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Short-term experiments with borehole heat exchangers and model validation in TRNSYS

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ABSTRACT

The short-term behavior of **b**orehole **h**eat **e**xchangers (BHE) is investigated using three 2 h test sequences each with constant inlet temperature and constant mass flow rate. Three models of the **tran**sient **sy**stems **s**imulation program (TRNSYS) have been compared to these measurements. In order to assess the deviations a 3D-FEM model, built in COMSOL Multiphysics®, is compared to the measurement as well.

The "Erdwärmesonden" model (EWS) shows a very good accuracy with a deviation less than 10%. The **s**uperposition **b**orehole **m**odel (SBM) and **d**uct ground heat **st**orage model (DST) neglect the internal borehole heat capacity of fluid and grout. In order to improve their short-term behavior, the models are modified with an adiabatic pipe model with wall capacity in front of the BHE model. Different parameter sets for the pre-pipe are investigated. The optimum parameter set reduces the error between simulation and measurement of the injected heat from 50% to about 5%. With this model modification, all investigated models SBM, DST, and EWS perform as accurate as the COMSOL model.

1. Introduction

For a couple of years now, a growing number of solar assisted **g**round-**c**oupled **h**eat **p**ump (GCHP) systems have been introduced to the market. According to Freeman et al. [1], they can be classified either if solar heat is delivered to the evaporator side (serial) or directly to the condenser side (parallel) of the heat pump. In a market survey Ruschenburg et al. [2] counts 46 solar assisted GCHP systems of which 15 are assisted on the evaporator side.

As the solar collector delivers the heat to the evaporator side at a low temperature level, unglazed collectors like metal roof collectors (e.g. Refs. [3–5]) and PV/thermal (PV/T) collectors (e.g. Ref. [6]) have been investigated for **serial systems**. Working only on the evaporator side, these systems perform robust regarding design-failures avoiding long-term temperature decrease even with undersized borehole heat exchangers. In contrary, **parallel systems** with glazed collectors that deliver directly useful heat are high-performing due to the low energy consumption of the solar circulation pump. See Bertram [7] for a comparison of serial and parallel solar assisted GCHP systems in TRNSYS.

The combination of both modes (serial, parallel) in a system concept permits achieving both types of advantages and, furthermore, reducing the collector stagnation time. On the other hand, the complexity of system design and control strategy is increased which necessitates detailed system simulations carried out by a **tran**sient **sy**stem **s**imulation program (like TRNSYS) [8].

A high accuracy of the applied models in the time range of minutes is very important for several reasons:

- Simulation time step

The simulations should be conducted with a time step in the range of one minute to consider both, the transient behavior of the system components and the control strategy. Furthermore, in a complex system it is important to account for all auxiliary energy consumers for the real electricity savings by solar collectors. Common standards for the assessment and intercomparison of simulations of all kind of combined solar and HP-systems are currently developed by Task 44 of the Solar Heating and Cooling Programme and the Annex 38 of the Heat Pump Programme of the International Energy Agency (IEA) (abbrev: T44/A38) [9].

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Nomenclature

a	ground thermal diffusivity [m^2/s]
D	diameter [m]
g	g-function [-]
H	length of borehole heat exchanger [m]
L	length of pre-pipe [m]
$\dot{m}$	mass flow rate [kg/s]
Q	heat [J]
$\dot{q}$	specific heat extraction rate [W/m]
r	radius [m]
Re	Reynolds number [-]
t	time [s]
T	temperature [K]

Greek letters

Δ	difference
λ	thermal conductivity [W/(m·K)]
ϑ	temperature [°C]

Subscripts

0	time = 0
b	borehole
equi	equivalent
g	ground
in	inside
m	mean
rel	relative
out	outside
S	steady-state
set	set point

- Typical heat pump running time

The typical running time of a ground-coupled heat pump is in the range of several minutes up to half an hour (see e.g. Refs. [10,11]), especially in monovalent GCHP systems with single speed compressor and direct coupling to the heating system. This is because all components are dimensioned for the max. heating load, though in reality most of the year the heating load is lower. In addition, planners tend to oversize components in case of doubt or just to be on the safe side. Consequently, the heat pump is often operated in intermittent operation.

- Solar irradiance fluctuation

Typically, the evaporator heat flow rate of a heat pump, which is depending on the temperature conditions, is rather constant. However, the heat flow rate of the solar collector field to the ground can be highly fluctuating due to varying irradiance conditions (factor of 5 within seconds). Thus, applied irradiance data should be measured with a high temporal resolution.

This paper focuses on short-term experiments for solar assisted BHE aiming at: first, assessment of existing BHE models in operation times less than 2 h, second, development and assessment of simple model modifications (pre-pipe) for BHE models that do not include the borehole heat capacity.

2. Test facility

In 2011, a test facility at ISFH for ground heat exchanger measurements has been commissioned. It comprises two different sized brine-water-heat pumps, three double-U-tube-BHE with a depth of about 70 m, one 300 l brine storage on source side, two ground-water measuring wells with a depth of 70 m, and three electric heaters and coolers to emulate solar heat production and heat demand as well.

The pipes in the BHE consist of cross-linked polyethylene (PEXa) and have an outer diameter of 32 mm, a wall thickness of 1.9 mm and a center-to-center distance of 60 mm (85 mm diagonal). The grout is ThermoCem® PLUS with a thermal conductivity of 2 W/(m K) and a volumetric heat capacity of 1.95 MJ/(m^3 K).

The whole test facility is equipped with high-precision sensors. Inlet and outlet temperature are measured directly at the top of the BHE inside the fluid with a standard uncertainty of 0.064 K. The mass flow rate is measured with a Coriolis mass flow sensor with a standard uncertainty of 0.1%. Undisturbed ground temperature can be calculated with ten buried temperature sensors placed on the surface of the BHE pipes. The logging interval is 1 min.

The ground has been analyzed inside the borehole by geophysical measurements and by lab tests of the State Authority for Mining, Energy and Geology of Lower Saxony, Germany. The upper 14 m are sand stone followed by marl and clay stone in varying concentration. The ground water level is at about 30 m depth. Double-head drilling was necessary due to fissured ground leading to a rather big borehole diameter of approximately 190 mm. See Pärisch et al. [12] for further information regarding the borehole field. The effective thermal conductivities and the borehole thermal resistances of each BHE have been determined by a combined thermal response test (see Table 1). BHE North shows an untypical high value for the borehole thermal resistance, probably caused by improper grouting, and is therefore not used for the tests and the model validation.

3. Test procedure

In general experiments of ground heat exchangers are not reproducible, because the heat injections of former experiments can influence the results of the current experiment. This is avoided by regenerating the BHE after each test according to Koenigsdorff et al. [13]. In doing this, the amount of injected heat is re-extracted by a heat pump and the subsurface recovers. The BHE is blocked for experiments until the buried temperature sensors have achieved undisturbed level with a deviation of <0.01 K to the value before the test. As a result, each experiment is conducted under nearly identical temperature conditions of the surrounding ground.

At the beginning of the experiment, the BHE is at undisturbed ground temperature. At first, the piping of the test facility and the brine storage are heated up to a set-point temperature by passing the BHE. The set-point temperature is higher than the undisturbed ground temperature. Then, a constant mass flow rate is led to the BHE. The brine storage helps stabilizing the flow temperature to the BHE and lowering the required power peak for the flow heater. Unlike in a thermal response test, the heat flow rate is highly

Table 1
Properties of the borehole heat exchanger.

BHE-ID	Length m	Diameter m	Effective thermal conductivity W/(m·K)	Thermal resistance (m·K)/W
North	68.5	0.19	2.1	0.117
East	69.3	0.19	2.5	0.095
West	69.5	0.19	2.6	0.083