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Sensitivity analysis of recovery efficiency in high-temperature aquifer thermal energy storage with single well

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ABSTRACT

High-temperature aquifer thermal energy storage system usually shows higher performance than other borehole thermal energy storage systems. Although there is a limitation in the widespread use of the HT-ATES system because of several technical problems such as clogging, corrosion, etc., it is getting more attention as these issues are gradually alleviated. In this study, a sensitivity analysis of recovery efficiency in two cases of HT-ATES system with a single well is conducted to select key parameters. For a fractional factorial design used to choose input parameters with uniformity, the optimal Latin hypercube sampling with an enhanced stochastic evolutionary algorithm is considered. Then, the recovery efficiency is obtained using a computer model developed by COMSOL Multiphysics. With input and output variables, the surrogate modeling technique, namely the Gaussian-Kriging method with Smoothly Clopped Absolute Deviation Penalty, is utilized. Finally, the sensitivity analysis is performed based on the variation decomposition. According to the result of sensitivity analysis, the most important input variables are selected and confirmed to consider the interaction effects for each case and it is confirmed that key parameters vary with the experiment domain of hydraulic and thermal properties as well as the number of input variables.

1. Introduction

Energy storage technology is an essential technology for efficient energy management and utilization. Typical energy storage is to transform electric energy obtained by fossil fuel, nuclear power, and renewable source to mechanical, chemical energy form and then save it. It has advantages to reduce energy use, greenhouse gas emission, and cost for heating and cooling. Thermal energy storage is the storage of energy in the form of heat, and hence it may be directly utilized for industrial heat, as well as providing heating or power generation. The thermal energy storage functions to compensate for the temporal and quantitative differences in the supply and demand of energy, and energy saving through it and to improve the energy use efficiency.

UTES (Underground thermal energy storage) systems are generally divided into ATES (aquifer thermal energy storage), CTES (cavern thermal energy storage), and BTES (borehole thermal energy storage). In ATES systems, thermal energy is stored in the ground water of an aquifer and groundwater is injected and extracted by one or more wells. CTES systems utilize underground cavern to store thermal energy using hot water and therefore thermal stratification has a key role in performance of the system. BTES systems are the most commonly used and thermal energy is stored in the storage medium, usually bedrock, using closed heat exchange pipe.

The ATES system has higher system performance than the BTES system and any other systems using low temperature geothermal heat because of directly using groundwater with relatively high volumetric heat capacity [1]. Andersson et al. [2] also showed similar results through investigation on the performance factor, energy saving and payback time for ATES systems in Sweden (Table 1). In this regard, ATES systems are more suitable for large scale systems than BTES systems and mainly are used for seasonal thermal energy storage both of heating and cooling. Many applications of ATES are employed in European countries such as Netherland, Sweden and Germany. In particular, five systems in 1990's, 214 systems in 2000's, and 1300 ATES systems in 2010's so far have been registered in Netherlands. The Netherlands has a leading position in the world with rapid growth of installing ATES system [3] (Fig. 1).

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Table 1
Benefits in terms of economic and energy saving (Andersson et al. [2])*.

System application	Performance factor	Energy saving (%)	Payback (year)
Direct heating and cooling	20–40	90–95	0–2
HP supported heating and cooling	5–7	80–87	1–3
HP supported heating only	3–4	60–75	4–8
Direct cooling only	20–60	90–97	0–2

*Direct heat and cooling could be considered as HT-ATES and second and third system could be considered as LT-ATES.

ATES is generally divided into HT-ATES (high temperature ATES) system and LT-ATES (low temperature ATES) system. In case of HT-ATES system, the high temperature can be used directly for heating. It helps to minimize or eliminate the usage of heat pump, and then more energy is saving than LT-ATES system, which generally use heat pumps to increase the temperature. Despite the significant advantages, the HT-ATES is hard to employ in practice due to severe operating problems. It covers the clogging due to particle, gas bubbles and precipitation of minerals, and corrosion of components in the ground water system, etc [4]. According to the definition of high temperature (minimum storage loading temperatures on the order of 50 °C) in ECES Annex 12, there are only two operational HT-ATES systems in Germany. These are installed in Neubrandenburg by 2004 with 80 °C storage loading temperature [5] and at the Reichstag building in Berlin by 1999 with 70 °C storage loading temperature [6]. However as mentioned issues are gradually alleviated, the application of HT-ATES is increasing especially in Germany.

To predict and understand the behavior of sophisticated problem, numerical simulation is usually used. The simulator also can be used to assess the feasibility of the project, as well as to help in storage design and optimization of well locations, monitoring, and well steering [7]. Based on numerical simulation, sensitivity analysis is one of the main interests in decision-making processes (e.g. storage design, optimization of well locations) because it makes possible to quantify the leverage of each input variable to the output [8]. Therefore, sensitivity analysis is widely employed in the many engineering fields where dealing the complex problem related to energy, geology, and geomechanics. For instance, sensitivity analysis is used for gas production from Class I hydrate reservoir by depressurization [9], robust design building energy systems [10], assessment of energy-related CO_2 emissions [11], subsoil parameter estimation in mechanized tunneling [12], volcanic source modeling quality assessment and model selection [13], and sedimentary basin geothermal system [14]. Several studies on sensitivity analysis of ATES were also recently introduced. Schout et al. [15] suggested a method to estimate the recovery efficiency based on the Rayleigh number using results of sensitivity analysis. According to their results, performance of HT-ATES, which can be calculated in terms of recovery efficiency, depends on the hydraulic and operation properties (eg. permeability, injection temperature and injection volume). Bridger and Allen [16] investigated the influence of geologic layering on heat transport and storage in ATES. Results of the sensitivity analysis state that vertical anisotropy and hydraulic gradient are most sensitive on heat transport in a non-layered aquifer, which is analogous to our case. Kim et al. [1] investigated the effect of injection rate, hydraulic conductivity, and distance between injection and production wells, and then they showed that system performance depends on the distance between boreholes, hydraulic conductivity of an aquifer, and the production/injection rate. Yapparova et al. [7] also performed numerical simulations to assess the effect of groundwater flow and injection temperature. Despite the results from previous several studies, the most sensitivity factor is different from ours. Even though the sensitivity analysis was used to select important factors, they did not confirm the interaction effects. Furthermore the once-at-time method was used in fractional factorial design corresponding to maximum and minimum values of each factor. It has the possibility to diminish the uniformity for sampling.

In our study, we investigated main and interaction effects on the efficiency recovery of HT-ATES with single well using a proper computer experiment procedure. We considered two different cases and variations in hydraulic, thermal, and operation properties. Our findings will be helpful for the preliminary design and operation phases of the HT-ATES (high temperature-aquifer thermal energy system). This paper is structured with a flowchart illustrated in Fig. 2. First, the development of computational model for HT-ATES with single well is conducted using commercial program. Through the comparison between the recovery efficiency and tilt angle in thermal contours obtained by field experimental data and numerical simulation data, the developed model is validated.

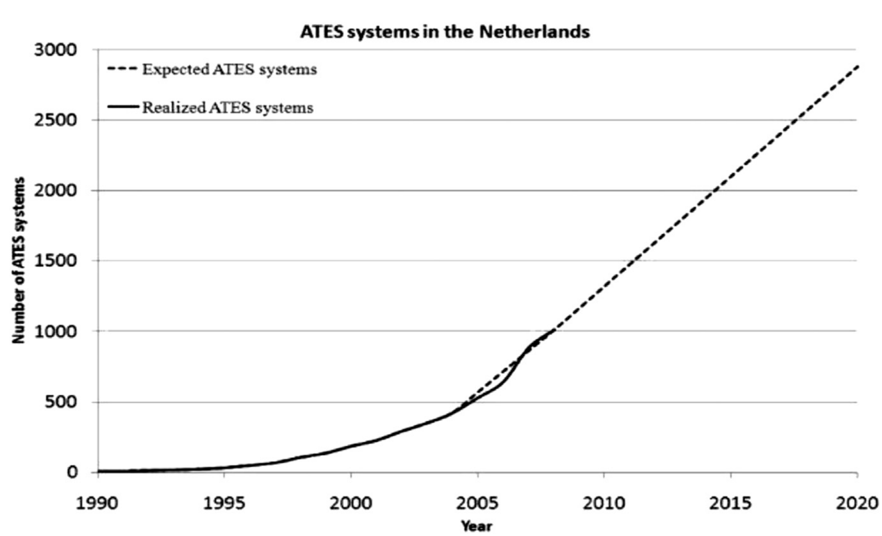

Fig. 1. ATES systems in the Netherlands (Godschalk and Bakerma [3]).