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Extremum seeking control for efficient operation of hybrid ground source heat pump system

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ABSTRACT

The Hybrid Ground Source Heat Pump (GSHP) systems combine the renewable geothermal energy and cooling tower for rejecting the cooling load, which is often adopted for high cooling demand. Model based control can be limited due to variations in ambient conditions, ground-loop heat exchanger (GHE) and equipment characteristics, cost and reliability of sensors. A self-optimizing control scheme is proposed for efficient operation of the hybrid GSHP based on Extremum Seeking Control (ESC), with feedback of the total power consumption and the control inputs of the relative flow rate of cooling tower and the water pump speed. The cooling capacity of the heat pump regulates the evaporator leaving water at 7 °C. A Modelica based dynamic simulation model is developed for a Hybrid GSHP system, with the vertical GHE model adopted from Modelica Buildings Library. The transient heat transfer is implemented with a finite volume method inside and outside the borehole. The proposed ESC scheme is evaluated under the scenarios of fixed cooling load, ramp change in the evaporator inlet water temperature, diurnal sinusoidal cycle of air wet-bulb temperature, and realistic ambient and cooling load condition. Simulation results show the proposed ESC strategy effectively achieves nearly optimal efficiency without the need for plant model.

1. Introduction

The Ground Source Heat Pump (GSHP) is a technology that utilizes the renewable geothermal energy for space heating and air conditioning of residential and commercial buildings, which has demonstrated higher energy efficiency for residential and commercial buildings [1]. It is well known that the GSHP systems can achieve better energy performance in locations where building heating and cooling loads demonstrate year-around balance. However, many commercial buildings are cooling dominated with unbalanced loads, especially those located in warm-climate areas. Under such circumstance, much more heat is rejected into the ground than that absorbed from the ground, causing heat accumulation in the ground. Such heat accumulation results in increase of the ground temperature and then higher temperature of water entering the heat pump and performance degradation of the GSHP system accordingly [2]. This problem may be solved by increasing the total capacity of ground heat exchanger (GHE); however, the system capacity is limited by the initial cost of construction. One cost-effective solution is ot enhance the GSHP into the so-called Hybrid GSHP as shown in Fig. 1, which utilizes supplemental heat rejecters such as cooling tower.

There have been extensive studies on the design strategies of hybrid GSHP systems [3]. Caneta Research [4] analyzed the advantages of hybrid GSHP systems in warm-climate areas with constraints of initial costs and available surface area. Caneta Research [4] and Kavanaugh and Rafferty [5] presented respective design approaches for cooling-dominant buildings that would require longer GHE to meet the total cooling demand rather than the total heating demand, and also made prediction for the capacity of the GSHP systems. Kavanaugh [6] revised and extended these design procedures for cooling tower design in hybrid systems. Experimental studies of GSHP systems have been reported for snow melting on pavements and bridge decks [7,8] and

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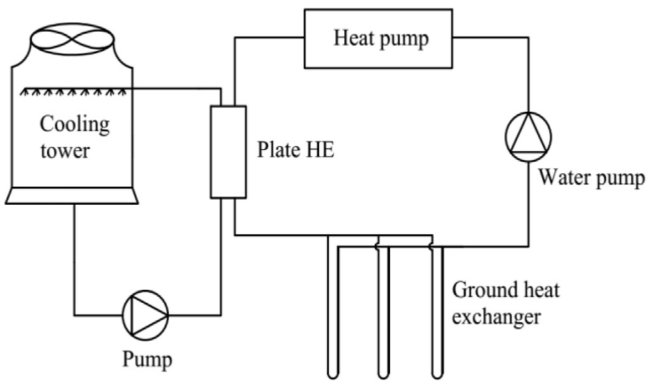

Fig. 1. Schematic diagram of a typical hybrid GSHP system.

greenhouse heating [9].

Simulation based studies have been conducted in the analysis of control and optimization of GSHP system operation. Madani et al. [10] compared three control strategies, i.e. constant hysteresis, floating hysteresis and degree-minute methods, over an annual profile through the use of a dynamic simulation model. For a simulated GSHP system, Edwards and Finn [11] investigated the optimal water flow rate under designed conditions. A particular branch of GSHP performance and analysis is based on data-driven approaches [12–15] such as artificial neural networks (ANN), support vector machine (SVM), and neuro-fuzzy methods. Data driven approaches typically require significant size of database in order to find the optimal condition.

There have been significant efforts in the control and optimization of Hybrid GSHP system operation for cooling dominated applications. Chiasson [16] investigated the optimal control and operating strategies for the annual thermal load balance in the ground and optimized the ground loop length and cooling tower capacity based on simulation. Ni et al. [17] present a brute-force approach to optimizing the design ratio for a GSHP with a gas boiler as the auxiliary heat source. Yavuzturk and Spitler [18,19] evaluated the advantages and disadvantages of several control strategies for a hybrid GSHP system with a cooling tower under different climatic conditions, including different night-time scheduling schemes at various times of the year. Ramamoorthy et al. [20] used a system simulation approach to finding the optimal capacity of supplemental cooling for a GHP system serving a cooling-dominated office building. For a system with both space conditioning and water heating requirement, Wrobel [21] presented a parameter estimation scheme for the hybrid GSHP design. Using the physics-based models of the hybrid GSHP system in TRNSYS, Hackel [22] proposed a simulation based design optimization algorithm which minimizes the life-cycle cost for cooling-dominated applications. Man et al. [23] developed an hourly simulation model of the hybrid GSHP system with a cooling tower in order to model and analyze the heat transfer processes of its main components. Some operational strategies are also investigated for a sample building. Gang et al. [24] present an ANN predictive control strategy for a hybrid GSHP system via a four-year simulation study. For a building heat distribution system that combines gas boilers and GSHP, Mokhtara et al. [25] optimize the system operation via an ANN approach.

Most existing methods for control and optimization of hybrid GSHP system operation have been based on nominal/empirical models. In practice, the actual behavior of such systems can be dramatically different from the nominal models due to several reasons. The actual composition of GHE is hard to measure and model accurately. There are significant variations in equipment characteristics due to manufacturing inconsistency and degradation. Calibrated models are elaborate and expensive to obtain online during the actual operation, and also imply high dependency on measurements of ambient conditions and internal variables, which induces the issues of cost, accuracy and reliability of the associated sensors. Also, data driven approaches typically require significant amount of training data that cover all relevant operation scenarios. Such data may not be available during an extended period of system operation before the associated control method can be applied. Therefore, real-time setpoint optimization not replying on exact system knowledge or existing operation data is more desirable for operations of the hybrid GSHP systems. The Extremum Seeking Control (ESC) has recently emerged as a major class of self-optimizing control strategies [26–28], which can search for the optimal input regarding a given performance index online in a nearly model-free fashion. As a dynamic realization of

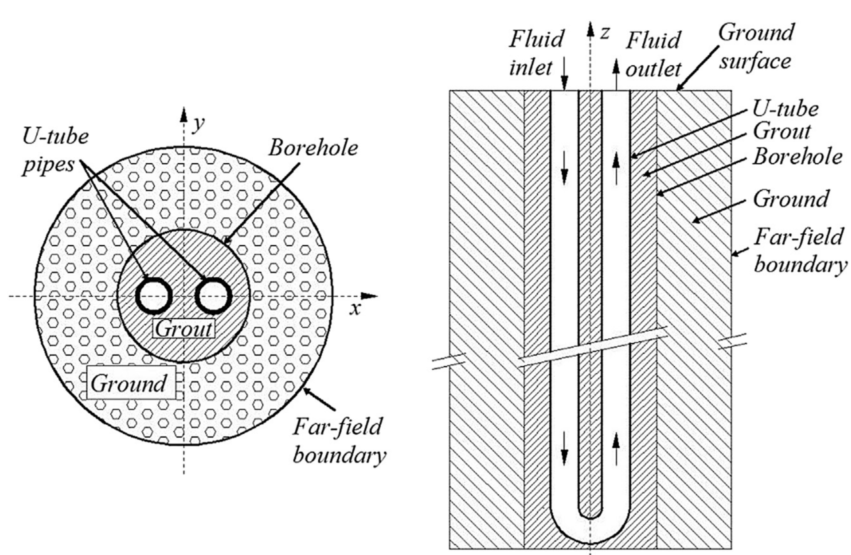

Fig. 2. Schematic diagram of a vertical U-tube ground heat exchanger (reproduced from a figure in Ref. [37]).