2.2.1 for more details).

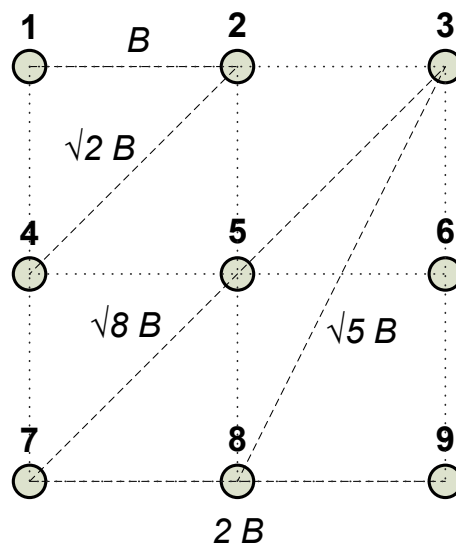


Figure 2.1: 9-borehole square configuration (Claesson & Javed, 2011)

Analytical models

Short-term analytical solution A new analytical solution (Javed & Claesson, 2011), developed recently at Building Services Engineering, Chalmers, emphasizes very much on short-term modeling of borehole heat transfer.

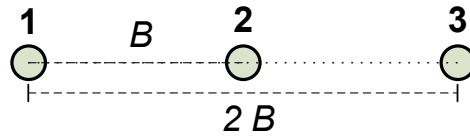


Figure 2.2: 3-borehole line configuration (Claesson & Javed, 2011)

The main idea is to transpose the heat transfer problem to the Laplace's domain to get a simple thermal network, hence an easier solving process. The model is fully analytical as the integration, to obtain the solution back in the time domain, is computed analytically.

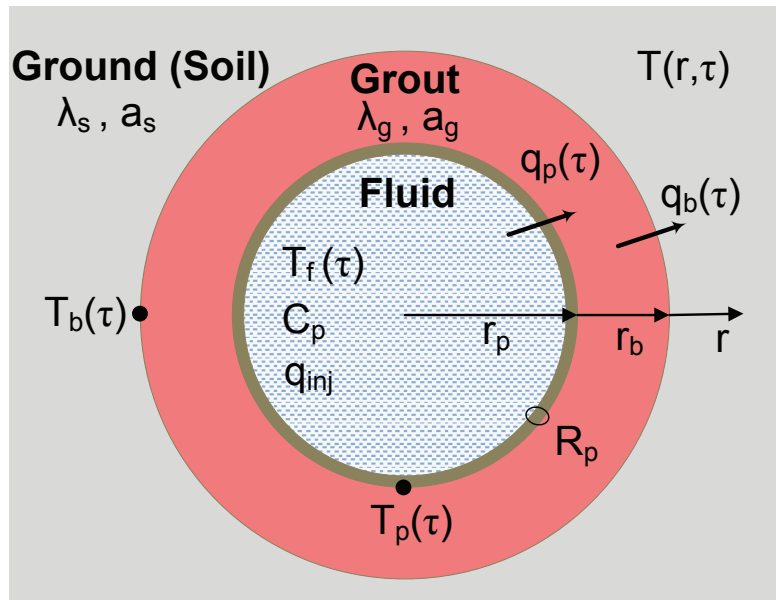


Figure 2.3: Geometry and thermal properties of the borehole in the short-term analytical solution (Claesson & Javed, 2011)

Limitations to remember are :

- the problem is one-dimensional (radial)
- the two pipes of the U-tubes are approximated as a single pipe with an equivalent diameter
- heat conduction is the only heat transfer process directly taken into account in the grout region (although convective heat transfer is modeled in the pipe through the thermal resistance of the internal film layer)

The heat transfer problem, from the fluid to the ground, is divided into three sub-regions:

1. the pipe region: the problem is solved for a step heat injection rate to the fluid. The thermal capacity of the fluid is kept equal to that in the U-tube. The thermal resistance includes the convective resistance and the conductive resistance of the tube thickness.
2. the annular region: transient heat conduction is considered in the grout, from the pipe outer wall to the borehole wall
3. the soil region: transient heat conduction is considered in the soil, from the borehole wall to the surrounding ground

See figure 2.3 to check the geometry of the radial heat transfer problem and the physical properties of the three sub-regions. Please refer to this report's nomenclature for the symbols. Basically, the heat conduction equation is solved in both the annular and soil region, as follows :

$$\frac{1}{a(r)} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r}, \quad a(r) = \begin{cases} a_g, r_p < r < r_b \\ a_s, r > r_b \end{cases} \quad (2.1)$$

As for the pipe region, the starting point is the heat balance of the fluid in the pipe with the injected heat q_{inj} , which reads as the following :

$$q_{inj} = C_p \frac{dT_f}{dt} + q(r_p, t) \quad (2.2)$$

It leads to a thermal network in the Laplace domain, in which there is the Laplace transform of the mean fluid temperature $\bar{T}_f(s)$, as can be seen in figure 2.4.

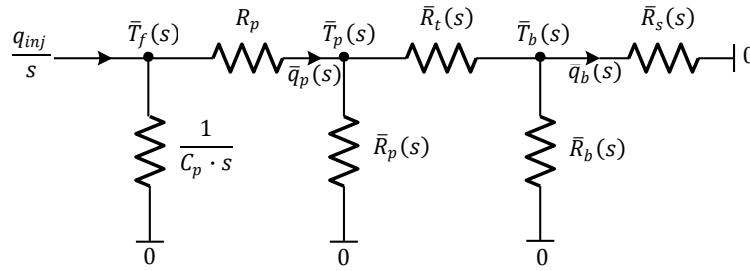


Figure 2.4: Radial heat transfer problem as a thermal network in the Laplace domain (Claesson & Javed, 2011)

The Laplace transform $\bar{T}_f(s)$ is obtained by solving the thermal network with usual resistor combination rules. The inversion integral to obtain fluid temperature in time domain is computed as follows:

$$T_r(t) = \frac{2}{\pi} \int_0^\infty \frac{1 - e^{-u^2 \frac{\tau}{\tau_0}}}{u} L(u) du \quad (2.3)$$

where

$$L(u) = \text{Im}[-s \cdot \bar{T}_f(s)]_{\Gamma} \quad \Gamma : \tau_0 \cdot s = -u^2 \quad (2.4)$$

Please refer to (Javed & Claesson, 2011) for further details about calculations and for an explicit definition of the resistances.

Finite line-source solution The finite line-source solution (Claesson & Javed, 2011) assumes that the borehole behaves as a continuous line heat source of strength q_0 [W/m] at $x = 0$, $y = 0$ and $0 < z < H$ (borehole depth). It gives the mean temperature over the borehole depth at any radius r from the borehole center. It can be reduced to a simple integral:

$$T_{ls}(r,t) - T_0 = \frac{q_0}{4\pi\lambda_s} \int_{\frac{1}{\sqrt{4a_s t}}}^{\infty} e^{-r^2 s^2} \frac{I_{ls}(Hs)}{Hs^2} L(u) ds \quad (2.5)$$

where

$$I_{ls}(h) = 4 \text{ierf}(h) - \text{ierf}(2h) \quad (2.6)$$

The solution does not take into account the local thermal process in the borehole (the only physical input is the ground conductivity λ_s). Then, it has to be adjusted and the circulating fluid temperature is obtained by accounting for borehole resistance. Read more about it in section 3.1.2.

The solution allows to calculate the temperature response of a N-borehole configuration, using spatial superposition. It is done by simply replacing the exponential term inside the integral in (2.5) with $I_e(s)$ functions, which depend on the size and the configuration (see section 2.2.1) of the borehole field.

Infinite line-source approximation The infinite line-source approximation (Gehlin, 2002) is mainly used in TRT parameter estimation methods. While this simplification gets rid of the integral, it is valid for times larger than 10-15 hours for a typical installation. Read more about TRT in section 3.1.1.

$$T_{ils}(t) - T_0 = \frac{q_0}{4\pi\lambda_s} \ln\left(\frac{4a_s t}{\gamma r_b^2}\right) + q_0 R_b, \quad t > \frac{5r_b^2}{a_s} \quad (2.7)$$

Note that all the line-source solutions presented above are of the form $T - T_0 = \frac{q_0}{\lambda_s} f(Fo)$, with the Fourier number $Fo = \frac{at}{r_b^2}$. The specific heat rate q_0 and the soil thermal conductivity λ_s are strongly influencing the temperature response. The borehole response, i.e. $f(Fo)$ is independent of the BHE size and configuration when it comes to short-term behavior whereas they have great influence (see $I_e(s)$ coefficients in section 2.2.1) in the long-term response.

Numerical models

Duct ground heat storage model The duct ground heat storage model (commonly called the DST model) (Hellström, 1989) solves the temperature field in a ground heat exchanger, as shown in figure 2.5. The basic problem is the interaction between the local thermal process around a pipe and the macro-scale thermal process throughout the storage and the ground. The temperature results from the superposition of the following three solutions:

1. a global temperature : takes into account the large-scale heat flow from the storage volume to the surrounding ground. It is computed numerically.
2. a local radial solution : covers the short-time variations. It is computed numerically.
3. a steady-flux part : redistributes the heat within a sub-region of the storage volume, it is used for pulses varying slowly in time. It is computed analytically.

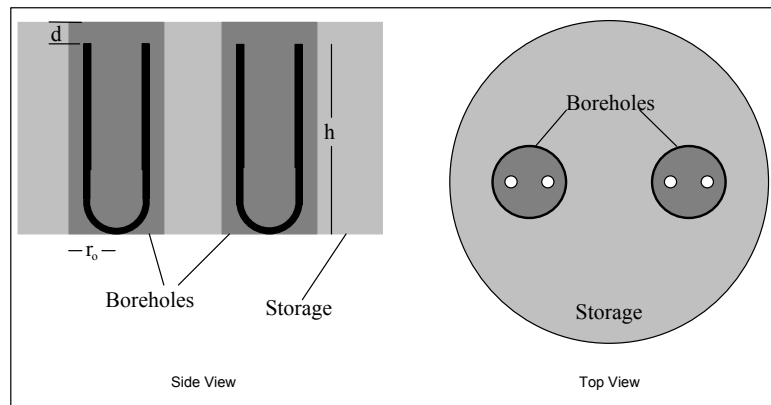


Figure 2.5: 2-borehole heat exchanger nomenclature in the DST model (TESS, 2012a)

It allows for the modeling of multiple boreholes heat exchanger, uniformly placed over a cylindrical storage volume. It is very well suited for compact configurations whereas it induces an error for open configurations. Simulations with a varying heat rate are possible.

The DST model is used in the vertical borehole heat exchanger (Type 557) in TRNSYS 17 (read 2.1.1). It is known as a fast and accurate simulation model for duct ground heat storage and has been extensively validated against other models and experimental measurements. Practically, it comes in two versions :

- 557a : the borehole geometry and composition is defined by the user (U-tube properties and grout properties)
- 557b : the borehole thermal resistance is entered, which is well suited when resistance is known (e.g. from a TRT)

Eskilson's g-functions Eskilson proposes a numerical method to model GHE with non-dimensional response functions, better known as g-functions (Eskilson, 1987). The temperature response to a unit heat injection is computed with a finite difference method. It can model the behavior of a multiple-borehole heat exchanger and accounts with good accuracy for the long-term thermal interaction between boreholes. The response to any heat input can be obtained approximating it as a succession of constant heat pulses. This is further developed in the section 3.1.2.

Temperatures are considered valid after a time of $\frac{5r_b^2}{a_s}$. One practical consideration to remember is that the step functions must be pre-computed and stored in a database. Typically, system simulation programs (read 2.1) access a bank of step functions large enough to cover the most common configurations. For other configurations, interpolation is done. Programs including GLHEPRO, EnergyPlus, HVACSIM+, eQuest and TRNSYS have this model.

2.2.2 Heat pump

A simple compressor-driven typically consists of :

- a compressor driven by an electrical motor
- a condenser
- an expansion valve
- an evaporator

In this project, only water-to-water heat pumps are considered, i.e. heat is extracted through a circulating fluid (ground loop) and rejected to the sink by conditioning a liquid stream (building loop). A schematic view is given on figure 2.6. Although physical models of water-to-water heat pumps exists (Spitler & Jin, 2002), it has been extensively shown (Fahlén, 2011) that black-box models, with polynomial fitting of manufacturer catalog data, offer a good compromise between simplicity and accuracy. The heat pump performance depends mainly on two variables :

- the source-side entering fluid temperature (EFT) T_{b1} : here is the interaction between the heat pump and the BHE in a GSHP system
- the load-side supply temperature T_{w2}

Per Fahlén has proposed a simple heat pump model (Fahlén, 2011), which can predict the heat pump performance by interpolating using data from standard EN255-2 (European Committee of Standardization, 1997) rating points. The performance of the heat pump is measured at $T_{w2} = 35^\circ\text{C}$ and $T_{w2} = 50^\circ\text{C}$. The heating capacity $\dot{Q}_{load}(T_{b1}, T_{w2})$, is:

$$\dot{Q}_{load}(T_{b1}, T_{w2}) = \dot{Q}_{35}(T_{b1}) + \left(\frac{T_{w2} - 35}{15}\right)(\dot{Q}_{50}(T_{b1}) - \dot{Q}_{35}(T_{b1})) \quad (2.8)$$

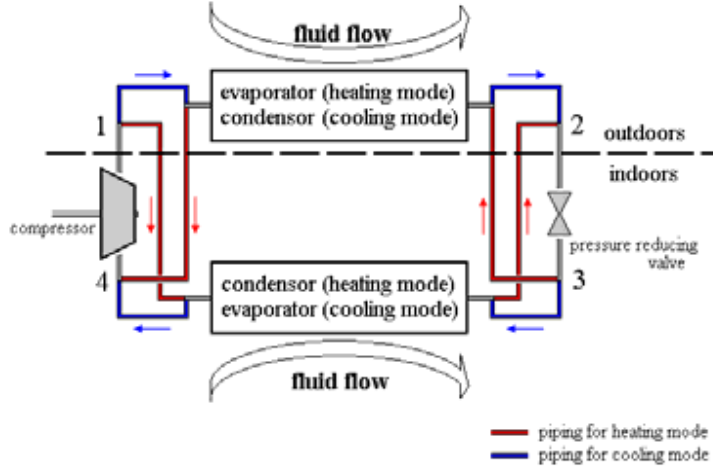


Figure 2.6: Reversible water-to-water heat pump (TESS, 2012b)

with a second-order polynomial interpolation :

$$\dot{Q}_{35}(T_{b1}) = \dot{Q}_{35.0}(T_{b1}) + \dot{Q}_{35.1}(T_{b1}) \cdot T_{b1} + \dot{Q}_{35.2}(T_{b1}) \cdot T_{b1}^2 \quad (2.9)$$

and similarly for $\dot{Q}_{50}(T_{b1})$.

The electrical input $W_{el}(T_{b1}, T_{w2})$ is obtained with the same methodology.

Note that the range for T_{b1} is one of the heat pump characteristics of greatest interest. A performance indicator worth remembering for heat pumps is the coefficient of performance (COP), defined as follows :

$$COP = \frac{\dot{Q}_{load}(T_{b1}, T_{w2})}{\dot{W}_{el}(T_{b1}, T_{w2})} \quad (2.10)$$

It is a state-of-the-art model. Similar models are used in system simulation software such as GLHEPRO, EED, or TRNSYS.

Type 668 from the TESS GHP library in TRNSYS 17 enables the user to normalize performance data (heating capacity $Q_{load,rated}$, electrical input $W_{el,rated}$) with performance at rated conditions (rated mass flows, rated entering temperatures). From a single set of data, one can approximate heat pumps with a different rated capacity.

The heat pump is turned on/off by a control signal. It is the only way to adapt the capacity to the load. Read more about the control strategy in section 3.1.3

3

Methodology

This chapter aims at describing the implementation of ground-source system models, from a simple TRT (section 3.1.1) setup to a coupled GSHP system (section 3.1.3), both in MATLAB and in TRNSYS. It is meant to emphasize how the project has been carried out, i.e. increasing model complexity to the next step only after validation (read section 3.2).

3.1 Implementation

The MATLAB GSHP system model can be used in a modular way. The global flowchart is presented in figure 3.6. However, part of the functions can be run if the complete system is not needed, as in section 3.1.1 and 3.1.2.

3.1.1 Parameter estimation method

Soil properties (soil thermal conductivity λ_s and soil heat capacity c_{ps}) and borehole properties (borehole thermal resistance R_b or grout thermal conductivity λ_g) are of great interest when it comes to designing an energy-effective (and so cost-effective) borehole heat exchanger. However, these properties can vary locally depending on underground formation and groundwater flow. For large systems, experimental measurements have to be done on site in order to obtain satisfying values. Thermal (or Geothermal) Response Tests (TRT) (Gehlin, 2002) measures experimentally the temperature (mean circulating fluid temperature) response to a heat injection (extraction) step to (from) the ground. A parameter estimation method is the whole process of finding a set of parameters (e.g. $(\lambda_s, \lambda_g, R_b)$) minimizing the sum of the squared errors (SSE) between the experimental and the modeled responses, as it follows:

$$\epsilon = T_f - T_{f,exp} \quad (3.1)$$

$$SSE = \sum_{i=0}^{n_{max}} \epsilon_i^2 \quad (3.2)$$

with ϵ_i the error at time step i as defined in 3.1 and n_{max} the last time step.

Different TRT evaluation methods exist depending on the borehole heat transfer model and on the minimization algorithm chosen. It stands as a first level of model complexity in this work (step heat injection in a single borehole).

Experimental data

In the scope of this work, a TRT test has been carried out at the GSHP test facility (read section 1.3 for more details). An electrical heating was used to supply a constant heat injection rate (68 W/m) to the circulating fluid. Only one borehole was used for the TRT. The test was performed for 72 hours (within the recommended range).

Figure 3.1 shows part of the GSHP system available at the laboratory. The key components of a TRT setup can be seen: an electrical heater, a borehole heat exchanger, a circulating pump, a set of vanes and a set of sensors (temperature, flow, power).

A TRT test report can be found in appendix C. Sensors are logged to collect the following experimental data:

- the electrical power $W_{el,exp}$
- the inlet fluid temperature $T_{in,exp}$
- the outlet fluid temperature $T_{out,exp}$
- the ambient temperature $T_{amb,exp}$
- the volume flow rate \dot{V}_{exp}

The mean fluid temperature is defined as:

$$T_{f,exp} = \frac{T_{in,exp} + T_{out,exp}}{2} \quad (3.3)$$

MATLAB

A parameter estimation method, based on the analytical models presented in section 2.2.1 and 2.2.1, is used (Javed *et al.*, 2012). Following figure 3.6, it takes the heat injection rate $W_{el,exp}$ (average value) from the experimental data as an input and computes the mean fluid temperature T_f . The soil and grout properties are the parameters to be estimated (the borehole resistance is calculated as in section 3.1.2). The error function 3.2 is minimized with the LSQNONLIN function (non-linear least square problem).

N.B : the left part of the flow-chart (heat pump) is not used for the TRT presented here.

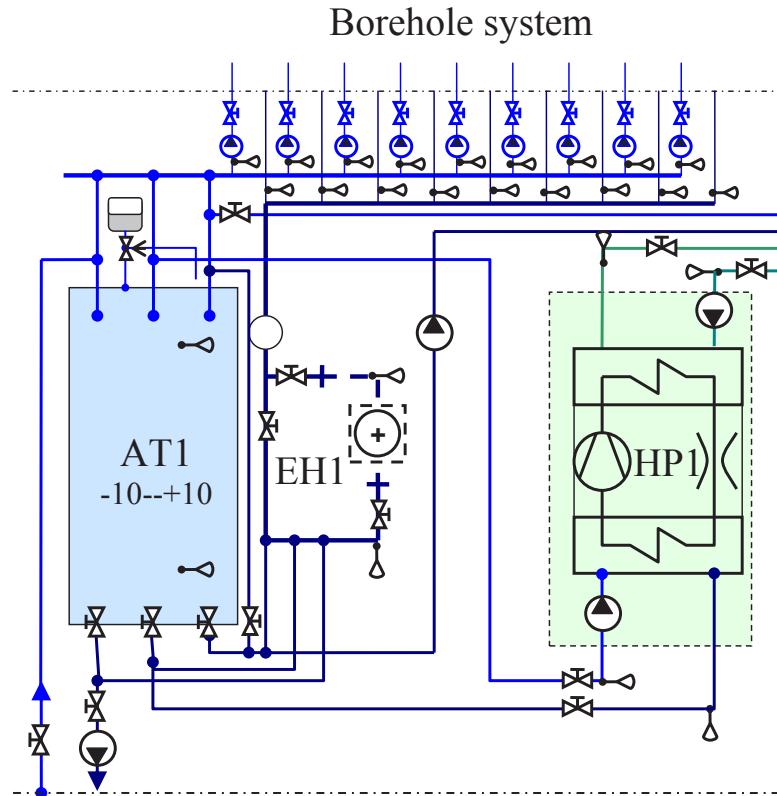


Figure 3.1: The TRT setup used at the laboratory of Building Services Engineering, Chalmers with a borehole system and a electrical heater (EH1)(Javed & Fahlén, 2010)

TRNSYS

The TRNSYS model, as can be seen in figure 3.2, is composed of :

- a single borehole heat exchanger using the DST model presented in section 2.2.1 (Type 557b because the overall effective borehole resistance is of interest, read 2.2.1)
- a variable speed drive (VSD) pump (it is assumed that no heat is transferred to the fluid)
- an electrical heater with a variable heating capacity
- a ground loop fluid volume taking into account fluid capacitance effects

The following input data are taken from the experimental measurements :

- the electrical power $W_{el,exp}$
- the ambient temperature $T_{amb,exp}$

- the outlet fluid temperature V_{exp}

The parameter estimation is performed using GenOpt (Wetter, 2004), an optimization program very well suited to this kind of problem. It allows for:

- the optimization of one or several parameters
- the definition of an initial value and of a range for each parameter (to find a realistic solution from a physical point of view)
- different algorithms

In this project, the soil thermal conductivity λ_s and borehole thermal resistance R_b are estimated whereas the soil heat capacity c_{ps} is kept fixed. Times larger than 15 hours are considered only (numerical model not accurate for short-term). Both Nelder Mead and Hooke Jeeves algorithms are used and compared. TRNOPT (TESS, 2012c), which is a dedicated graphical interface between TRNSYS and GenOpt, is used. Another approach

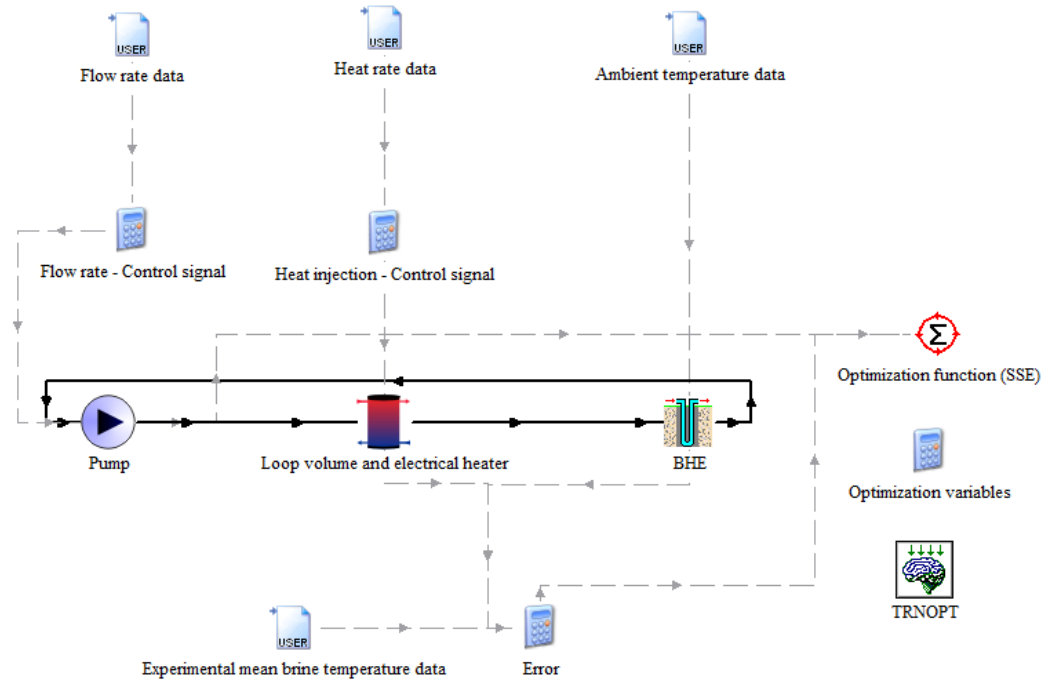


Figure 3.2: Parameter estimation method using TRNSYS and GENOPT

to parameter estimation methods in TRNSYS is to provide the inlet temperature $T_{in,exp}$ as an input to the borehole model. The error is, in that case, defined as:

$$\epsilon = T_{out} - T_{out,exp} \quad (3.4)$$

The system has less degrees of freedom than with the previous approach. A loop volume is not needed. This alternative gives satisfying results, as in (Witte, 2006a) and (Witte, 2006b), but is not adapted to this project.

3.1.2 Borehole heat exchanger simulations

In this section, borehole heat exchanger simulation methodology is explained. Complexity is taken to a higher level with hourly loads, multiple boreholes and simulation times up to decades.

MATLAB

Longer time scales (larger amount of data), varying loads (thermal history) and multiple boreholes (interaction) are the three major challenges to solve here, with respect to section 3.1.1.

Combined step response A step response is the mean fluid temperature increase in time to a constant heat injection q_{step} for a given borehole configuration (number of boreholes, geometry, ground properties). It defines the borehole behavior.

The step response is computed combining two solutions :

- the analytical radial solution T_r presented in section 2.2.1 for the short-term behavior.
- the finite line-source solution T_{ls} presented in section 2.2.1 for the long-term behavior.

The choice of using different solutions for short and long times is motivated by two reasons:

- the former solution is more accurate at short time scales but computationally expensive.
- although borehole field configuration has no influence for the short-term response, it has a significant impact at longer times. The latter solution takes borehole interactions into account through $I_e(s)$ coefficients.

Switching time t_s (also called breaking time) can occur in a range between 100 and 1000 hours. It is noted in section 2.2.1 that T_{ls} must be adjusted (see figure 3.3) in order to consider thermal processes occurring inside the borehole. Thus, the combined step response (see figure 3.4) reads:

$$T_{step}(t) = \begin{cases} T_r(t), & t < t_s \\ T_{ls}(t) + (T_r(t_s) - T_{ls}(t_s)), & t \geq t_s \end{cases} \quad (3.5)$$

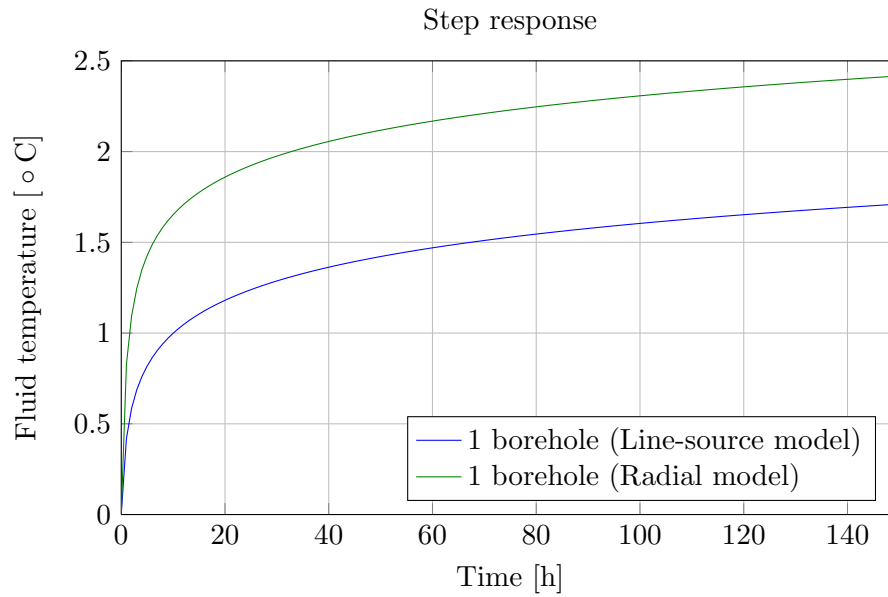


Figure 3.3: Step response of 1 borehole, from analytical and finite line-source solutions

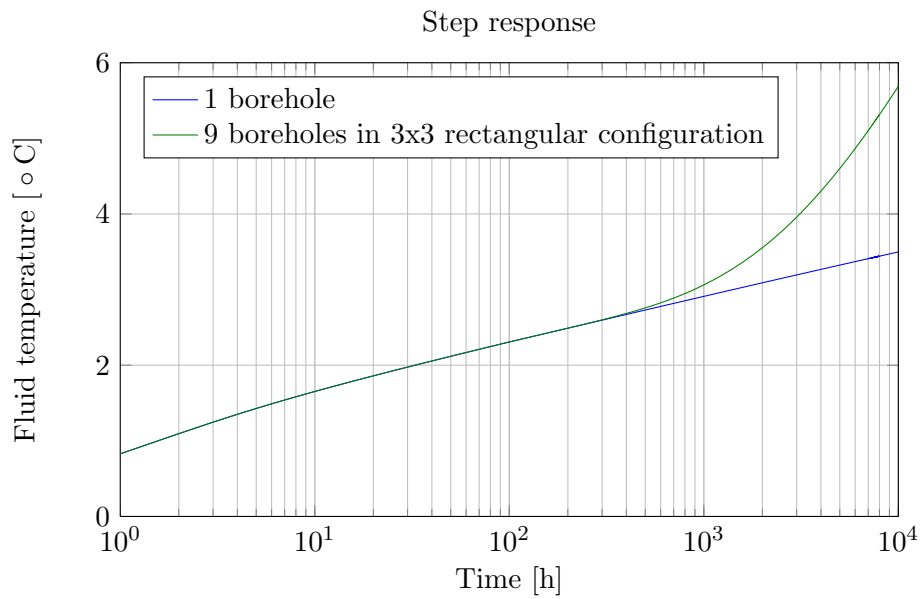


Figure 3.4: Combined step response of 1 and 9 boreholes

The borehole thermal resistance (steady-state thermal resistance between the circulating fluid and the borehole wall) is estimated next, as it follows :

$$R_b = \frac{T_r - T_{ls}}{q_{step}} \quad (3.6)$$

It is averaged for all times larger than $\frac{20r_b^2}{a_s}$.

Superposition Time-varying load profiles $Q(t)$ are considered as a succession of constant heat pulses Q_n , such as :

$$Q(t) = Q_n, \quad nh - h < t \leq nh, \quad n = 1, n_{max} \quad (3.7)$$

N.B. : from now on, time steps are of 1h in the MATLAB implementation.

The temperature response is considered to be equal to the sum of the response to each time step:

$$T_f(nh) = \sum_{v=1}^n \frac{Q_{n+1-v}}{Q_{step}} (T_{step}(vh) - T_{step}(vh - h)) \quad (3.8)$$

with v enumerating the heat pulses backwards in time, at each time step n . Typically, step response is determined for much longer times (e.g. 20-50 years). The temperature response is deduced from the prescribed heat loads, according to the superposition principle.

The approach here is similar to what is described in section 2.2.1 with Eskilson's g -functions.

Load aggregation Multi-year borehole energy simulations involve a huge amount of data (e.g. 200 000 hourly values for a period of 20 years). One approach to reduce computational time is to aggregate loads (Claesson & Javed, 2012). Indeed, the recent loads have the largest influence on the fluid response. In other words, when prescribing a heat load to a borehole, most of the temperature increase occurs in the first hours (see figure 3.3 and 3.4). Subsequently, the idea behind the load-aggregation scheme is to average loads occurring at large times in the past without losing significant accuracy in the temperature response. The trend is shown in figure 3.5. However, while it decays strongly for a single borehole, the weighting functions are not negligible at very long times for multi-borehole heat transfer (interaction). This behavior is in figure 3.5 by multiplying the time derivative of the fluid temperature by time t .

Here is the procedure to perform a load-aggregation scheme (for more details, refer to (Claesson & Javed, 2012) and to the code available under the Appendix section A.2). The following explanation is applied to this example, it is meant so as not to confuse the reader.

1. Heat loads are aggregated on 11 levels l . At the first level $l = 1$, loads are not aggregated. It corresponds to the past p hours. Here $p = 5$ but any number of non-aggregated loads can be considered. At $l = 2$, two values of hourly loads are aggregated, at $l = 3$ four values of hourly loads are aggregated and so on until $l = 11$.

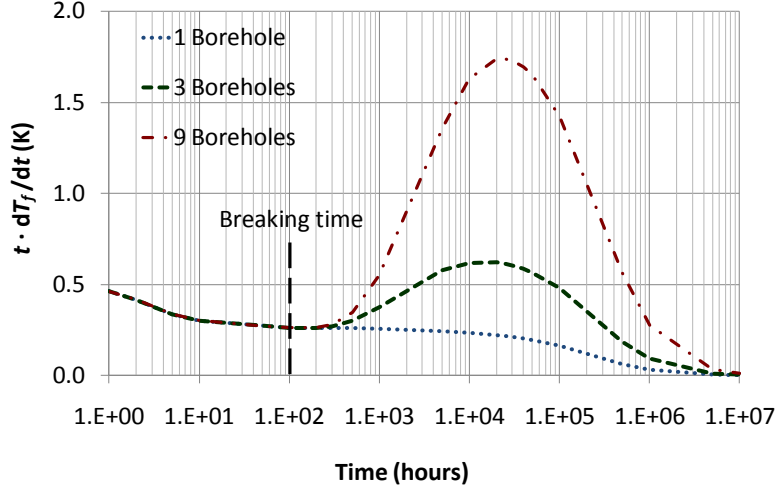


Figure 3.5: Weighting functions for 1, 3 and 9 boreholes (Claesson & Javed, 2011)

2. From the step function, weighting factors are computed for each cell l,p . It represents the temperature increase during the time spanned by the cell. Note that the largest temperature increase occurs during the first hour. Interaction between boreholes at large times can be noticed at $l = 10$ and $l = 11$.

The general formula for the weighing factors computation is:

$$\bar{k}_{l,p} = \frac{T_{step}(v_{l,p}h) - T_{step}(v_{q,p-1}h)}{Q_{step}} \quad (3.9)$$

Due to the aggregated representation of the loads, the fluid temperature is given by the following approximation:

$$T_f(nh) \cong \sum_{l=1}^{l_{max}} \sum_{p=1}^{P_l} \bar{Q}_{l,p}^{(n)} \bar{k}_{l,p} \quad (3.10)$$

with $\bar{Q}_{l,p}^{(n)}$ the past aggregated load at time step n , $l_{max} = 11$ and $P_l = 5$ in this example. Note the similarity between 3.10 and 3.8. The number of terms decreases significantly.

The user is free to enable the load-aggregation scheme depending on its needs.

TRNSYS

The TRNSYS model presented in section 3.1.1 is able to handle time-varying loads and multiple boreholes (read section 2.2.1). Comparable simulations with respect to the analytical model presented in section 3.1.2 without further changes.

3.1.3 Ground Source Heat Pump system simulations

In GSHP systems, there are 3 sub-systems :

1. the ground loop: the circulating fluid extracts heat from the surrounding ground and rejects it to the heat pump evaporator (heat pump source side)
2. the heat pump loop: heat from the evaporator and work on the compressor shaft add up to meet the building heating demand (heat pump load side)
3. the building loop: heat delivered by the heat pump is transferred to the building heating system

In section 3.1.2, implementation of sub-systems 1. and 3. was discussed (considering evaporator loads as prescribed loads Q). Coupling between the heat pump performance and the ground loop fluid temperature is to be solved in this section.

N.B. : The above description is valid in heating mode only.

The terminology used in this section should be clarified :

- the source-side Entering Fluid Temperature (EFT) : temperature leaving the bore-hole(s) T_{b1} (T_{out} in section 3.1.1)
- the source-side Leaving Fluid Temperature (LFT) : temperature entering the bore-hole(s) T_{b2} (T_{in} in section 3.1.1)
- the load-side Entering Fluid Temperature (EFT) : temperature returning from the building T_{w1} . It will be referred as the return temperature.
- the load-side Leaving Fluid Temperature (LFT) : temperature supplied to the building T_{w2} . It will be referred as the supply temperature.

MATLAB

Refer to appendix A for the code implementation.

Heating The complete flow chart is shown in figure 3.6. The central and right part are used in borehole heat exchanger simulations, as discussed in section 3.1.2. It corresponds to sub-systems 1. and 3. The left part couples the heat pump to the ground heat exchanger. It corresponds to sub-system 2. The heat pump model is explained in section 2.2.2. The major limitation of the model is the constant supply temperature. By default, $T_{w2} = 50C$. Thus, heat pump performance is dependent on a single variable, T_{b1} . It is extensively shown throughout the report that T_{b1} is largely influenced by the prescribed ground load. This coupling must be solved at each time step, iteratively within the time step. The system is governed by the following set of equations, completed with equations 2.8 and 2.10 for the heat pump performance and with 3.8 (or 3.10 if aggregated loads) for borehole heat transfer:

$$Q_{ground} = Q_{load} - W_{el} \quad (3.11)$$

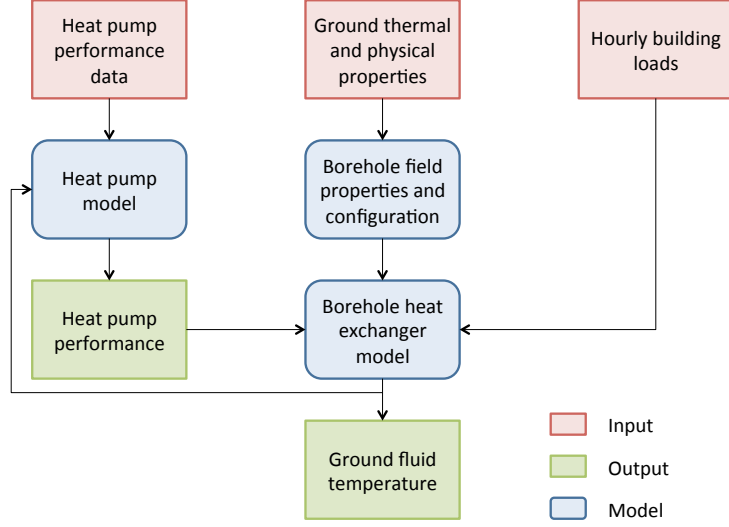


Figure 3.6: GSHP model flow chart

$$T_{b1} = T_f - \frac{Q_{ground}}{2\dot{m} \cdot c_p} \quad (3.12)$$

with \dot{m} and c_p respectively the mass flow rate and the specific heat capacity of the circulating fluid.

$$q = \frac{Q_{ground}}{N_b \cdot H} \quad (3.13)$$

with N_b and H respectively the number of boreholes and the borehole active depth. It can be reduced to a set of 3 equations with 3 unknowns, namely Q_{ground} , T_{b1} and T_f . It is solved with the MATLAB function FSOLVE, with the Trust-region Dogleg method. The algorithm is specially designed to solve non-linear problems and is known as a robust solver, even far from the solution. Nonetheless, it cannot converge to physically acceptable values if the initial point is set as the previous time step solution. One workaround is to run a preliminary borehole energy simulation with a constant COP and to load the solution at each time step as an initial point in the coupling problem. N.B. : Implementation of GSHP system models, based on Eskilson's g-functions (section 2.2.1), has been achieved in other works. Read (Bernier, 2001) for a program including load aggregation and (Fisher *et al.*, 2006) for an implementation integrated in a building system simulation environment.

Cooling In the scope of this work, only free-cooling have been considered, i.e. rejecting heat from the building simply by circulating the fluid in the ground loop. From an implementation point of view, the code is the same as in section 3.1.2

TRNSYS

Refer to appendix B for the complete TRNSYS input file. The GSHP model in TRNSYS

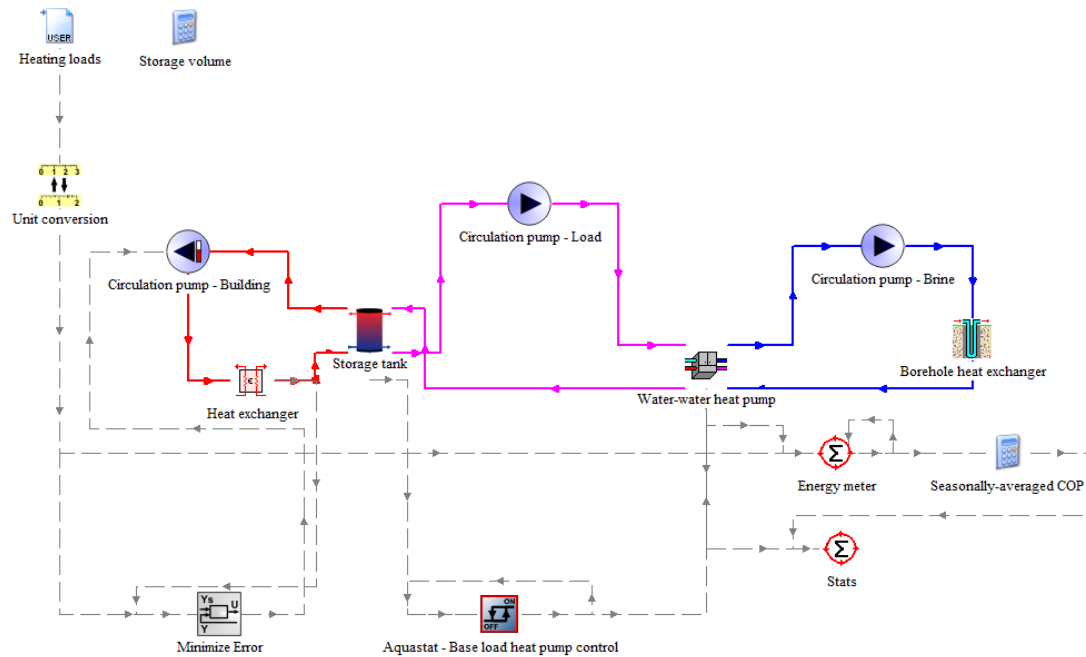


Figure 3.7: GSHP model in TRNSYS

is much more complex than the model presented in section 3.1.1 despite efforts to keep it as simple as possible to be comparable with the GSHP model in MATLAB.

In order to supply heat to the building, through the water-to-water heat pump, new components are added to the previous model:

1. a water-to-water heat pump, connecting the ground and heat pump loops (Type 668, read 2.2.2)
2. a constant speed drive (CSD) water pump (Type 114, with no heat transferred to the fluid) in the heat pump loop. The volume flow rate is fixed to heat pump rated operating conditions.
3. a warm-water storage tank (Type 4, with stratification, without losses to the ambient), connecting the heat pump and building loops.
4. a variable speed drive (VSD) water pump (Type 110, with no heat transferred to the fluid), drawing warm water at a flow rate depending on the demand, from the storage to the heat exchanger.
5. a liquid-liquid heat exchanger (Type 91, with perfect effectiveness) supplying heat to a liquid cold stream.

To maintain a supply temperature T_{w2} of 50°C , it is necessary to set up a control strategy. Indeed, the heat pump can be run in on/off operation only and the heating capacity Q_{load}

is then fairly constant (depending only on the source-side and load-side temperature). Meanwhile, the heating loads through the heat exchanger are time-varying. The control strategy is implemented as follows:

- the heat transfer rate across the heat exchanger is compared to the heating demand. The VSD water pump speed is controlled in order to minimize the error (Type 2). The secant method is used by the controller.
- the tank average temperature is kept at $49\pm 2^\circ\text{C}$ with a proper heat pump control. The controller is an aquastat (Type 2, in heating mode) with hysteresis effect.

In order to reduce the supply temperature variations, a base-load heat pump and two peak-load heat pumps could be used instead of the single heat pump. A number of utility component are added to the TRNSYS project to print and plot results, convert units and read data files.

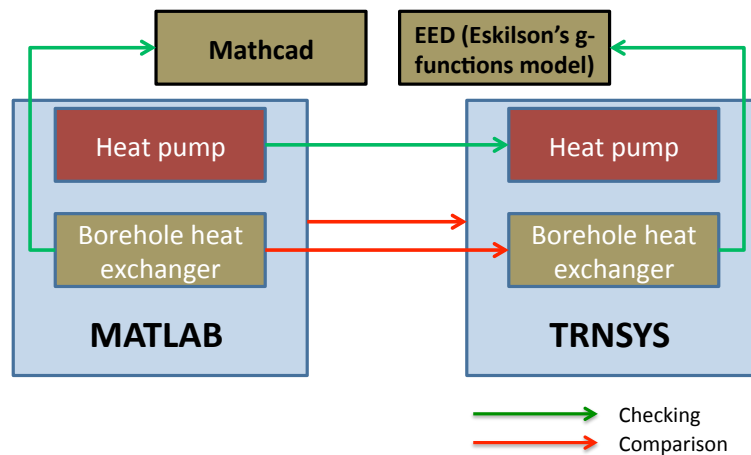


Figure 3.8: Checking and comparison process

3.2 Checking and comparison

The checking process is meant to ensure that there is no mistake in the implementation (or to make sure that TRNSYS components are properly understood). Consistency against similar models (or identical but written in another language or environment) output is checked. Here is a list of reference implementations used in this step :

- an implementation of the short-term analytical solution in MATHCAD
- the EED software
- the water-to-water heat pump component in TRNSYS

It is of fundamental importance to debug a model before increasing its complexity. The checking and validation processes are summed up in figure 3.8.

Ultimately, results from two different approaches, namely MATLAB and TRNSYS can be compared. One must keep in mind to what extent both models are comparable (see section 4.3) before drawing any conclusion. The two models will be compared based on computational time and accuracy. The analytical model accuracy will be judged upon the mean fluid temperature and the seasonally-averaged COP in heating mode over a simulation.

4

Results

In this section, a selection of relevant results obtained with the analytical model implemented in MATLAB and ranging from TRT evaluation models to GSHP simulation models are presented. Ultimately, results are compared with those obtained from a commercial software, TRNSYS, following the methodology discussed in section 3.2.

4.1 Parameters estimation from TRT

Table 4.1 presents the results of parameter estimation procedures conducted in MATLAB and in TRNSYS. Experimental data (see figure C.1) are taken from the TRT discussed in section 3.1.1.

Table 4.1: Parameter estimation method results, with the analytical model in MATLAB and the DST model in TRNSYS

Model	Type	Algorithm	λ_s	λ_g	R_b	$\max \epsilon $
MATLAB	Analytical	Non-linear least square	3.54	2.36	0.0601	0.25
TRNSYS	Numerical	Hooke-Jeeves	3.70	*	0.0605	0.15

* The grout conductivity λ_g is not a parameter in Type 557b (R_b is).

When evaluating λ_s and R_b values from TRTs, uncertainties of about 10% and 30% are expected respectively (Javed, 2012). Results from the two models fall into this range (5% and 1%). The analytical model gives acceptable results with respect to the reference program. It is important to note that both λ_s and R_b are under-estimated with MATLAB. This is a consistent result as a lower soil conductivity counter-balances a lower borehole thermal resistance.

4.2 GSHP simulation

Table 4.2 shows the parameters used in a typical annual simulations conducted in MATLAB.

Table 4.2: Parameters for GSHP system simulation in MATLAB

Mode	Heating	Yes
	Cooling	Yes
Times scales	Simulation time [h]	8760
	Time step [h]	1
BHE	Configuration	3x3 square
	H [m]	200
	B [m]	5
	R_b [mK/W]	0.07
Ground	λ_s [W/mK]	3.0
	cp_s [kJ/m ³ K]	1850
	T_0 [°C]	8.0
Heat pump	Type	Water-to-water
	Compressor	Single stage
	$Q_{load,rated}$ [kW]	83
Cooling	Type	Free cooling
Supply temperature	T_{w2} [°C]	50

The heat load profile can be seen on figure 4.1. It must be read as:

$$Q_{load} = \begin{cases} heating & \text{when } Q_{load} < 0 \\ cooling & \text{when } Q_{load} > 0 \end{cases} \quad (4.1)$$

N.B. : Do not confuse Q_{load} with Q_{ground} . Refer to 3.11 if needed.

The mean fluid temperature response T_f is shown in figure 4.2. Q_{load} and T_f follow a similar trend. In both figures, there are 3 peaks in winter. As for the heat demand, it occur at $t = 288$ h, $t = 1083$ h and $t = 8621$ h. Temperature peaks occur a few hours later. It gives values of 1.48°C, 1.47°C, and 1.55°C, respectively. The heat pump performance is most critical and so, the value of the source-side entering fluid temperature must be checked. Figure 4.3 and figure 4.4, respectively show the COP and the source-side entering fluid temperature T_{b1} , for the first two months. T_{b1} shows

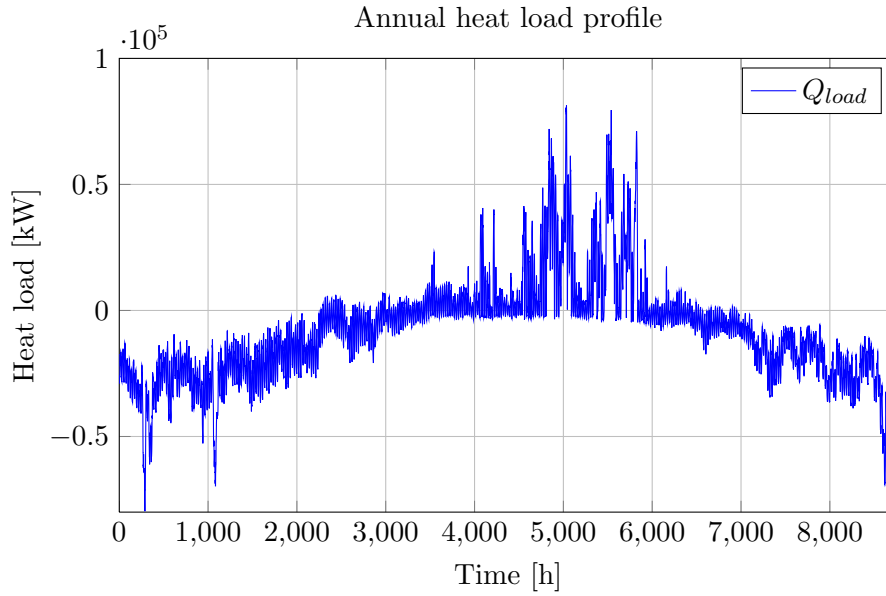


Figure 4.1: Heat load profile for an annual GSHP simulation (Javed, 2012)

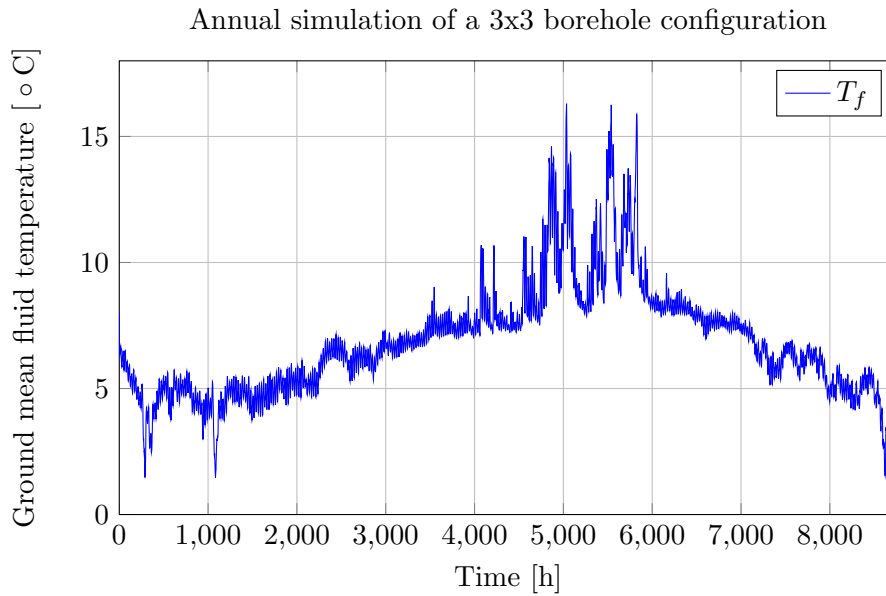


Figure 4.2: Fluid temperature for an annual GSHP simulation

peak values of 3.72°C and 3.46°C . As expected, COP reaches its lowest values, i.e. 3.59, and 3.57 at these peak value conditions. In this example, the values are acceptable. Yet, it can turn out to be critical if the circulating fluid reaches lower temperatures and slip out of the heat pump operating range.

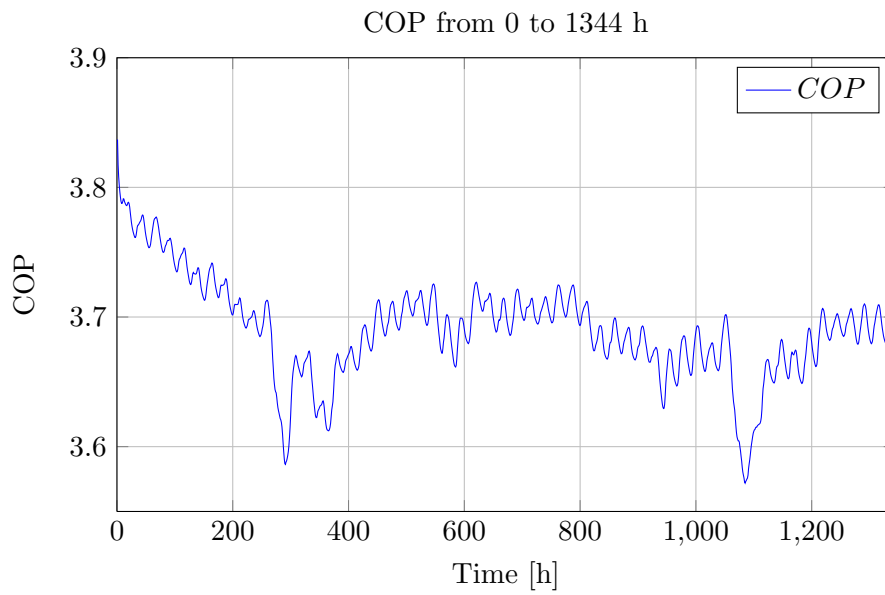


Figure 4.3: COP for the 2 first months of an annual GSHP simulation

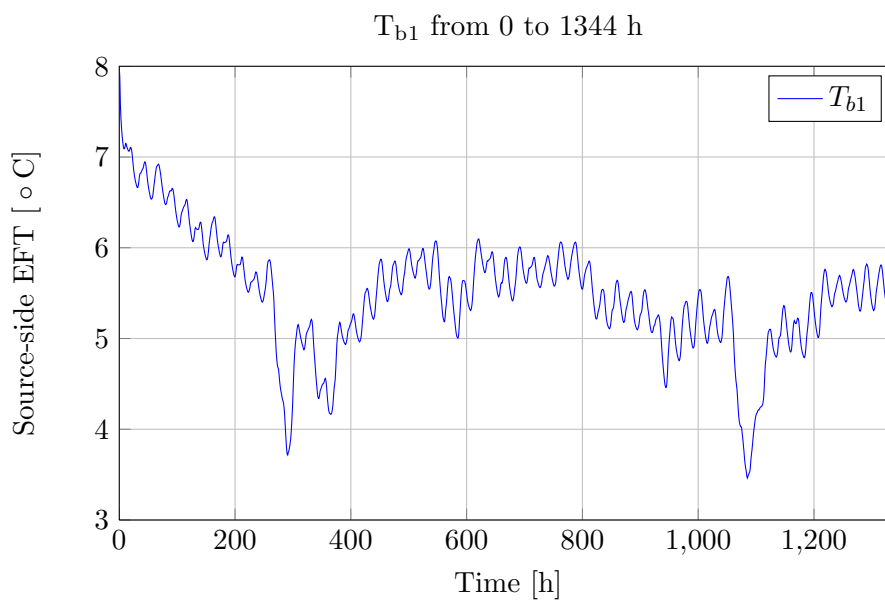


Figure 4.4: Source-side entering fluid temperature for the 2 first months of an annual GSHP simulation

The previous simulation can be run either with or without the load-aggregation scheme, explained in section 3.1.2.

Let us define the error induced by aggregating the heat loads :

$$\epsilon_a = T_f - T_{f,a} \quad (4.2)$$

On figure 4.5, ϵ_a is plotted for an annual GSHP simulation. Load aggregation is performed as explained in section 3.1.2, with $l_{max} = 11$ and $P_l = 5$. The largest errors occur during peak loads. The average absolute value of ϵ_a is $0.09K$, which is reasonable. With regards to computational time, it takes 170 s and 190 s to perform the simulation, respectively with and without the load-aggregation scheme enabled. A much more important speed gain is expected for longer simulations.

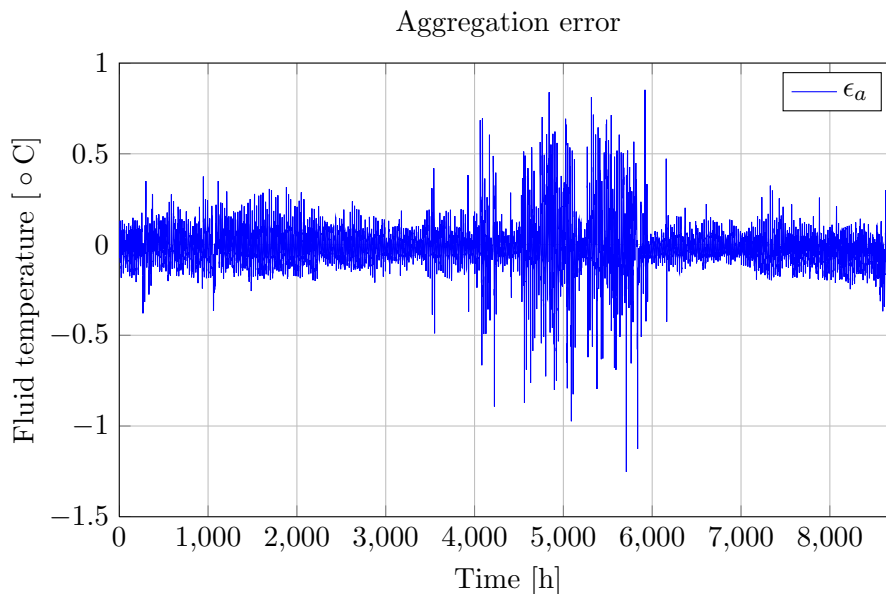


Figure 4.5: Load-aggregation scheme accuracy

4.3 Model validation

Comparison with the reference software TRNSYS will be held on the basis of a GSHP simulation in heating mode. Both models have been described extensively in section 3.1. On table 4.3 can be found the parameters used in the simulation conducted in MATLAB. Through the project, great efforts have been put to design two GSHP models, in MATLAB and in TRNSYS, which are as comparable, as similar, as possible. However, some differences (summarized in table 4.4) remain. In TRNSYS :

1. heat pumps are controlled with an on/off signal as it would be done in a typical real system
2. a control strategy is implemented. Secondary components are then needed (storage tank, VSD pump, heat exchanger, ...). Read section 3.1.3 for more details.

Table 4.3: Parameters of a GSHP system heating mode simulation in MATLAB

Mode	Heating	Yes
	Cooling	No
Times scales	Simulation time [h]	3760
	Time step [h]	1
BHE	Configuration	3x3 square
	H [m]	200
	B [m]	5
	R_b [mK/W]	0.07
Ground	λ_s [W/mK]	3.0
	cp_s [kJ/m ³ K]	1850
	T_0 [°C]	8.0
Heat pump	Type	Water-to-water
	Compressor	Single stage
	$Q_{load,rated}$ [kW]	300 000
Supply temperature	T_{w2} [°C]	50

3. there are 3 heat pumps, of which 1 is run as a base-load heat pump and 2 as peak-load heat pumps. It reduces the on/off signal frequency and the temperature variation following a signal change. Thus, a more stable supply temperature is obtained.
4. despite the modifications enumerated above, the supply temperature is of $T_{b1} = 50 \pm 3.8$ °C

Mean coefficient of performance $C\bar{O}P$, averaged fluid temperature \bar{T}_f and minimum fluid temperature $min(T_f)$ are compared. Results are summarized in table 4.5. One can observe that the MATLAB model gives higher fluid temperature (mean and minimum) and COP. It is consistent as a hotter circulating fluid yields to a more efficient heat pump. The difference on $C\bar{O}P$ is of 0.06, i.e. less than 2%. The difference of \bar{T}_f is of 0.06 K. Both results are acceptable. However, both models differ to a greater extent when it comes to instant values, such as the minimum fluid temperature, which is a critical specification of GSHP systems. In this case, the difference is of 0.14 K. It is recalled here that in the TRNSYS model, at this time step, all 3 heat pumps are turned on, which can lead to a total heating capacity larger than the demand, i.e. larger than the heating capacity in the MATLAB model. Thus, the resulting fluid temperature is lower. In spite of this issue, the total energy supplied to the building during the simulation time is very

Table 4.4: Main differences between the MATLAB and the reference model in TRNSYS

		MATLAB	TRNSYS
T_{b1} [°C]		50 (fixed)	50 ± 3.8
HP	Number	1	3
	Q_{load} [kW]	83	28
	Capacity	Variable	On/Off
Time step [min]		60	1
Complexity		Simple	Advanced

Table 4.5: Comparison of the COP and the fluid temperature between MATLAB and TRNSYS

		MATLAB	TRNSYS
\bar{COP}		3.68	3.62
T_f [C]	\bar{T}_f	4.68	4.62
	$\min(T_f)$	0.6	0.46
Computational time [s]		$\simeq 180$	$\simeq 170$

close from one model to the other.

These last results must be put in the right context and uncertainties taken into account before drawing any conclusions. If T_{b1} is increased from 50°C to 53.8°C in the MATLAB model, \bar{COP} decreases from 3.68 to 3.51, lower than 3.61, the value obtained in TRNSYS. On the other hand, one could vary the borehole thermal resistance set in TRNSYS. Indeed, it is recalled that R_b in the analytical model is not a direct input, as described in section 3.1.2. Convective effect in the fill region (in groundwater-filled boreholes) is also neglected. Then, uncertainties induced by these simplifications allow a variation in the range of borehole thermal resistance. If R_b is decreased from 0.07 to 0.065 mK/W (by 7%), the minimum fluid temperature increases from 0.46°C to 0.58°C and the average value equals 4.68°C, value obtained with TRNSYS.

5

Conclusion

5.1 Summary and conclusions

A Ground Source Heat Pump system model have been implemented in the MATLAB environment. It uses analytical models for both the borehole heat exchanger and the heat pump. The program is flexible, allowing the user to set up a fairly wide range of installations. Starting from heating demand data, GSHP simulations can be performed on a a multi-year scale. Heating is performed with a water-to-water heat pump while cooling utilizes lower ground temperature, with the so-called free cooling technique. The circulating fluid temperature, the heating capacity and the power consumption are modeled with an hourly time step. However, a major limitation of the project is the constant supply temperature to the building. A load-aggregation scheme, has been implemented to decrease computational time significantly with an acceptable loss of accuracy.

Meanwhile, a GSHP system in TRNSYS, which serves as a reference system, has been developed. This model is more complex than the MATLAB model, in the sense that it consists of more components and includes a control strategy. These developments had to be done in order to obtain a fairly constant supply temperature from the heat pump and be able to compare the results with the analytical model. Over a period of 3760 hours in heating mode, the averaged COP obtained with both models are less than 2% different and the average fluid temperature is less than 1.5% different. Uncertainties over the borehole thermal resistance and supply temperature variations explain, at least partly, differences in average and instantaneous temperature from one model to the other. To conclude, the analytical Ground Source Heat Pump model implemented in MATLAB is a simple tool able to run multi-year GSHP simulations and gives satisfactory results when compared to a more complex TRNSYS model.

5.2 Future work

In future works, the GSHP system model implementation could be the core of a design and optimization software. Cooling with a chilling unit and variable supply temperature modeling are two possible improvements. As for the TRNSYS model, it could be used to optimize control strategy and operation of complex GSHP systems, thanks to its modularity and great number of built-in HVAC components.

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A

Implementation

A.1 Main program

```
clear all
close all
clc

global T_0
global m cp
global Qhp_35_coeffs We_35_coeffs Qhp_50_coeffs We_50_coeffs T_supply
global Q_load Q_step T_step
global T_f_guess

%% BHE field configuration

% load res_opt
% Ground and grout conductivity (from analytical parameter estimation)

ls = 3.0;
lg = 1.5;

q_inj = 10;
% Specific heat injection rate used for the step response [W/m]
T_0 = 8;
% Undisturbed ground temperature
H = 200;
B = 5;
% Spacing [m]
```

```
rb = 0.055;
% Borehole radius [m]
N_bx = 3;
N_by = 3;
conf = 'r';
N_b = N_bx*N_by;
% Number of boreholes

%% Flow properties

rho = 960;
% [kg/m3]
V = 10.98;
% [m3/h]
m = V*rho/3600;
% [kg/s]
cp = 4250;
% [J/kg*K]

%% Heat pump

% Curve fit for tw2 = 35

load('data_heating_35_50kW.txt');
fid = fopen('data_heating_35_50kW.txt');
data_35 = fscanf (fid, '%g', [3,inf]);
fclose(fid);
tbl_35=data_35(1,:);
Qhp_35=data_35(2,:);
We_35=data_35(3,:);
Qhp_35_coeffs = polyfit(tbl_35,Qhp_35,2);
% coefficients of descending powers
We_35_coeffs = polyfit(tbl_35,We_35,2);

% Curve fit for tw2 = 50

load('data_heating_50_50kW.txt');
fid = fopen('data_heating_50_50kW.txt');
data_50 = fscanf (fid, '%g', [3,inf]);
fclose(fid);
tbl_50=data_50(1,:);
Qhp_50=data_50(2,:);
We_50=data_50(3,:);
Qhp_50_coeffs = polyfit(tbl_50,Qhp_50,2);
We_50_coeffs = polyfit(tbl_50,We_50,2);

T_supply = 50;

%% Simulation parameters (step response)

N_h = 1.1e4;
% Step response duration
```

```

n_switch = 101;
% time step from which ls is used

%% Simulation parameters (response to prescribed loads)

N_year = 1;
% Number of years
t = 0:1:N_h;
t = t';
agg = false;
% whether loads are aggregated (true) or not (false)

%% Step response (time step = 1h ; unit heat injection rate)

% load 3x3_200m_5m

[T_rad_1 T_ls_1 T_ls_N R_b] = step_response([ls lg],N_bx,N_by,B,rb,conf,N_h+1);
T_N = [T_rad_1(1:n_switch); T_ls_N(n_switch+1:end)+(T_rad_1(n_switch)-T_ls_N(n_switch))];
T_1 = [T_rad_1(1:n_switch); T_ls_1(n_switch+1:end)+(T_rad_1(n_switch)-T_ls_1(n_switch))];

% save 3x3_200m_5m T_N T_1 R_b

%% Hourly annual load response

Q_step = q_inj*H*N_b;
T_step = T_N;

load('Q_load_annual.txt');
fid = fopen('Q_load_annual.txt');
Q_load_1 = fscanf(fid,'%g',[1,inf]);
Q_load = Q_load_1;

for i = 1:N_year-1
    % Annual load copied for the next years

    Q_load = [Q_load Q_load_1];
end

load guess

tic

[ T_f , T_out, Q_ground ] = superposition_coupled(agg);

toc

Q_load = [Q_load(1) Q_load];

```

```

Q_load = Q_load(1:end-1);
Q_ground = [Q_ground(1) Q_ground];
Q_ground = Q_ground(1:end-1);

%% Performances

W_el = abs(Q_load - Q_ground);
% Power input [W]
Heating = (Q_load < 0);
% 1 if heating, 0 otherwise
COP = zeros(1,length(Q_load));

for i = 1:length(Q_load)

if Heating(i)

    COP(i) = abs(Q_load(i)/W_el(i));
    % 0 if cooling

end

end

COP_mean = mean(COP(2:end));
COP_m = [];

for i = 1:3

    COP_m = [COP_m mean(COP(2:672*i))];
    % Monthly averaged COP after 1, 2 and 3 months

end

T_out_min = min(T_out);
Q_load_max = max(abs(Q_load));
Q_load_mean = mean(abs(Q_load(2:end)));

%% Load aggregation implementation checking

agg = true;

tic

[ T_f_a T_out_a Q_ground_a ] = superposition_coupled(agg);
% Mean fluid temperature response

toc

error_a = T_f - T_f_a;
error_a = error_a(1:8761);

```

A.2 Load-aggregation

```

function [ T_f , T_out , Q_ground ] = superposition_coupled(agg)

% T_step : step response
% Q_step : step heat rate
% Q_load : building loads
% m : mass flow rate
% cp : brine heat capacity
% T_0 : undisturbed ground temperature

global T_0 Q_load Q_step T_step m cp
global T_f_guess

%% Step response analysis

n_max = length(Q_load);
Q_ground_guess = Q_load*(1-1/3.8800);
T_out_guess = T_f_guess(1:end-1) - Q_ground_guess'/(2*m*cp);

T_f = zeros(1,n_max)+T_0;
T_out = zeros(1,n_max)+T_0;
Q_ground = zeros(1,n_max);

%% Preliminary calculations - Aggregation

if agg

% (3.44)

q_max = 11;
% number of levels
q = 1:q_max;
Pq = ones(1,q_max)*5;
rq = 2.^(q-1);
% width of a lumped cell on level q
v_max = sum(Pq.*rq);
% oldest time step

% (3.45)

v = zeros(q_max,max(Pq)+1);
v(1,1) = 0;

for i = 1:q_max-1

    v(i+1,1) = v(i,1)+rq(i)*Pq(i);

end

```

```

for i = 1:q_max
    for j = 1:Pq(i)
        v(i,j+1) = v(i,1)+rq(i)*j;
    end
end

% (3.49)

for i = 1:q_max
    for j = 2:Pq(i)+1

        k(i,j) = (T_step(v(i,j)+1)-T_step(v(i,j-1)+1))/Q_step;
    end

end

kqp = k(:,2:max(Pq)+1)*1000000;
% to plot only

% (3.51)

% Aggregation performed at each time step, looking backwards

Qn = zeros(q_max,max(Pq)+1);
Qn1 = zeros(q_max,max(Pq)+1);

end

%% Superposition

for n = 1:n_max-1

    % without aggregated loads

    if not (agg)

        if (Q_load(n)<0)

            % Heating with HP

            x_0 = [Q_ground_guess(n) T_f_guess(n+1) T_out_guess(n+1)];
            % options = optimset('Display','iter');
            [x,fval,exitflag,output] = fsolve(@myfun,x_0);
        end
    end
end

```

```

    Q_ground(n) = x(1);
    T_f(n+1) = x(2);
    T_out(n+1) = x(3);

else

    % Cooling without cooling machine (free cooling FC)

    Q_ground(n) = Q_load(n);

    for vv = 1:n

        Q_nv = Q_ground(n+1-vv);
        R_v = (T_step(vv+1) - T_step(vv)) / Q_step;
        T_f(n+1) = T_f(n+1) + Q_nv*R_v;

    end

    T_out(n+1) = T_f(n+1) - Q_ground(n) / (2*m*cp);

end

else

    % with aggregated loads

    if (Q_load(n)<0)

        % Heating with HP

        x_0 = [Q_ground_guess(n) T_f_guess(n+1) T_out_guess(n+1)];
        options = optimset('Display','iter');
        [x,fval,exitflag,output] = fsolve(@myfun_agg,x_0);

        Q_ground(n) = x(1);
        T_f(n+1) = x(2);
        T_out(n+1) = x(3);

        Qn1 = Qn;

    else

        % Cooling without cooling machine (free cooling FC)

        Qn1(1,1) = Q_load(n);

        for i = 2:q_max

            Qn(i,1) = Qn1(i-1,Pq(i)+1);

        end

    end

end

```

```

    for i = 1:q_max
        for j = 2:Pq(i)+1
            Qn(i,j)=Qn1(i,j)+1/rq(i)*(Qn1(i,j-1)-Qn1(i,j));
        end
    end

    for i = 1:q_max
        for j = 2:Pq(i)+1
            T_f(n+1) = T_f(n+1) + Qn(i,j)*k(i,j);
        end
    end

    Qn1 = Qn;

    T_out(n+1) = T_f(n+1) - Q_ground(n)/(2*m*cp);

end

end

end

% The nonlinear system of equations to solve. fun is a function that
% accepts a vector x and returns a vector F, the nonlinear equations
% evaluated at x. The function fun can be specified as a function
% handle for an M-file function
% x = fsolve(@myfun,x0)
% where myfun is a MATLAB function such as

function F = myfun(x)
% Compute function values at x

F(1) = x(1) - hp_operation(x(3),Q_load(n));

F(2) = x(1)*(T_step(2)-T_step(1))/Q_step - x(2) + T_0;

if (n > 1)

    for vv = 2:n

        Q_nv = Q_ground(n+1-vv);
        R_v = (T_step(vv+1) - T_step(vv)) / Q_step;
    end
end

```



```

        F(2) = F(2) + Q_nv*R_v;

    end

end

F(3) = x(1)/(2*m*cp) - x(2) + x(3);

end

function F = myfun_agg(x)
% Compute function values at x

dTf = 0;

Qn1(1,1) = x(1);

for i = 2:q_max

    Qn(i,1) = Qn1(i-1,Pq(i)+1);

end

for i = 1:q_max

    for j = 2:Pq(i)+1

        Qn(i,j)=Qn1(i,j)+1/rq(i)*(Qn1(i,j-1)-Qn1(i,j));

    end

end

for i = 1:q_max

    for j = 2:Pq(i)+1

        dTf = dTf + Qn(i,j)*k(i,j);

    end

end

F(1) = x(1) - hp_operation(x(3),Q_load(n));

F(2) = dTf - x(2) + T_0;

F(3) = x(1)/(2*m*cp) - x(2) + x(3);

end

end

```

A.3 Heat pump

```
function [ Q_ground ] = hp_operation( T_out_bh , Q_load)

% Inputs
% T_out_bh : entering fluid temperature, from bhe
% Q_load : load required at this time step
% Outputs
% Q_ground : average (over the time step) value of the heat rate to the ground

% Note : the strategy here is to scale-up the heat pump (from a reference
% model) in order to meet the load
% One could choose instead an on/off operation of a number of heat pumps
% in parallel (future improvement?)

% Heating mode

global Qhp_35_coeffs We_35_coeffs Qhp_50_coeffs We_50_coeffs T_supply

if Q_load < 0

    tw2 = T_supply;
    % load temperature, assumed constant
    Q_load = -Q_load;
    [Q_hp, W_e, COP_h] =
    hp_heating(T_out_bh,tw2,Qhp_35_coeffs,We_35_coeffs,Qhp_50_coeffs,We_50_coeffs);
    Q_ground = Q_load*(1-1/COP_h);
    Q_ground = -Q_ground;

end
```

A.4 $I_e(s)$ coefficients

```

function [ res ] = I_e( s, Nx, Ny, rb, B, conf )
% I_e(s) coefficients calculated as in (3.32)

% Inputs :
% - s : integration variable
% - Nx : number of boreholes in the x-direction
% - Ny : number of boreholes in the y-direction
% - rb : borehole radius
% - B : borehole spacing
% - conf (see below)

% Configuration available (conf)
% - square/rectangular (r)
% - square/rectangular open (ro)
% - U (u)
% - L (l)
% - triangular (t)

% Outputs :
% I_e coefficient used in equation (3.34)

x = zeros(Ny, Nx);
y = zeros(Ny, Nx);
xn = [];
yn = [];

for j=1:Nx

    y(:, j) = 0:B:(Ny-1)*B;

end

for i=1:Ny

    x(i, :) = 0:B:(Nx-1)*B;

end

%% Square/Rectangular configuration

% 1 2 3
% 4 5 6
% 7 8 9

if conf == 'r'

```

```
for i=1:Ny
    xn = [xn x(i,:)];
    yn = [yn y(i,:)];
end
end

%% Open square/Rectangular configuration

% 1 2 3
% 4 5
% 6 7 8

if conf == 'ro'
    xn = x(1,:);
    for i = 2:Ny-1
        xn = [xn x(i,1) x(i,Nx)];
    end
    xn = [xn x(Ny,:)];
    yn = y(1,:);
    for i = 2:Ny-1
        yn = [yn y(i,1) y(i,Nx)];
    end
    yn = [yn y(Ny,:)];
end

%% U-configuration

% 1 2
% 3 4 5

if conf == 'u'
    for i = 1:Ny-1
        xn = [xn x(i,1) x(i,Nx)];
    end
end
```

```
xn = [xn x(Ny,:)];

for i = 1:Ny-1
    yn = [yn y(i,1) y(i,Nx)];
end

yn = [yn y(Ny,:)];
end

%% L-configuration

% 1
% 2
% 3 4 5

if conf == 'l'

xn = x(:,1)';

xn = [xn x(Ny,2:Nx)];

yn = y(:,1)';

yn = [yn y(Ny,2:Nx)];

end

%% Triangular configuration

% 1
% 2 3
% 4 5 6

if conf == 't'

for i = 1:Ny

    for j = 1:i

        xn = [xn x(i,j)];
        yn = [yn y(i,j)];

    end

end

end

end

%%
```

```
N = length(xn);
% Number of boreholes

for i=1:N

    for j=1:N

        if (j == i)

            rij(i,j) = rb;

        else

            rij(i,j) = sqrt((xn(i)-xn(j))^2+(yn(i)-yn(j))^2);

        end

    end

end

res = 0;

% Close configuration (square/rectangular)

for i=1:N

    for j=1:N

        res = res+exp(-rij(i,j)^2.*s.^2);

    end

end

res = res/N;

end
```

B

TRNSYS input file

Here is the input file (project description) of the GSHP model in TRNSYS 17, as presented in section 3.1.3.

```

VERSION 17
*****
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on Tuesday, June 26, 2012 at 17:16
*** from TrnsysStudio project: C:\Trnsys17\MyProjects\GSHP_heating\GSHP_heating.tpf
***
*** If you edit this file, use the File/Import TRNSYS Input File function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your local
*** TRNSYS distributor or mailto:software@cstb.fr
***
*****

*****
*** Units
*****

*****
*** Control cards
*****
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=3761
STEP=0.016666666
* User defined CONSTANTS

SIMULATION   START   STOP   STEP   ! Start time   End time   Time step

```

APPENDIX B. TRNSYS INPUT FILE

```

TOLERANCES 0.001 0.001          ! Integration      Convergence
LIMITS 30 500 50                ! Max iterations  Max warnings  Trace limit
DFQ 1                            ! TRNSYS numerical integration solver method
WIDTH 80                         ! TRNSYS output file width, number of characters
LIST                             ! NOLIST statement
                                ! MAP statement
SOLVER 0 1 1                    ! Solver statement  Minimum relaxation factor  Maximum relaxation
NAN_CHECK 0                     ! Nan DEBUG statement
OVERWRITE_CHECK 0              ! Overwrite DEBUG statement
TIME_REPORT 0                  ! disable time report
EQSOLVER 0                     ! EQUATION SOLVER statement

```

* Model "Circulation pump - Brine" (Type 114)

*

```

UNIT 3 TYPE 114  Circulation pump - Brine
*$UNIT_NAME Circulation pump - Brine
*$MODEL .\Hydronics\Pumps\Single Speed\Type114.tmf
*$POSITION 792 245
*$LAYER HP loop #
*$# SINGLE-SPEED PUMP
PARAMETERS 4
10548.00024      ! 1 Rated flow rate
4.26            ! 2 Fluid specific heat
1439.999962     ! 3 Rated power
0.0            ! 4 Motor heat loss fraction
INPUTS 5
5,1            ! Water-water heat pump:Outlet source temperature ->Inlet fluid temperature
5,2            ! Water-water heat pump:Source flow rate ->Inlet fluid flow rate
0,0           ! [unconnected] Control signal
0,0           ! [unconnected] Overall pump efficiency
0,0           ! [unconnected] Motor efficiency
*** INITIAL INPUT VALUES
8 0.0 1.0 1 1

```

* Model "Circulation pump CSD - Load" (Type 114)

*

```

UNIT 4 TYPE 114  Circulation pump CSD - Load
*$UNIT_NAME Circulation pump CSD - Load
*$MODEL .\Hydronics\Pumps\Single Speed\Type114.tmf
*$POSITION 609 253
*$LAYER OutputSystem #
*$# SINGLE-SPEED PUMP
PARAMETERS 4
3780            ! 1 Rated flow rate
4.139           ! 2 Fluid specific heat
413.999989     ! 3 Rated power
0.0            ! 4 Motor heat loss fraction
INPUTS 5
10,1           ! Storage tank:Temperature to heat source ->Inlet fluid temperature
10,2           ! Storage tank:Flowrate to heat source ->Inlet fluid flow rate

```


APPENDIX B. TRNSYS INPUT FILE

```

0,0      ! [unconnected] Control signal
0,0      ! [unconnected] Overall pump efficiency
0,0      ! [unconnected] Motor efficiency
*** INITIAL INPUT VALUES
50 1440 1.0 1 1
*
* Model "Water-water heat pump" (Type 927)
*
UNIT 5 TYPE 927 Water-water heat pump
*$UNIT_NAME Water-water heat pump
*$MODEL .\GHP Library (TESS)\Water-Water Heat Pump\Single-Stage\Type927.tmf
*$POSITION 786 389
*$LAYER Outputs #
PARAMETERS 19
4.26      ! 1 Source fluid specific heat
4.139     ! 2 Load fluid specific heat
956       ! 3 Source fluid density
1000.     ! 4 Load fluid density
33        ! 5 Logical unit number for cooling data file
8         ! 6 Number of source temperatures - cooling
4         ! 7 Number of load temperatures - cooling
34        ! 8 Logical unit for heating data
4         ! 9 Number of source temps. - heating
6         ! 10 Number of load temps. - heating
3         ! 11 Number of source flow rates
3         ! 12 Number of load flow rates
30000     ! 13 Rated cooling capacity per heat pump
6000      ! 14 Rated cooling power per heat pump
300000    ! 15 Rated heating capacity per heat pump
60000     ! 16 Rated heating power per heat pump
3.05      ! 17 Rated source flow rate per heat pump
1.05      ! 18 Rated load flow rate per heat pump
1         ! 19 Number of identical heat pumps
INPUTS 8
28,1      ! 9-Borehole heat exchanger:Outlet temperature ->Inlet source temperature
28,2      ! 9-Borehole heat exchanger:Outlet flow rate (total) ->Source flow rate
4,1       ! Circulation pump CSD - Load:Outlet fluid temperature ->Inlet load temperature
4,2       ! Circulation pump CSD - Load:Outlet flow rate ->Load flow rate
0,0       ! [unconnected] Cooling control signal
0,0       ! [unconnected] Heating control signal
0,0       ! [unconnected] Scale factor
26,1      ! Aquastat - Base load heat pump control:Output control function ->Number of heat
*** INITIAL INPUT VALUES
8 1440.0 50 3780 0 1 1 1
*** External files
ASSIGN "C:\Trnsys17\Tess Models\SampleCatalogData\Water-to-WaterHeatPump\Normalized\WWHP_Cooli
*|? Which file contains the cooling performance data? |1000
ASSIGN "C:\Trnsys17\Tess Models\SampleCatalogData\Water-to-WaterHeatPump\Normalized\catalog_he
*|? Which file contains the heating performance data? |1000
*

```

APPENDIX B. TRNSYS INPUT FILE

```
* Model "System_Plotter" (Type 65)
*
UNIT 7 TYPE 65   System_Plotter
*$UNIT_NAME System_Plotter
*$MODEL \Trnsys17\Studio\lib\System_Output\TYPE65d.tmf
*$POSITION 882 197
*$LAYER Outputs #
PARAMETERS 12
5          ! 1 Nb. of left-axis variables
3          ! 2 Nb. of right-axis variables
-10        ! 3 Left axis minimum
10         ! 4 Left axis maximum
0.0        ! 5 Right axis minimum
100000.0   ! 6 Right axis maximum
1          ! 7 Number of plots per simulation
12         ! 8 X-axis gridpoints
0          ! 9 Shut off Online w/o removing
-1         ! 10 Logical unit for output file
0          ! 11 Output file units
0          ! 12 Output file delimiter
INPUTS 8
5,3        ! Water-water heat pump:Outlet load temperature ->Left axis variable-1
4,1        ! Circulation pump CSD - Load:Outlet fluid temperature ->Left axis variable-2
5,1        ! Water-water heat pump:Outlet source temperature ->Left axis variable-3
3,1        ! Circulation pump - Brine:Outlet fluid temperature ->Left axis variable-4
T_mean     ! Equations:T_mean ->Left axis variable-5
23,1       ! Unit conversion:Output ->Right axis variable-1
5,5        ! Water-water heat pump:Heat transfer to load ->Right axis variable-2
5,6        ! Water-water heat pump:Heat transfer from source ->Right axis variable-3
*** INITIAL INPUT VALUES
T_load_out T_load_in T_source_out T_source_in T_source_mean Q_demand
Q_load Q_source
LABELS 3
"Temperatures"
"Heat transfer rates"
"Heat pump"
*
* Model "System_Plotter-2" (Type 65)
*
UNIT 9 TYPE 65   System_Plotter-2
*$UNIT_NAME System_Plotter-2
*$MODEL \Trnsys17\Studio\lib\System_Output\TYPE65d.tmf
*$POSITION 1004 165
*$LAYER Outputs #
PARAMETERS 12
1          ! 1 Nb. of left-axis variables
1          ! 2 Nb. of right-axis variables
40         ! 3 Left axis minimum
70         ! 4 Left axis maximum
0.0        ! 5 Right axis minimum
```

APPENDIX B. TRNSYS INPUT FILE

```

2      ! 6 Right axis maximum
1      ! 7 Number of plots per simulation
12     ! 8 X-axis gridpoints
0      ! 9 Shut off Online w/o removing
-1     ! 10 Logical unit for output file
0      ! 11 Output file units
0      ! 12 Output file delimiter
INPUTS 2
10,12   ! Storage tank:Average tank temperature ->Left axis variable
26,1    ! Aquastat - Base load heat pump control:Output control function ->Right axis vari
*** INITIAL INPUT VALUES
T_tank_avg Control_signal
LABELS 3
"Temperatures"
"Control signal"
"HP Control"
*-----*

* Model "Storage tank" (Type 4)
*

UNIT 10 TYPE 4   Storage tank
*$UNIT_NAME Storage tank
*$MODEL .\Thermal Storage\Stratified Storage Tank\Fixed Inlets\Uniform Losses\Type4a.tmf
*$POSITION 448 325
*$LAYER Main #
PARAMETERS 22
1      ! 1 Fixed inlet positions
1      ! 2 Tank volume
4.190   ! 3 Fluid specific heat
1000.0  ! 4 Fluid density
0      ! 5 Tank loss coefficient
0.5     ! 6 Height of node-1
0.5     ! 7 Height of node-2
0.5     ! 8 Height of node-3
1      ! 9 Auxiliary heater mode
1      ! 10 Node containing heating element 1
1      ! 11 Node containing thermostat 1
55.0    ! 12 Set point temperature for element 1
5.0     ! 13 Deadband for heating element 1
0      ! 14 Maximum heating rate of element 1
1      ! 15 Node containing heating element 2
1      ! 16 Node containing thermostat 2
55.0    ! 17 Set point temperature for element 2
5.0     ! 18 Deadband for heating element 2
0      ! 19 Maximum heating rate of element 2
0.0     ! 20 Not used (Flue UA)
20.0    ! 21 Not used (Tflue)
100.0   ! 22 Boiling point
INPUTS 7
5,3     ! Water-water heat pump:Outlet load temperature ->Hot-side temperature
5,4     ! Water-water heat pump:Load flow rate ->Hot-side flowrate
16,1    ! Heat exchanger:Hot-side outlet temperature ->Cold-side temperature

```

APPENDIX B. TRNSYS INPUT FILE

```
16,2      ! Heat exchanger:Hot-side flow rate ->Cold-side flowrate
0,0      ! [unconnected] Environment temperature
0,0      ! [unconnected] Control signal for element 1
0,0      ! [unconnected] Control signal for element 2
*** INITIAL INPUT VALUES
50 1000 20.0 1000 22.0 0 0
DERIVATIVES 3
49      ! 1 Initial temperature of node-1
49      ! 2 Initial temperature of node-2
49      ! 3 Initial temperature of node-3
*
* Model "System_Plotter-3" (Type 65)
*
UNIT 12 TYPE 65 System_Plotter-3
*$UNIT_NAME System_Plotter-3
*$MODEL \Trnsys17\Studio\lib\System_Output\TYPE65d.tmf
*$POSITION 1182 197
*$LAYER Outputs #
PARAMETERS 12
3      ! 1 Nb. of left-axis variables
2      ! 2 Nb. of right-axis variables
0.0    ! 3 Left axis minimum
4e8    ! 4 Left axis maximum
0.0    ! 5 Right axis minimum
2e5    ! 6 Right axis maximum
1      ! 7 Number of plots per simulation
12     ! 8 X-axis gridpoints
0      ! 9 Shut off Online w/o removing
-1     ! 10 Logical unit for output file
0      ! 11 Output file units
0      ! 12 Output file delimiter
INPUTS 5
19,1   ! Energy meter:Integral of input-1 ->Left axis variable-1
19,11  ! Energy meter:Integral of input-2 ->Left axis variable-2
19,21  ! Energy meter:Integral of input-3 ->Left axis variable-3
19,3   ! Energy meter:Mean value of input-1 ->Right axis variable-1
19,9   ! Energy meter:Maximum value of input-1 ->Right axis variable-2
*** INITIAL INPUT VALUES
Q_demand Q_load_HP Power_HP Q_demand_mean Q_demand_max
LABELS 3
"Energy [kJ]"
"Heat rate [kJ/hr]"
"Energy meter"
*
* Model "Circulation pump VSD - Building" (Type 110)
*
UNIT 13 TYPE 110 Circulation pump VSD - Building
*$UNIT_NAME Circulation pump VSD - Building
*$MODEL .\Hydronics\Pumps\Variable Speed\Type110.tmf
```

APPENDIX B. TRNSYS INPUT FILE

```

*$POSITION 163 250
*$LAYER Building loop #
*$$ VARIABLE-SPEED PUMP
PARAMETERS 6
6000      ! 1 Rated flow rate
4.19      ! 2 Fluid specific heat
413.999989 ! 3 Rated power
0.0       ! 4 Motor heat loss fraction
1         ! 5 Number of power coefficients
1.0       ! 6 Power coefficient
INPUTS 5
10,3      ! Storage tank:Temperature to load ->Inlet fluid temperature
10,4      ! Storage tank:Flowrate to load ->Inlet fluid flow rate
20,1      ! Minimize Error:Control signal ->Control signal
0,0       ! [unconnected] Total pump efficiency
0,0       ! [unconnected] Motor efficiency
*** INITIAL INPUT VALUES
20.0 0.0 1.0 1 1
*
* Model "System_Plotter-4" (Type 65)
*
UNIT 14 TYPE 65 System_Plotter-4
*$UNIT_NAME System_Plotter-4
*$MODEL \Trnsys17\Studio\lib\System_Output\TYPE65d.tmf
*$POSITION 1332 197
*$LAYER Outputs #
PARAMETERS 12
5         ! 1 Nb. of left-axis variables
2         ! 2 Nb. of right-axis variables
40        ! 3 Left axis minimum
70        ! 4 Left axis maximum
0.0       ! 5 Right axis minimum
300000    ! 6 Right axis maximum
1         ! 7 Number of plots per simulation
12        ! 8 X-axis gridpoints
0         ! 9 Shut off Online w/o removing
-1        ! 10 Logical unit for output file
0         ! 11 Output file units
0         ! 12 Output file delimiter
INPUTS 7
10,1      ! Storage tank:Temperature to heat source ->Left axis variable-1
10,3      ! Storage tank:Temperature to load ->Left axis variable-2
5,3       ! Water-water heat pump:Outlet load temperature ->Left axis variable-3
16,1      ! Heat exchanger:Hot-side outlet temperature ->Left axis variable-4
10,12     ! Storage tank:Average tank temperature ->Left axis variable-5
10,6      ! Storage tank:Energy rate to load ->Right axis variable-1
10,11     ! Storage tank:Energy rate from heat source ->Right axis variable-2
*** INITIAL INPUT VALUES
T_to_source T_top T_hot T_replace T_average Q_to_load Q_from_source

LABELS 3

```

APPENDIX B. TRNSYS INPUT FILE

```
"Temperatures"  
"Heat transfer rates"  
"Tank"
```

```
*
```

```
* Model "Heating loads" (Type 9)
```

```
*
```

```
UNIT 15 TYPE 9 Heating loads
```

```
*$UNIT_NAME Heating loads
```

```
*$MODEL .\Utility\Data Readers\Generic Data Files\Expert Mode\Free Format\Type9e.tmf
```

```
*$POSITION 51 47
```

```
*$LAYER Main #
```

```
PARAMETERS 10
```

```
2 ! 1 Mode
```

```
0 ! 2 Header Lines to Skip
```

```
1 ! 3 No. of values to read
```

```
1.0 ! 4 Time interval of data
```

```
1 ! 5 Interpolate or not
```

```
-1.0 ! 6 Multiplication factor
```

```
0 ! 7 Addition factor
```

```
1 ! 8 Average or instantaneous value
```

```
35 ! 9 Logical unit for input file
```

```
-1 ! 10 Free format mode
```

```
*** External files
```

```
ASSIGN "Q_load_heating.txt" 35
```

```
*|? Input file name |1000
```

```
*
```

```
* Model "Heat exchanger" (Type 91)
```

```
*
```

```
UNIT 16 TYPE 91 Heat exchanger
```

```
*$UNIT_NAME Heat exchanger
```

```
*$MODEL .\Heat Exchangers\Constant Effectiveness\Type91.tmf
```

```
*$POSITION 224 385
```

```
*$LAYER HP loop #
```

```
PARAMETERS 3
```

```
1 ! 1 Heat exchanger effectiveness
```

```
4.19 ! 2 Specific heat of hot side fluid
```

```
4.19 ! 3 Specific heat of cold side fluid
```

```
INPUTS 4
```

```
13,1 ! Circulation pump VSD - Building:Outlet fluid temperature ->Hot side inlet temper
```

```
13,2 ! Circulation pump VSD - Building:Outlet flow rate ->Hot side flow rate
```

```
0,0 ! [unconnected] Cold side inlet temperature
```

```
0,0 ! [unconnected] Cold side flow rate
```

```
*** INITIAL INPUT VALUES
```

```
30 100.0 30 7000
```

```
*
```

```
* Model "Minimize Error" (Type 22)
```

```
*
```

APPENDIX B. TRNSYS INPUT FILE

```
UNIT 20 TYPE 22 Minimize Error
*$UNIT_NAME Minimize Error
*$MODEL .\Controllers\Iterative Feedback Controller\Type22.tmf
*$POSITION 217 626
*$LAYER Main #
PARAMETERS 2
0      ! 1 mode
5      ! 2 Maximum number of oscillations
INPUTS 7
23,1   ! Unit conversion:Output ->Setpoint
16,5   ! Heat exchanger:Heat transfer rate ->Controlled variable
0,0    ! [unconnected] On / Off signal
0,0    ! [unconnected] Minimum control signal
0,0    ! [unconnected] Maximum control signal
0,0    ! [unconnected] Threshold for non-zero output
0,0    ! [unconnected] Tolerance on tracking error
*** INITIAL INPUT VALUES
0 0 1 0 1 0 0
```

```
* Model "Unit conversion" (Type 57)
*
```

```
UNIT 23 TYPE 57 Unit conversion
*$UNIT_NAME Unit conversion
*$MODEL .\Utility\Unit Conversion Routine\Type57.tmf
*$POSITION 51 191
*$LAYER Main #
PARAMETERS 3
12     ! 1 Table Nb. for input
2      ! 2 ID number from table for input
1      ! 3 ID number from table for output
INPUTS 1
15,1   ! Heating loads:Output 1 ->Input
*** INITIAL INPUT VALUES
0.0
```

```
* Model "System_Plotter-5" (Type 65)
*
```

```
UNIT 24 TYPE 65 System_Plotter-5
*$UNIT_NAME System_Plotter-5
*$MODEL \Trnsys17\Studio\lib\System_Output\TYPE65d.tmf
*$POSITION 1482 100
*$LAYER OutputSystem #
PARAMETERS 12
2      ! 1 Nb. of left-axis variables
2      ! 2 Nb. of right-axis variables
0.0    ! 3 Left axis minimum
2e5    ! 4 Left axis maximum
0.0    ! 5 Right axis minimum
12000  ! 6 Right axis maximum
```

APPENDIX B. TRNSYS INPUT FILE

```
1      ! 7 Number of plots per simulation
12     ! 8 X-axis gridpoints
0      ! 9 Shut off Online w/o removing
-1     ! 10 Logical unit for output file
0      ! 11 Output file units
0      ! 12 Output file delimiter
INPUTS 4
16,5   ! Heat exchanger:Heat transfer rate ->Left axis variable-1
23,1   ! Unit conversion:Output ->Left axis variable-2
13,2   ! Circulation pump VSD - Building:Outlet flow rate ->Right axis variable-1
0,0    ! [unconnected] Right axis variable-2
*** INITIAL INPUT VALUES
Q_HX Q_set m_building label
LABELS 3
"Heat rates"
"Flow rates"
"Building loop"
*-----*

* Model "Aquastat - Base load heat pump control" (Type 2)
*
UNIT 26 TYPE 2   Aquastat - Base load heat pump control
*$UNIT_NAME Aquastat - Base load heat pump control
*$MODEL .\Controllers\Aquastat\Heating Mode\Type2-AquastatH.tmf
*$POSITION 570 623
*$LAYER Ground loop #
*$# NOTE: This controller can only be used with solver 0 (Successive substitution)
*$#
PARAMETERS 2
5      ! 1 No. of oscillations
100.   ! 2 Safety limit temperature
INPUTS 6
0,0    ! [unconnected] Setpoint temperature
10,12  ! Storage tank:Average tank temperature ->Temperature to watch
0,0    ! [unconnected] High limit monitoring temperature
26,1   ! Aquastat - Base load heat pump control:Output control function ->Input control f
0,0    ! [unconnected] Turn on temperature difference
0,0    ! [unconnected] Turn off temperature difference
*** INITIAL INPUT VALUES
49 10.0 80 0 0.5 -0.5
*-----*

* Model "System_Plotter-6" (Type 65)
*
UNIT 21 TYPE 65   System_Plotter-6
*$UNIT_NAME System_Plotter-6
*$MODEL \Trnsys17\Studio\lib\System_Output\TYPE65d.tmf
*$POSITION 1632 100
*$LAYER Ground loop #
PARAMETERS 12
4      ! 1 Nb. of left-axis variables
```


APPENDIX B. TRNSYS INPUT FILE

```

2      ! 2 Nb. of right-axis variables
30     ! 3 Left axis minimum
60     ! 4 Left axis maximum
0.0   ! 5 Right axis minimum
2e5   ! 6 Right axis maximum
1      ! 7 Number of plots per simulation
12     ! 8 X-axis gridpoints
0      ! 9 Shut off Online w/o removing
-1     ! 10 Logical unit for output file
0      ! 11 Output file units
0      ! 12 Output file delimiter
INPUTS 6
10,3   ! Storage tank:Temperature to load ->Left axis variable-1
16,1   ! Heat exchanger:Hot-side outlet temperature ->Left axis variable-2
16,3   ! Heat exchanger:Cold-side outlet temperature ->Left axis variable-3
0,0    ! [unconnected] Left axis variable-4
16,5   ! Heat exchanger:Heat transfer rate ->Right axis variable-1
0,0    ! [unconnected] Right axis variable-2
*** INITIAL INPUT VALUES
T_top T_replace T_hw T_top Q label
LABELS 3
"Temperatures"
"Heat transfer rates"
"HX"
*
* Model "Energy meter" (Type 55)
*
UNIT 19 TYPE 55 Energy meter
*$UNIT_NAME Energy meter
*$MODEL .\Utility\Integrators\Periodic Integrator\Type55.tmf
*$POSITION 750 431
*$LAYER OutputSystem #
PARAMETERS 21
1      ! 1 Integrate or sum input-1
0      ! 2 Relative starting hour for input-1
4000   ! 3 Duration for input-1
4000   ! 4 Cycle repeat time for input-1
4000   ! 5 Reset time for input-1
0      ! 6 Absolute starting hour for input-1
8760   ! 7 Absolute stopping hour for input -1
2      ! 8 Integrate or sum input-2
0      ! 9 Relative starting hour for input-2
4000   ! 10 Duration for input-2
4000   ! 11 Cycle repeat time for input-2
4000   ! 12 Reset time for input-2
0      ! 13 Absolute starting hour for input-2
8760   ! 14 Absolute stopping hour for input -2
3      ! 15 Integrate or sum input-3
0      ! 16 Relative starting hour for input-3
4000   ! 17 Duration for input-3
4000   ! 18 Cycle repeat time for input-3

```

APPENDIX B. TRNSYS INPUT FILE

```
4000      ! 19 Reset time for input-3
0         ! 20 Absolute starting hour for input-3
8760     ! 21 Absolute stopping hour for input -3
INPUTS 3
23,1     ! Unit conversion:Output ->Input-1
5,5      ! Water-water heat pump:Heat transfer to load ->Input-2
5,7      ! Water-water heat pump:Heat pump power ->Input-3
*** INITIAL INPUT VALUES
0. 0. 0.
```

```
* Model "Stats" (Type 55)
```

```
*
```

```
UNIT 22 TYPE 55 Stats
```

```
*$UNIT_NAME Stats
```

```
*$MODEL .\Utility\Integrators\Periodic Integrator\Type55.tmf
```

```
*$POSITION 748 517
```

```
*$LAYER Main #
```

```
PARAMETERS 21
```

```
1         ! 1 Integrate or sum input-1
0         ! 2 Relative starting hour for input-1
4000     ! 3 Duration for input-1
4000     ! 4 Cycle repeat time for input-1
4000     ! 5 Reset time for input-1
0         ! 6 Absolute starting hour for input-1
8760     ! 7 Absolute stopping hour for input -1
1         ! 8 Integrate or sum input-2
0         ! 9 Relative starting hour for input-2
4000     ! 10 Duration for input-2
4000     ! 11 Cycle repeat time for input-2
4000     ! 12 Reset time for input-2
0         ! 13 Absolute starting hour for input-2
8760     ! 14 Absolute stopping hour for input -2
-3       ! 15 Integrate or sum input-3
0         ! 16 Relative starting hour for input-3
4000     ! 17 Duration for input-3
4000     ! 18 Cycle repeat time for input-3
4000     ! 19 Reset time for input-3
0         ! 20 Absolute starting hour for input-3
8760     ! 21 Absolute stopping hour for input -3
INPUTS 3
5,3      ! Water-water heat pump:Outlet load temperature ->Input-1
T_mean   ! Equations:T_mean ->Input-2
COP      ! Seasonally-averaged COP :COP ->Input-3
*** INITIAL INPUT VALUES
0. 0. 0.
```

```
* Model "System_Plotter-7" (Type 65)
```

```
*
```

```
UNIT 25 TYPE 65 System_Plotter-7
```

APPENDIX B. TRNSYS INPUT FILE

```
*$UNIT_NAME System_Plotter-7
*$MODEL \Trnsys17\Studio\lib\System_Output\TYPE65d.tmf
*$POSITION 1782 100
*$LAYER Outputs #
PARAMETERS 12
2          ! 1 Nb. of left-axis variables
1          ! 2 Nb. of right-axis variables
45         ! 3 Left axis minimum
55         ! 4 Left axis maximum
0.0        ! 5 Right axis minimum
5          ! 6 Right axis maximum
1          ! 7 Number of plots per simulation
12         ! 8 X-axis gridpoints
0          ! 9 Shut off Online w/o removing
-1         ! 10 Logical unit for output file
0          ! 11 Output file units
0          ! 12 Output file delimiter
INPUTS 3
22,3       ! Stats:Mean value of input-1 ->Left axis variable-1
5,3        ! Water-water heat pump:Outlet load temperature ->Left axis variable-2
22,4       ! Stats:Standard deviation of input-1 ->Right axis variable
*** INITIAL INPUT VALUES
T_supply_avg T_supply T_supply_stdev
LABELS 3
"Temperatures"
"Stats"
"T_supply"
*
* EQUATIONS "Equations"
*
EQUATIONS 1
T_mean = 0.5*([3,1]+[28,1])
*$UNIT_NAME Equations
*$LAYER OutputSystem
*$POSITION 942 655
*
* Model "9-Borehole heat exchanger" (Type 557)
*
UNIT 28 TYPE 557      9-Borehole heat exchanger
*$UNIT_NAME 9-Borehole heat exchanger
*$MODEL .\GHP Library (TESS)\Ground Heat Exchangers\Vertical\U-Tube\Thermal Resistance Known\T
*$POSITION 884 329
*$LAYER HP loop #
PARAMETERS 35
STORAGE_VOLUME      ! 1 Storage volume
205                 ! 2 Borehole depth
5                   ! 3 Header depth
9                   ! 4 Number of boreholes
```

APPENDIX B. TRNSYS INPUT FILE

```

0.055      ! 5 Borehole radius
1          ! 6 No. of boreholes in series
1          ! 7 Number of radial regions
10         ! 8 Number of vertical regions
10.8       ! 9 Storage thermal conductivity
1845       ! 10 Storage heat capacity
0.0195     ! 11 Fluid to ground resistance
0          ! 12 Negative of pipe-to-pipe resistance
4.25       ! 13 Fluid specific heat
960        ! 14 Fluid density
0          ! 15 Insulation indicator
0.5        ! 16 Insulation height fraction
0.0254     ! 17 Insulation thickness
9999       ! 18 Insulation thermal conductivity
1          ! 19 Number of simulation years
100.0      ! 20 Maximum storage temperature
8          ! 21 Initial surface temperature of storage volume
0.0        ! 22 Initial thermal gradient of storage volume
0          ! 23 Number of preheating years
30.0       ! 24 Maximum preheat temperature
10.0       ! 25 Minimum preheat temperature
90         ! 26 Preheat phase delay
20.0       ! 27 Average air temperature - preheat years
15.0       ! 28 Amplitude of air temperature - preheat years
240        ! 29 Air temperature phase delay - preheat years
1          ! 30 Number of ground layers
10.8       ! 31 Thermal conductivity of layer
1850       ! 32 Heat capacity of layer
1000.0     ! 33 Thickness of layer
0          ! 34 Not used (printing 1)
0          ! 35 Not used (printing 2)
INPUTS 5
3,1        ! Circulation pump - Brine:Outlet fluid temperature ->Inlet fluid temperature
3,2        ! Circulation pump - Brine:Outlet flow rate ->Inlet flowrate (total)
0,0        ! [unconnected] Temperature on top of storage
0,0        ! [unconnected] Air temperature
0,0        ! [unconnected] Circulation switch
*** INITIAL INPUT VALUES
20.0 0.0 3 3 1
*
* EQUATIONS "Storage volume"
*
EQUATIONS 1
STORAGE_VOLUME = 3.14159265 * 205 * 9 * (0.525 * 5) * (0.525 * 5)
*$UNIT_NAME Storage volume
*$LAYER Main
*$POSITION 164 49
*
* Model "System_Printer" (Type 25)

```

APPENDIX B. TRNSYS INPUT FILE

```
*
UNIT 30 TYPE 25 System_Printer
*$UNIT_NAME System_Printer
*$MODEL \Trnsys17\Studio\lib\System_Output\Type25a.tmf
*$POSITION 1415 79
*$LAYER Outputs #
PARAMETERS 10
1 ! 1 Printing interval
START ! 2 Start time
STOP ! 3 Stop time
36 ! 4 Logical unit
2 ! 5 Units printing mode
0 ! 6 Relative or absolute start time
-1 ! 7 Overwrite or Append
-1 ! 8 Print header
0 ! 9 Delimiter
1 ! 10 Print labels
INPUTS 2
T_mean ! Equations:T_mean ->Input to be printed-1
28,1 ! 9-Borehole heat exchanger:Outlet temperature ->Input to be printed-2
*** INITIAL INPUT VALUES
T_mean T_out
*** External files
ASSIGN "***_T.out" 36
*|? Which file should contain the printed results? You can use the deck filename by entering "
|1000
*
* Model "System_Printer-2" (Type 25)
*
UNIT 31 TYPE 25 System_Printer-2
*$UNIT_NAME System_Printer-2
*$MODEL \Trnsys17\Studio\lib\System_Output\Type25a.tmf
*$POSITION 1697 90
*$LAYER Main #
PARAMETERS 10
672 ! 1 Printing interval
START ! 2 Start time
STOP ! 3 Stop time
37 ! 4 Logical unit
2 ! 5 Units printing mode
0 ! 6 Relative or absolute start time
-1 ! 7 Overwrite or Append
-1 ! 8 Print header
0 ! 9 Delimiter
1 ! 10 Print labels
INPUTS 1
22,23 ! Stats:Mean value of input-3 ->Input to be printed
*** INITIAL INPUT VALUES
COP
*** External files
```

APPENDIX B. TRNSYS INPUT FILE

```
ASSIGN "***_COP.out" 37
*|? Which file should contain the printed results? You can use the deck filename by entering "
|1000
*
* EQUATIONS "Seasonally-averaged COP "
*
EQUATIONS 1
COP = [19,11]/max([19,21],0.0001)
*$UNIT_NAME Seasonally-averaged COP
*$LAYER Building loop
*$POSITION 905 431
*
END
```

C

TRT test report

The test was performed on the 07/05/2012 at the laboratory of Building Services Engineering, Chalmers Javed & Fahlén (2010). Collected data are used in section 3.1.1.

C.1 Test description

Test is performed on borehole 7. Temperatures along the borehole (groundwater-filled region) are checked and are back to undisturbed conditions after the previous test perturbation. A heating sequence (5.5 kW – 0 kW) is injected to the borehole. Flow, temperature, power and pressure are measured. The accumulator tank is by-passed and the heat pump is turned off.

C.2 Aim

C.2.1 Personal

- Get hands on the experimental setup.
- Perform my own thermal response test and collect my own measurements.
- Measure the flow rate with an external flow meter and compare it to the measurements from the Grundfos flow meter.

C.2.2 Supervisor

- Estimate the undisturbed ground temperature by the fluid-circulation method and compare it with undisturbed borehole temperatures.

- Derive a convective heat transfer coefficient (natural convection in the groundwater-filled region) along the U-tube from the fluid temperature (modelled), grout temperature (measured) and wall temperature (modelled).

C.3 Measurements

C.3.1 Temperature (logged each 5 minutes)

- BH7: borehole inlet temperature
- BH16: borehole return temperature
- KB1-2: electrical heater inlet
- KB1-3: electrical heater outlet

C.3.2 Flow (logged each 5 minutes)

- KB1-1
- External flow meter

C.3.3 Power (logged each 5 minutes)

- Power meter (forcing sequence)

C.3.4 Pressure (checked at start-up)

- Manometer

C.4 Duration

72 hours (it is recommended to perform Thermal Response Tests for between 50 and 100 hours)

C.5 Notes

- Monitoring will be performed each day to check if everything is ok (leakages, power supply).
- Relative pressure at start-up must be between 0.8 and 1.2 bars (if too low, more solution can be added).
- 3-4 months are needed to go back to undisturbed conditions (it implies 2-3 tests per year).

- The piping can be divided in three loops: the building loop, the ground loop and the borehole loop.

C.6 Results

Power and mean fluid temperature from the TRT measurements are plotted on figure C.1. The undisturbed ground temperature $T_0 = 8.96^\circ\text{C}$ has been calculated from the data. A parameter estimation method (read section 4.1) has also been carried out.

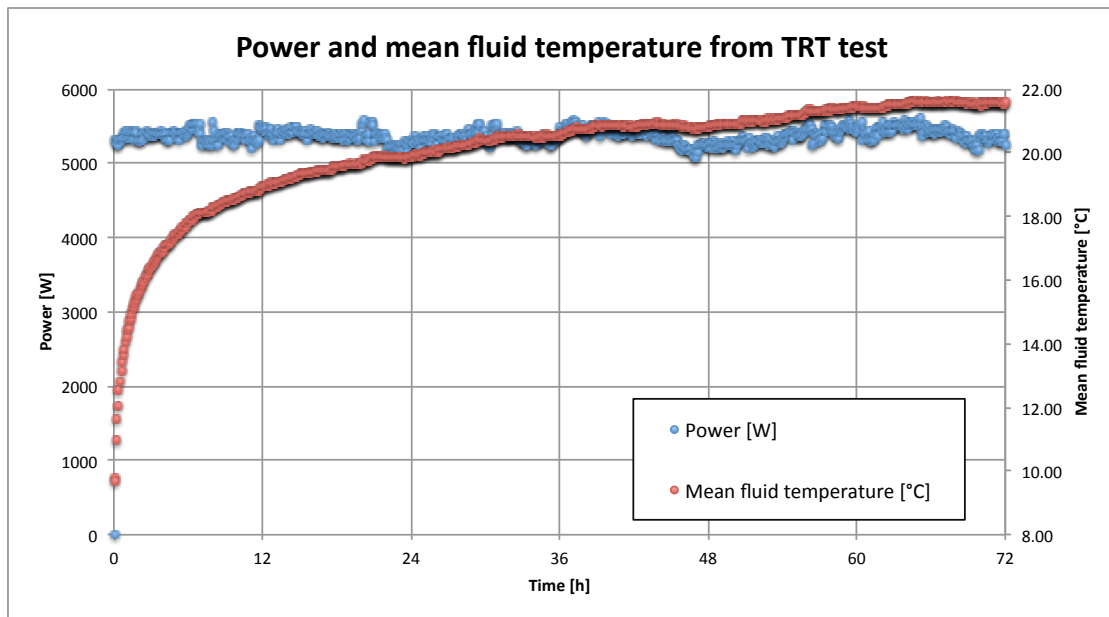


Figure C.1: Power and mean fluid temperature from TRT