



Control-oriented modeling of geothermal borefield thermal dynamics through Hammerstein-Wiener models

Ercan Atam^{a,*}, Daniel Otto Schulte^{b,c}, Alessia Arteconi^d, Ingo Sass^{b,c}, Lieve Helsen^{e,f}

^a Boğaziçi University, Department of Industrial Engineering, Bebek, Istanbul 34342, Turkey

^b Technische Universität Darmstadt, Institute of Applied Geosciences, Department of Geothermal Science and Technology, Schnitzspahnstrasse 9, 64287 Darmstadt, Germany

^c Darmstadt Graduate School of Excellence Energy Science and Engineering, Technische Universität Darmstadt, Jovanka-Bontschits-Straße 2, 64287 Darmstadt, Germany

^d Università degli Studi eCampus, via Isimbardi 10, Novedrate, CO 22060, Italy

^e Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300 box 2421, Leuven 3001, Belgium

^f EnergyVille, Waterschei, Belgium

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ABSTRACT

Geothermal energy is considered a clean and sustainable form of renewable energy, that can be exploited directly or indirectly by means of specific devices. Ground-coupled heat pumps are widely used systems to obtain this energy. Control of ground-coupled heat pump systems, where thermal energy is extracted or injected from and to a geothermal borefield, is important for optimal geothermal energy use in the building sector and smart grids. Model-based control of such systems is potentially an optimal solution but this requires control-oriented models for the borefield thermal dynamics, which is quite complicated due to thermal interactions between the boreholes, large-scale nonlinear system dynamics, transient surface boundary conditions, etc. In this paper, we propose and demonstrate the successful identification of these complex dynamics through simple and well-structured nonlinear Hammerstein-Wiener models, which can be used in some advanced convex model-based control algorithms. The results are validated for different borefield configurations and parameters with reference to a detailed finite-element borefield thermal model. Finally, a set of advanced convex model-based control methods are shortly described where Hammerstein-Wiener models can be used as control models.

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1. Introduction

Geothermal energy is one of the forms of renewable energy, which started to be used extensively in the last decades mainly through ground-coupled heat pump (GCHP) systems [1]. A GCHP system consists of a heat pump, a borehole or borefield, and a circulating heat carrier fluid. Borefields are arrays of vertical boreholes, which are drilled into the ground typically varying in length 60 m–150 m. These holes are fitted mostly with polyethylene single or double U-tubes and grouted with a backfill material. A heat carrier fluid (typically, water-antifreeze mixture) circulates in these tubes to exchange heat with the ground. Next, a heat pump is used to make use of the low enthalpy heat accumulated in the heat carrier fluid.

GCHPs find applications mainly for HVAC purposes in the building sector [2–5] and, thanks to their high potential for electric load management, they also have an important role in the smart grids framework [6]. Design of control systems for buildings or smart grids integrating GCHPs requires control of each main component in the system, and hence controlling the GCHPs as well. A first step towards model-based control of a GCHP system requires development of a control model for such a system. The modeling of heat pump in a GCHP system is not hard but the real challenge comes from control-oriented modeling of the temperature dynamics of borehole or borefield, which are utilized for heat exchange/storage [7–10]. Once a successful control-oriented model for the borehole/borefield is developed, this model can be coupled to the model of the heat pump, and then a model-based controller can be designed for the GCHP system with the desired control objective. Examples of such objectives can be the optimal operation of the heat pump so that its COP (coefficient of performance) stays in a desired band with some constraints on T_o : outlet temperature

* Corresponding author.

E-mail address: ercan.atam@boun.edu.tr (E. Atam).

of the circulating fluid in borehole/borefield (for example, $T_o > 0$ to prevent freezing of the circulating fluid during winter); reference tracking to maintain circulating fluid outlet temperature at maximum possible levels for maximum heat extraction, etc. The typical manipulated variables (control inputs) can be the mass flow rate of the circulating fluid in the borehole/borefield, on/off timings of the heat pump if an on/off heat pump is used or modulation level of the heat pump if a variable speed heat pump is used. The typical measured variables in such control problems can be the inlet and outlet temperatures of the circulating fluid, COP, etc.

Unfortunately, the thermal dynamics of GCHP systems are challenging to model for control purposes due to the involved complex nonlinear borefield thermal dynamics and thermal interaction between the boreholes. While thermodynamic models for single borehole heat exchangers can be described with comparably simple solutions, borehole heat exchangers in arrays have to consider the disturbance of the temperature field caused by neighboring boreholes, which directly effects the heat exchange with the ground. The state-of-the-art geothermal borefield simulators can be categorized mainly as “numerical models” and “analytical models”. Numerical models employ g-functions [11], finite-element or finite-volume methods to represent the complex thermal dynamics and to account for thermal interaction between boreholes, transient surface boundaries, variation of ground temperature with depth, etc. Such models are in general developed for detailed simulations to analyze the thermal response of these systems, and they are not suitable for control-oriented purposes since they are, in general, nonlinear and large-scale models, and they cannot be put easily into a state-space form. The analytical models, for example [10,12,13], use spatial superposition results from infinite or finite line-source analytical solutions. These models are simpler compared to numerical models, but still they are far from being used as control-oriented models since it is hard to put such models into a state-space representation with a low model order for which available linear and/or nonlinear model-based control techniques can be used. A state-of-the-art review of modeling and control challenges for the borefield systems are covered in the recent works [14–16].

G-function-based, finite-element (FE) or finite-volume borefield numerical models are not useful for model-based control designs. Such models are numeric, rarely they have a state-space form, and even when have a state-space form, they are large-scale with complex nonlinearities. As a result, for model-based control, one has to resort to model order reduction or system identification approaches to obtain low-order and simpler models. In the open literature, although few, there have appeared some studies in that direction. For example, in Ref. [17] the authors developed a first-order linear differential equation model for the evolution of mean ground temperature of a geothermal borefield system, where the control time step for the system was one week. The parameters of this model were obtained from the Trnsys [18] simulation of the considered borefield system. However, the chosen control time step of one week is very long since typical control actions for buildings may require control time steps in order of minutes or hours. Moreover, the realization of a designed controller based on such a model requires the measurement of underground mean field temperature, which may be either difficult or inaccurate.

In Ref. [19], a control model was obtained through system identification for a single borehole. In Refs. [20,21], the proper orthogonal decomposition-based model order reduction scheme [22] was used to obtain a simpler model for a borehole. Since a single borehole was considered, the approaches of [19–21] are not suitable for a general borefield system. In the literature, some neural networks-based identification models for GCHP systems exist, for example those described in Refs. [23,24]. However, such

models may not be appropriate for model-based control of GCHP systems since (i) the developed neural networks are complex, (ii) in such studies the focus was on the prediction of coefficient of performance of the heat pump. However, in control applications involving GCHPs with geothermal borefields, it is crucial to have simple models in the state-space form which predict the borefield outlet temperature. Accurate prediction of borefield outlet temperature is important to prevent thermal build-up in the ground during summer periods and depletion of the borefield, or preventing freezing of the circulating fluid, during winter periods.

In this paper, we study borefield systems with different configurations and parameters, and investigate control-oriented model development for such systems using system identification with a special nonlinear model structure, the Hammerstein-Wiener (HW) model form [25,26]. The applicability of model structure for different system parameters is important as emphasized in Ref. [27]. Moreover, we consider a shorter control time step of one hour compared to other studies in the literature. These are the main contributions of the paper. To the best knowledge of authors, this study is the first in the open-literature developing a control-oriented model of geothermal borefields for model-based control methods. As it will be detailed in the next section, a Hammerstein-Wiener model form consists of a linear time-invariant system and two static nonlinearities: one for input and the other for the output. Based on the fact that borefield temperature dynamics are nonlinear, the suitability of nonlinear Hammerstein-Wiener model structure was investigated as a simpler model form for control-oriented purposes, and it is shown that indeed this model form works reasonably well. Different borefield configurations with different system parameters are considered, and the results are validated for separate validation data sets. The input-output data generation system was the FE borefield model considered in Refs. [28,29]. Moreover, the prediction performance of HW borefield models is compared to prediction performance of models based on linear polynomial models such as ARMAX, BJ, and state-space. As another contribution, we discuss compactly a set of advanced convex model-based control methods where HW borefield models can be used as control models for various control objectives.

The rest of this paper is organized as follows. In Section 2, the identification/validation data generating FE borefield emulator model is described shortly, and then the HW model form together with the identification/validation setup are introduced. The prediction performance of identified HW borefield models for different borefield configurations with different parameters, the discussion of results, and prediction performance comparison of HW models with some linear models are studied in Section 3. Section 4 discusses very briefly the appropriate advanced model-based candidate control frameworks where the identified HW borefield models can be used as control design models. Finally, the main findings of this study along with some future research directions are given in the Conclusions section.

2. System identification

2.1. Data generating borefield emulator model

The data of the borefield operation are generated with BASIMO, a software tool specifically designed for the simulation of borehole heat exchanger (BHE) arrays [28,29]. It was successfully used for simulations of borefield thermal energy storage systems [28,30] and validated [31] against other numerical codes showing good agreement with benchmark simulation runs in OpenGeoSys [32] and FEFLOW [33]. BASIMO considers the thermal interaction of the BHEs with the conductive heat transport in surrounding rock,

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