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Using duct storage (DST) model for irregular arrangements of borehole heat exchangers

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ABSTRACT

The duct storage (DST) model is one of the most widely used borehole heat exchanger (BHE) models owing to its fast calculation scheme and usability. However, the DST model can simulate only regularly placed BHEs, particularly in cylindrical borefield configurations. As a possibility to describe irregular borefield configurations by adjusting BHE spacing has been reported, we propose optimal values of BHE spacing for typical irregular BHE cases using the GenOpt optimization tool. A regression model based on a set of results obtained from the optimization is proposed to calculate the modified spacing for the DST model directly without optimization simulations. The proposed regression model fits to the datasets of the optimization with an accuracy of 96.5% in predicting the modified BHE spacing. The differences in time-averaged EWTs between the DST model with the proposed modified spacing and a reference model are close to zero, and they are less than 0.5 °C. However, other borefield configurations that have not been used for the model development can result in higher errors.

1. Introduction

Ground source heat pump (GSHP) systems are regarded as high-performance systems as they consume less energy [1–5]. A GSHP system has been mainly used for heating and cooling commercial buildings or family house but also for heating greenhouses and bridge slabs [6–8]. The GSHP system is conventionally composed of ground heat exchangers, heat pumps, and load-side loops. Ground heat exchangers, on the source side of the GSHP system, are of various types such as boreholes, horizontal exchangers, energy piles, and groundwater wells [9–12]. The selection of the type of ground heat exchangers is affected by the geological or site conditions. The installation of horizontal heat exchangers requires relatively large surface areas, and the presence of a shallow water table is a prerequisite for groundwater wells [13].

On the other hand, borehole heat exchangers (BHE) are both relatively cost-effective and site-unconstrained [14–16]. BHEs are normally used for single family houses or large buildings [17–19], and they have the highest market share in several countries [20]. GSHP systems typically require high initial cost to install the ground heat exchangers. Drilling accounts for the main initial cost of the BHE [21,22]. From an economical point of view, there is a trade-off between the initial installation cost and operating cost [17]. Undersized BHEs may result in higher operating costs because entering water temperatures (EWT) of heat pumps are too low in the heating mode or too high in the cooling mode [17]. In some cases, these cause system failure, which is an operational problem [4,23]. This is because EWTs may exceed the acceptable temperature range of the heat pumps. For these reasons, proper sizing of BHEs is an important issue to reduce the initial cost, while ensuring operational stability and high system performance [24–26].

The ground thermal capacity is an important parameter that has a continual effect on the system performance of the whole period, which is related to long-term EWT evaluation, particularly in the case of heating and cooling imbalance [4,25,27,28]. The thermal imbalance may be mitigated when there is an aquifer in the underground [29,30]. In many cases, the heat build-up caused by the cooling-dominant buildings is being increased over time, and the thermal conditions become unfavorable [24,31]. Such heat build-up is easily observed in cases of multiple BHEs in large buildings [31]. Thus, effects of thermal interference between boreholes must be taken into account in the design or engineering phase.

Existing BHE models consider these thermal interference effects

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by different methods. Some recent works aimed at optimizing borehole arrangements to reduce the impact of thermal interferences [9,26,27]. One of the well-known methods is the temperature penalty method that is commonly used for design [23,25,32]. The temperature penalty method is employed to describe the thermal interference effects by adjusting the borehole wall temperatures, which affect the EWTs. It is proposed for a limited number of borefield configurations in the ASHRAE Handbook [33]. Because the effects of thermal interferences on the sizing of BHEs are a dominant factor, more-precise calculation methods for temperature penalty have been proposed. The ground-response function (*g-function*) [34] has been used to calculate the temperature penalty for a given borefield configuration [25], where differences between the undisturbed and multiple borehole wall temperatures are used to calculated the temperature penalty [35].

Several numerical models that directly describe the borefield in detail are flexible to account for thermal interference effects. However, they are rarely used for sizing and system engineering works as important computational resources are required for those models. The duct storage (DST) model is a fast numerical model [36] that considers only regular borehole arrangements to use cylindrical grids. Such an assumption is justified by the fact that the DST model was developed for thermal storage applications where regular arrangements of BHEs are common. The DST model has been used as a reference model for benchmarking of newly developed models [37–39], and the comparisons were limited to single-borehole or regular simulations [40–42]. Recent studies [43,44] proposed TRNSYS [45] simulation-based sizing methods. They used Type 557, the TRNSYS version of the DST model, combined with the GenOpt optimization program [46]. With several iterations of the Type 557 simulation project using a GenOpt solver, an optimal unit length for boreholes of a given borefield configuration is determined. This strong iteration method is practically possible since the DST model is simulated rapidly. An advantage of this simulation-based design method over conventional design methods is its flexibility. For instance, the variable COPs that are usually assumed as constant can be taken into account during simulations in TRNSYS [43]. The same TRNSYS project developed for sizing can also be used for hourly detailed simulations for various engineering purposes [44].

However, the DST-based design method is applicable only for regularly arranged cylindrical borehole configurations, as mentioned earlier. The previous works [43,44] also mention such a limitation. Regarding the issue of the DST geometry, Bertagnolio et al. [41] showed a possibility to adopt the DST model for an irregular BHE arrangement, such as a line-shape (*I*-shape) configuration, by modifying the storage volume parameter, a main control parameter in the DST model. They found that the modified parameter in the DST model could describe the approximate thermal dynamics of the *I*-shape borefield. However, this proposed modification parameter was not discussed in detail in the work. Approximations for the use of the DST model in alternative borefield shapes are useful for future applications of the DST model.

This work proposes a modification method of the DST parameter to account for various types of irregular borefields. The irregular borefields are not only common cases of GSHP applications for heating or cooling of buildings, but also the configuration is one major drawback to the use of the DST model.

2. Methodology of adopting the DST model for irregular BHE configurations

2.1. Parameter modification of the DST model

The DST model was developed by Hellström [36] as a 3D simulation model for seasonal thermal storage by vertical BHEs. Ground thermal storage can be treated as a cylindrical volume. Radial symmetry can be found around the vertical axis when the boreholes are regularly placed in the cylindrical bore field [42], as shown in Fig. 1. The storage volume in the DST model is expressed as V_{DST}, as given in Eq. (1). Here, N represents the number of BHEs, H is the length of the BHE, and B is the spacing between BHEs. In the DST model, B is equal for all BHEs. Thus, a small V_{DST} represents close spacing between BHEs for a constant number of BHEs with a given H.

$$V_{DST} = \pi \times N \times H \times (0.525 \times B)^2 \tag{1}$$

As mentioned in the introduction, the modified value for this V_{DST} parameter, namely B, may describe a borefield configuration other than the cylindrical regular configuration. This modification approach adjusts the borehole spacing in the regular configuration so that the DST model has the same thermal interference effects as the test irregular BHE arrangement. Their work proposes making the perimeter of a modified storage volume equal to that of the area of an *I*-shape borefield, as shown in Fig. 2. The perimeter of the red *I*-shape borefield can be the circumference of the cylindrical area of the DST model. In this case, only the borehole spacing (B) is adjusted; other conditions, such as number of boreholes (N), borehole depth (H), and other ground parameters, are kept intact. This modification is used to compare borehole wall temperatures in 8 × 1 boreholes. In their study, the modified DST model has an error of less than 0.6 °C from the curve of Eskilson's *g-function.* Applications for other configurations were not investigated in the work.

Similarly, alternative BHE arrangements may also be taken into account in the DST model. When adopting the principle, less compact configurations of borefield result in larger BHE spacing. Table 1 shows some typical borefield configurations, as well as equivalent borefield configurations for the DST model. The corresponding equivalent spacing increases when BHEs are placed such that effects of thermal interferences are less dominant. The modified borehole spacing for the DST model is given in Table 1, where $B'_{REC} < B'_{U} < B'_{L} < B'_{I}$. Further quantitative analysis is presented in the following section.

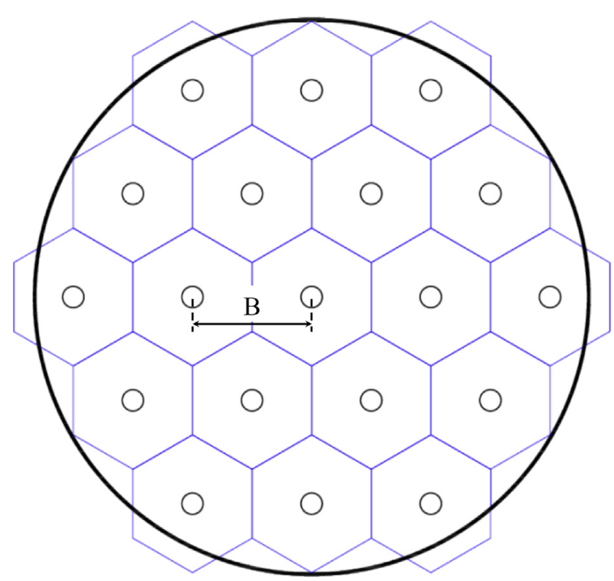

Fig. 1. Hypothetical cylindrical borehole configuration in the DST model (19 boreholes).