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Geothermal energy piles and boreholes design with heat pump in a whole building simulation software

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ABSTRACT

With growing demand in improving building's energy efficiency, utilization of energy from renewable sources, such as ground energy, becomes more common. This paper focuses on the detailed modelling issues in a whole building simulation environment providing an approach for a design of a heat pump plant with boreholes or energy piles, that was developed for a case of one storey commercial hall building. Modelling was performed in whole building simulation software IDA-ICE, where most of the modelled components were defined as manufacturer specific products. Recently developed three dimensional borehole model was validated with the use of actual borehole measurement data. Heat pump model calibration parameters equations, which are needed to setup model according to manufacturer specific performance map product data, were derived and applied. According to results of conducted 20-years long-term simulations, consideration of seasonal thermal storage can become feasible. Validation of borehole model showed that the model can simulate very accurate dynamic performance and is highly suitable for coupling with dynamic plant models. Different ground surfaces boundary conditions of geothermal energy piles and field of boreholes resulted in 23% more efficient performance of energy piles in the case of the same field configuration.

1. Introduction

Geothermal energy, as a renewable energy source, can be efficiently utilized with an application of ground-source heat pump (GHSP) coupled with ground heat exchanger (GHE). GHSPs are widely used all over the world [1] to meet buildings with high energy performance heating and cooling demand. GHEs are generally classified according to their installation position – horizontal or vertical. One common vertical GHE solution is a borehole heat exchanger (BHE), which can be installed as a single borehole or in a group – BHE field [2]. Another vertical GHE solution is geothermal pile foundation [3], which is frequently referred to as geothermal energy piles (GEP). GEPs have two main functions – building load bearing to ground and ground heat exchanger. Because of these multiple features, GEPs can be highly cost-effective.

Thermal performance of GEPs differs from the common BHE field performance due to different ground surface boundary conditions. Generally, BHE field is located next to the building, where ground surface of BHE field is exposed to outdoor air and solar radiation. In case of GEPs, ground surface of pile foundation is interconnected with building's floor structure and solar radiation incident is limited by the building. Floor structure above the GEPs is exposed to indoor air, which temperature exceeds undisturbed ground temperature during the year in most climate zones. In GEPs case, heat conduction through the floor structure heats up the ground over the year and produces natural thermal storage effect, which BHE field lacks. Amount of GEPs in the design is usually limited by the foundation plan. When piles are located close to each other, thermal interference between adjacent piles appear. Therefore, assessment of GEPs or BHE field thermal performance and design includes quite many complex aspects typically modelled numerically.

The most recent European standard describing the design of heat pump heating systems EN 15450:2007 [4] lacks design guidelines for GHSPs coupled with GEPs or BHE field. The design and thermal performance assessment of BHE field is commonly performed in commercial software such as EED [5], GLHEPRO [6], Energy Plus [7] and TRNSYS [8].

In GLHEPRO, Energy plus and EED software, heat exchange between boreholes and ground is modelled with Eskilson's g-function [9]. Building operation is described with the input of

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Nomenclature

Pr	Prandtl number
μ	dynamic viscosity (Pa s)
C_p	specific heat [W/(m K)]
ρ	density (kg/m^3)
m	mass flow (kg/s)
V	volume (m^3)
K	heat transfer coefficient (W/K)
κ	thermal conductivity [W/(m K)]
k_g	grout thermal conductivity [W/(m K)]
R_b	borehole resistance [(m K)/W]
d_b	borehole diameter (m)
d_p	pipe diameter (m)
n	number of U-pipes
T	temperature (°C)
$\Delta Tlog$	logarithmic mean temperature difference (°C)
Q	thermal power (W)
P	electric power (W)
COP	coefficient of performance
EER	energy efficiency ratio
out	index for outlet
in	index for inlet
$cond$	index for condenser
$evap$	index for evaporator
dim	index for parameter value at rating conditions
f	index for full load
e	exponent
NTU	number of transfer units
t	time

average monthly load data. *G*-function value depends on the depth of boreholes in ground and the distance between them. *G*-function is used to describe specific borehole configuration performance over time and calculate the temperature at borehole wall. According to [10], determination of *g*-function is a time consuming process. Therefore, *g*-functions are pre-calculated for a limited amount of borehole field configurations and stored in software databases. This allows the software to instantly calculate and plot the results of the long-term simulation, where simulated period may exceed 20 years. Though, software user is limited to pre-determined borehole field configurations. Also, the results are only available as an average monthly data. As it is not possible to define ground surface boundary conditions, calculation of GEPs case in such software can become problematic. A detailed simulation of a single borehole in TRNSYS is possible with EWS model [20], which can perform at short time-step and accounts for thermal capacitance of fluid and borehole filling materials. EWS model utilizes finite difference method – Crank–Nicolson method. BHE field in TRNSYS can be simulated using a DST component model [11]. DST model is capable of annual hourly simulation and has also ground surface temperature input variable, which makes it possible to simulate the GEPs case. Depending on the software, the applied heat pump model [12] is either a simple quasi steady state performance map model or more complex parameter estimation based model [13].

The aim of this study was to model and assess the performance of the detailed heating/cooling plant with heat pump and GEPs/BHE field in the whole-building IDA-ICE simulation environment. The modelled plant considers application of recently developed three-dimensional model for an arbitrary combination of boreholes, correlation parameter based heat pump model with physical heat exchangers models and standard IDA-ICE model library components. This approach is suitable for detailed design, i.e. sizing of plant and BHE/GHE components with known limitations. Detailed plant was implemented in the whole-year energy performance simulation of a one storey commercial hall-type building.

To ensure the results accuracy, we validated IDA-ICE borehole model extension using experimental borehole measurements data. We studied IDA-ICE heat pump mathematical model and derived straightforward equations for calibration parameters, which are needed to setup heat pump model according to actual heat pump performance map product data. To simulate GEPs case, we modelled the impact of heat losses through floor structure on ground temperature and assessed its impact on the energy performance relative to BHE field. We studied the impact of borehole thermal resistance and long-term application of GEPs/BHE field on absorbed ground heat allowing to assess the importance of seasonal thermal storage [14].

2. Methods

The modelling in IDA-ICE was performed in advanced level interface, where user can manually edit connections between model components, edit and log model specific parameters, observe models code. An early stage building optimization (ESBO) plant, which is a part of a standard IDA model library, was utilized to generate the plant model. Abovementioned plant was modified to meet specific simulated case design intent. Total of two plant modifications were modelled – plant for building with GEPs (Fig. 1) and plant for building with BHE field (Fig. 1).

2.1. Building model description

Modelled plant modifications were coupled with a commercial hall-type one storey building (Fig. 2) located in Helsinki, Finland.

Ambient boundary conditions, regarding local weather data were described in recently updated Helsinki test reference year climate file [15] that was applied in the simulation. In cold climate conditions, buildings indoor climate requirements are generally ensured with heating. The heating and cooling energy use ratio in particular building is 1 to 0.056. Building's heating and cooling demand is met with radiant heating/cooling panels. Abovementioned room units were modelled with standard IDA ICE component library model, where manufacturer specific performance are described with the input of power law coefficient and exponent values. Detailed overview of general parameters describing the building model is presented in Table 1.

2.2. Heat pump model description

The design intent was to size the heat pump at ca 40% of building's design heat load at design ambient air temperature of −26 °C. The rest of the peak load was meant to be covered with electric top-up heating. Model of the brine-to-brine heat pump from the standard IDA ICE component library was applied in the study. The parameter estimation based heat pump model consists of a heat exchanger model [16] and compressor performance descriptive correlation model. The heat exchanger model, which is based on the NTU-method, describes heat pump condenser and evaporator. Abovementioned heat pump model is capable of performing at either full or part load. Plant design intent in this study considers application of "ON/OFF" heat pump. Therefore, part load operation of the heat pump model is not discussed in this paper. In the following, mathematical model of IDA ICE heat pump operation at full load is presented.

Heat pump condenser side produced heat at full load is described with the following equation:

$$Q_{cond_f} = P_f + Q_{evap_f} \tag{1}$$