Importance of long-term ground-loop temperature variation in performance optimization of Ground Source Heat Pump system

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Abstract

In a recent article published in this journal, a series of design optimization was executed for a ground source heat pump system. The optimization was conducted based on a COP_{all} index, which considers both the hydraulic loss on the buried pipe network, as well as the soil thermal balance over a one-year period. In that article, it was concluded that a borehole spacing of 4 m is the optimal value. In this short communication, the comprehensive COP_{all} index is re-evaluated with the same system setup with both the TRNSYS and OpenGeoSys-TESPy software, but over a 20-year period. The results show that the borehole heat exchanger array with a spacing of 4 m will suffer severe heat accumulation over a 20-year operation. This causes the soil temperature to rise by 5.68 °C, along with a decrease of COP_{all} from 4.59 to 4.18. Due to the smaller increase of ground-loop temperature and lower electricity consumption from heat pumps, a larger spacing of 6 m will bring better COP_{all} value over the long term, and thus should be recommended. The extended numerical study in this work suggests that when evaluating the

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performance of a ground source heat pump system, different time duration will lead to different results. Therefore, the variation of long-term ground-loop temperature needs to be quantitatively evaluated in advance, and the system optimization is recommended to be conducted over the entire life cycle of the system.

Keywords: Shallow geothermal energy utilization, Borehole heat exchanger array, Ground-loop temperature, Soil thermal balance, System optimization

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Nomenclature

Roman letter

B_s	borehole spacing (m)
COP_{all}	comprehensive COP of GSHP system (-)
N_m	accumulative electricity consumption of the circulation pump (W)
N_z	accumulative electricity consumption of the heat pump (W)
Q	accumulative annual thermal load (W)
T	temperature (°C)

Subscripts

c	cooling
h	heating

Abbreviations

BHE	Borehole Heat Exchanger
COP	Coefficient of performance
FEM	Finite Element Method
GSHP	Ground Source Heat Pump

1. Introduction

In the article of Zhang et al. [1] recently published in this journal, an optimal design method for the Ground Source Heat Pump (GSHP) system was proposed, in which the hydraulic loss on the buried pipe network is considered together with the soil thermal balance in the objective function. In most real-world GSHP projects, Borehole Heat Exchangers (BHEs) are often connected through a buried pipe network. In Zhang et al. [1], a buried pipe network was built in TRNSYS by taking an actual GSHP system as the blueprint, and a series of simulations were conducted to find the optimal design for the system. By taking the hydraulic resistance into consideration, a comprehensive coefficient of performance ($\mathrm{COP_{all}}$) index was proposed to present the overall efficiency of the GSHP system in their work. This index is defined as the ratio of thermal energy output over the total electricity consumption over one-year period:

$$\mathrm{COP_{all}} = \frac{Q_c + Q_h}{N_{z,c} + N_{z,h} + N_m(t_c + t_h)} \tag{1}$$

where Q_c and Q_h are the accumulative annual cooling and heating demand of the GSHP system respectively. $N_{z,c}$ and $N_{z,h}$ are accumulative electricity consumption used by the heat pump unit in summer and winter. N_m is the electricity consumption used by the circulation pump. t_c and t_h are the accumulative operating hours of the system in summer and winter, respectively.

By applying this index into the optimized procedure for buried pipe network, Zhang et al. showed in their simulation results that the $\mathrm{COP_{all}}$ value will reach maximum with a minimum borehole spacing of 3 m (Fig. 4.15 in [1]). They also concluded that with the increase of borehole spacing, the maximum $\mathrm{COP_{all}}$ gradually decreases.

It is known to the GSHP community that, when annual heating and cooling load is unbalanced, the accumulation of heat in the subsurface may lead to the change of the circulation temperature during the life cycle of the system [2, 3]. This effect can determine the variation of the heat pump efficiency over the long term, and eventually also alter the system performance.

In recent publications, there have been a series of research reported on the performance evaluation and optimization of GSHP system. To avoid the tremendous cost in long-term in-situ measurement, the experimental tests on the actual performance of practical GSHP system are always performed in short term, typically one year [4, 5]. During the long-term operation of GSHP equipped with BHE array, many researchers point out that the imbalance of ground thermal load yields to heat/cold accumulation in the surrounding subsurface [6, 7]. With proper layout of the BHE array, including the geometric arrangement [8] and borehole spacing [9], this phenomenon can be alleviated to maintain the stable system performance. Besides, as for the performance criterion, the COP of heat pump is usually used as an index when evaluating the performance [3]. In the last few years, some researchers [10, 11] proposed to consider both electricity consumption of heat pump and circulation pump in the performance evaluation. In this context, it is important to quantify the amount of electricity consumption by both the heat pump and circulation pump, as well as their sensitivity to the change in borehole spacing, ideally over the entire life cycle of the system. In Zhang et al. [1], the comprehensive $\mathrm{COP_{all}}$ index is proposed to evaluate the performance of GSHP system. The impacts of borehole depth and spacing of BHE array are investigated over a one-year operation in their work and the optimized suggestions are given.

Inspired by Zhang et al.'s work, our main intention of this short communication is to show whether different duration will have a strong impact on the system performance evaluation and hence influence the optimization. Our work intends to answer the following question: what determines system performance variation over the long term? The method applied in this short communication is a series of case studies based on the same settings as in Zhang et al. [1]. Rather than evaluating the system efficiency based on the one-year simulation result, long-term numerical modeling of soil and circulation temperature evolution is conducted over a period of 20 years. The corresponding electricity consumption and comprehensive performance index are also re-evaluated accordingly. Based on the new results and evaluations obtained in this work, a different perspective is shown on how the performance of GSHP system varies in the long term.

2. Methodology

Considering the flexible boundary condition of the GSHP system, versatile numerical software is usually chosen to serve as the simulation tool by the researchers. In the work of Zhang et al. [1], the GSHP system and the coupled BHE array are modeled by the TRNSYS software. In this short communication, the same GSHP system is simulated both in TRNSYS and OpenGeoSys numerical software during the long-term operational duration.

2.1. DST model in TRNSYS

In the TRNSYS software, the component type 557 adopts the Duct Heat Storage Model (DST) proposed by Hellström [12], which predicts the behavior of BHE with a line-source based analytical solution. It is further coupled with the heat transfer process in the surrounding soil, which is modeled by the Finite Difference Method (FDM). The thermal effect produced by each BHE is superimposed in TRNSYS and produces the resulting soil temperature values used for the calculation of heat flux between the BHE and the soil. Owing to the rapid deployment and fast calculation speed of TRNSYS, it has been a popular choice for many researchers to simulate the GSHP system (c.f. Bernier [13], Garber et al. [14], Kavian et al. [15]).

2.2. OpenGeoSys-TESPy

OpenGeoSys (OGS) is an open-source scientific modeling software, designed for the numerical simulation of coupled Thermal, Hydro, Mechanical and Chemical (THMC) processes [16]. It has been widely applied in geotechnical engineering [17], energy storage [18] and waste repository research [19]. In the field of shallow geothermal energy utilization, OGS implements the Dual Continuum Finite Element Method (DC-FEM) to simulate the thermal interaction between BHEs and the surrounding subsurface. Following the DC-FEM approach, the simulation domain is divided into two compartments, while governing equations are respectively imposed on 1D line elements for the boreholes and 3D prism elements for the surrounding subsurface. The heat flux between the boreholes and the surrounding subsurface is set as the Neumann-type boundary conditions. The detailed mathematical framework and discretized approach can be found in the publication of Al-Khoury et al. [20] and Diersch et al [21, 22].

Besides, the modeling of the real-world GSHP project has to consider the dynamic heat exchange behavior of the BHE array connected to it. For this purpose, the Thermal Engineering Systems in Python (TESPy) [23] has been coupled with OGS to depict the thermal-hydraulic features in the buried pipe network. More detail about the calculating logic between OGS and TESPy can be found in our previous work [24, 25]. In this work, both TRNSYS and OGS-TESPy models are employed to simulate the same scenarios as described in Zhang et al. [1], and both model results are compared to reveal long-term accumulated thermal plumes in the subsurface, as well as its impact on the COP_{all} value.

2.3. Model validation

The BHE array model implemented in OpenGeoSys-TESPy software has previously been verified against analytical solution [24, 26]. The same software module has already been applied in real-world projects and its results have been validated against monitoring data from actual GSHP projects in Cologne [27], Leicester [7] and Xi'an [25]. As for the COP of the heat pump, it can be dynamically calculated based on the ground-loop temperature in the OpenGeoSys software [2, 28]. These previous work ensure that the BHE array model in OpenGeoSys is capable of reproducing the evolution of circulation temperature over the long-term operational duration and thus can be applied in investigating the long-term performance variation of the BHE array coupled GSHP system.

3. Model Configuration

In Zhang et al. [1], the authors proposed to optimize the GSHP system design based on the COP_{all} index. They concluded that the COP_{all} value will achieve its maximum when the borehole spacing is 3 m. They also suggested that when the hydraulic resistance of the pipe network and soil thermal balance are both considered, the recommended range for borehole spacing is from 4.0 m to 5.0 m.

In order to verify the conclusion of Zhang et al. [1], several independent GSHP models are built up and re-simulated by TRNSYS and OGS-TESPy respectively. In the first step, two single-BHE scenarios are set up to verify the simulation results from the two different software. Secondly, two GSHP models with a spacing of 4.0 m in buried pipe network were configured to manifest the inter-BHE thermal interaction among BHE array. It needs to be mentioned that the GSHP models established in this work contain a buried pipe network with 25 BHEs, which is scaled down from the 140 BHEs in Zhang et al. [1]). This was designed to accelerate the model simulations. Finally, the borehole spacing is extended from 4.0 m to 6.0 m, and both TRNSYS and OGS-TESPy models were repeated, in order to investigate the impact of spacing on the system efficiency. In total, six scenarios were executed to examine the performance variation of GSHP system in response to long-term operation.

Following the configuration in Zhang et al. [1], the 25-BHE array is placed in a 216 × 216 × 200 m model domain, with a 4.0 m inter-borehole distance. These BHEs are connected through a buried pipe network to transfer heat from the subsurface to the heat pump installed in the building. Fig. 1 illustrates the schematics of the GSHP model in TRNSYS, as well as the model domain in OGS. The annual system thermal load is assumed to be cooling-dominant as the case in Zhang et al. [1]. The BHE and subsurface parameters are set to be the same as in Zhang et al. [1]. The duration of the model simulations is set to 20 years rather than one year, so that it can reflect the typical behavior of a GSHP system over its entire life cycle.

Considering the specific performance curve of the heat pump is not given by Zhang et al. [1], the curve in Hein et al. [2] is adopted to calculate the heat pump electricity consumption $N_{z,h}$ and $N_{z,c}$, using predicted outlet temperature from the ground loop as the input. Moreover, the same method as used in Zhang et al. [1] is repeated to calculate the hydraulic loss and electricity consumption N_m by the circulation pump. By inserting $N_{z,c}$, $N_{z,h}$ and N_m into Eq. (1), the corresponding COP_{all} values can be estimated over twenty years instead of just one year. For the conciseness of this manuscript, details on the model settings are provided along with the input files, and provided as the supplementary material attached with this manuscript. Interested readers may access them to reproduce the simulation results presented in the next section.

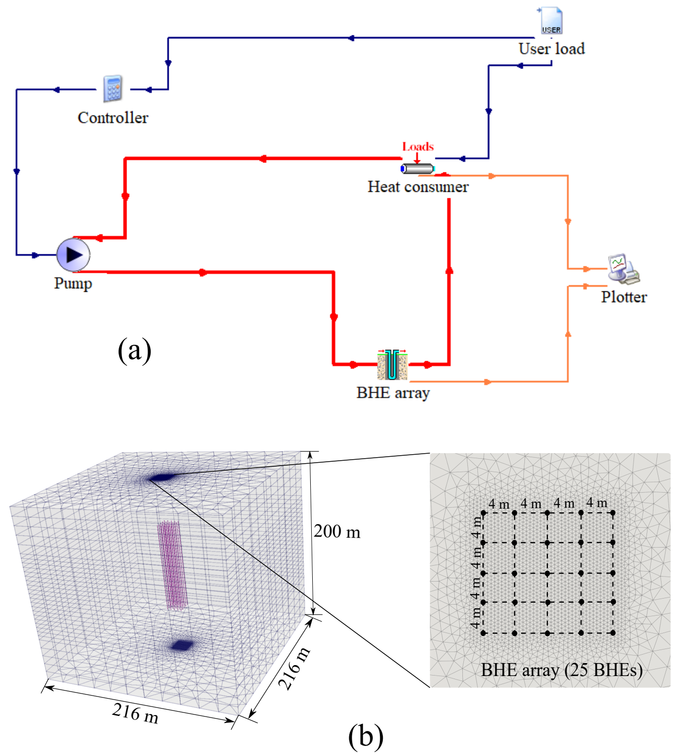

Figure 1: (a) Schematic diagram about calculating logic in TRNSYS; (b) Modeling domain for the BHE array simulated by OpenGeoSys

4. Results

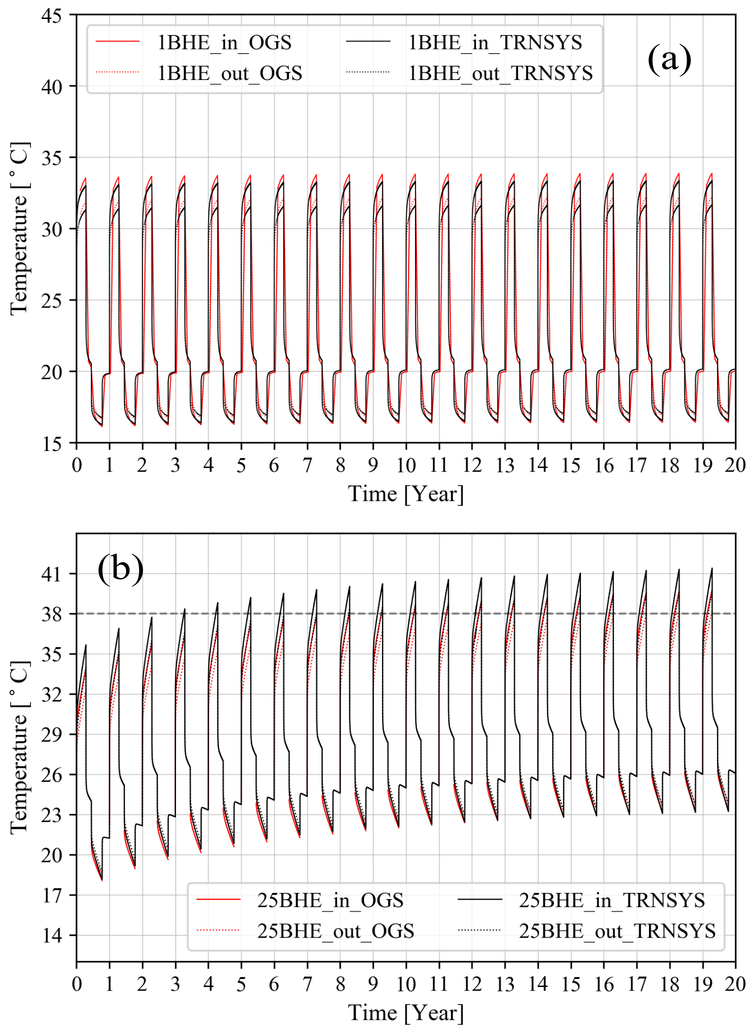

Figure 2: (a) Outlet temperature of a single BHE over the 20-year operation; (b) Overall outlet temperature of BHE array over the 20 years

Fig. 2 illustrates the long-term evolution of inlet and outlet temperature from the ground loop. For a single BHE (Fig. 2(a)), the results simulated by TRNSYS and OGS are very close to each other. The maximum temperature difference is only 0.51 °C (1.60 %). Over 20 years, the trend of both modeling results remains similar, with maximum temperature value over 33 °C and the minimum about 16 °C. As for the 25-BHE array (Fig. 2(b)), the maximum difference between TRNSYS and OGS-TESPy simulation results is 1.51 °C (3.81 %). Considering the circulation temperatures predicted by OGS-TESPy match well with that from TRNSYS, the correctness of both numerical models can be verified. This also means the one-year model prediction made by Zhang et al. [1] is valid. Different from the single BHE scenario, it is noticed that the ground loop temperature shows a gradually ascending trend, which is caused by the accumulation of heat in the subsurface and the thermal interaction among multiple BHEs. For a typical heat pump unit, the upper-threshold of inlet temperature for the cooling mode is usually around 38 °C [29]. Beyond this temperature, the heat pump unit may be shut down. As shown in Fig. 2(b), both TRNSYS and OGS-TESPy predict that the temperature of the ground loop will exceed 38 °C after 5 years of operation. This suggests that, the design of the BHE array with 4.0 m spacing actually can not be operated sustainably over the long term with the given cooling-dominated thermal load.

In the DST model used by TRNSYS, the surrounding soil is regarded as an entire body. Fig. 3 manifests the TRNSYS predicted average soil temperature and $\mathrm{COP_{all}}$ for the BHE array over 20 years. It can be found that the accumulated heat in the subsurface causes the temperature to increase from 19.8 °C (the initial value) to 30.6 °C (the maximum soil temperature) after 20 years. Due to this cyclical increase over time, the temperature of circulating fluid will also lift itself so that the cooling demand from the building side can be satisfied. Meanwhile, the nominal $\mathrm{COP_{all}}$ of the system also suffers an obvious decrease from 4.59 to 4.20 during the long-term operation. Actually, Fig. 2(b) already suggests that the system will be shut down after 5 years because the circulation temperature exceeds the upper limit of the heat pump. In Zhang et al. [1], the authors performed the TRNSYS simulation for only one year. As a result, they were not able to catch the ascending trend in ground-loop temperature as illustrated in Fig. 2(b). The lesson to be learned here is that the long-term behavior of the ground loop is the determining factor when evaluating the $\mathrm{COP_{all}}$ index, as well as the system sustainability, especially when an unbalanced thermal load is imposed over the years.

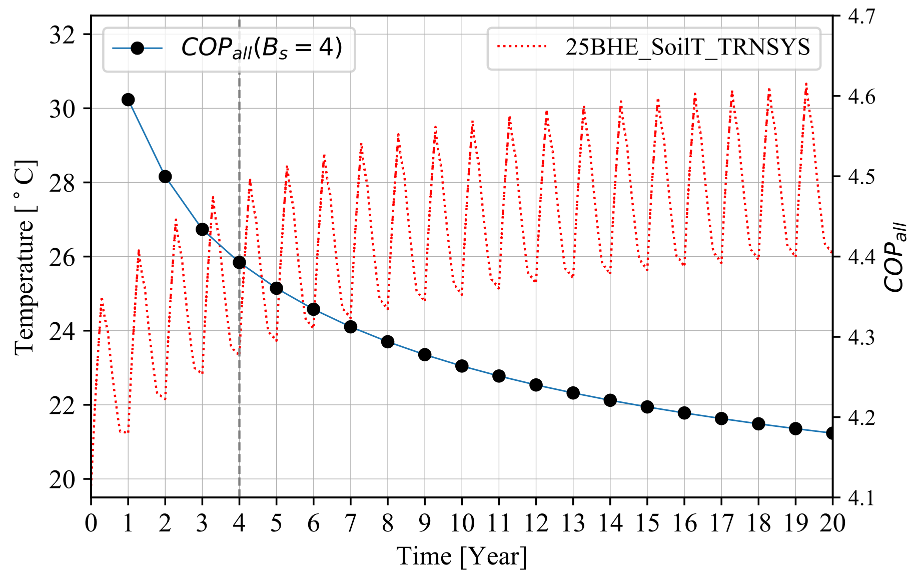

Figure 3: Variation of the average storage temperature predicted by TRNSYS over 20 years

In comparison to TRNSYS, the subsurface temperature is treated as discrete values by OGS-TESPy both in space and over time. Fig. 4 illustrates a clip view of soil temperature distribution in the subsurface at the end of the 20-th cooling season. A distinguishable heat accumulation can be found within and around the BHE array. It demonstrates that the 4.0 m BHE spacing will lead to severe heat accumulation over long-term operation. Furthermore, the temperature distribution along A-A' profile in Fig. 4 is illustrated in Fig. 5. It shows that the heat accumulation gradually enhances itself over the years, and this phenomenon can be observed in the TRNSYS result as well.

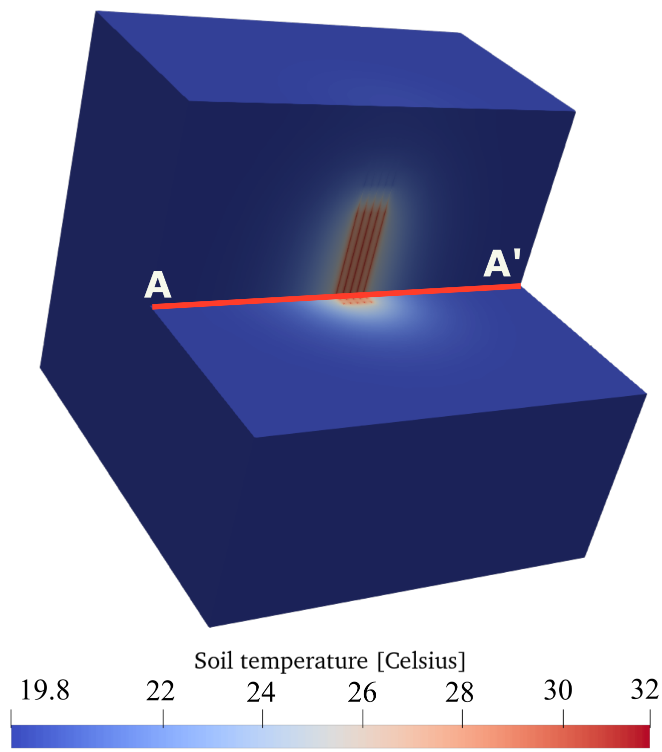

Figure 4: Soil temperature distribution at the end of the 20-th cooling season

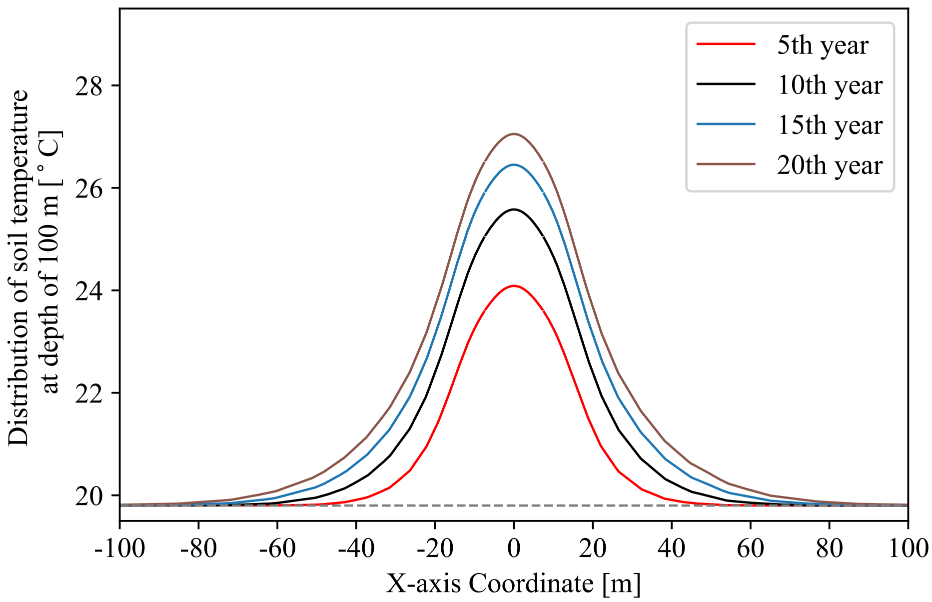

Figure 5: Soil temperature profile at the end of 5th, 10th, 15th, and 20th year, along $y = 108\,\mathrm{m}$ and the depth of 100m

Since the heat accumulation phenomena are confirmed by both OGS-TESPy and TRNSYS models, two additional scenarios were added, with the borehole spacing set to 4 m and 6 m respectively. The former setting was recommended by Zhang et al. [1] and the latter one is added to reveal the general impact of borehole spacing on the system efficiency. Fig. 6(a) shows the evolution of ground loop inlet and outlet temperatures simulated by TRNSYS, and the corresponding $\mathrm{COP_{all}}$ values (Fig. 6(b)). It can be found that with larger borehole spacing, the inlet and outlet temperatures will still increase over time (Fig. 6(a)), yet with a smaller magnitude. In the first year, the $\mathrm{COP_{all}}$ values of both scenarios are nearly the same. As with the increasing operation time, the $\mathrm{COP_{all}}$ values in both scenarios decrease, but at a different pace. Over 20 years, the $\mathrm{COP_{all}}$ value with larger borehole spacing of 6 m will have a decrease of 6.6 % (from 4.58 to 4.28), in comparison that the 4 m configuration suffers a bigger drop of 9.0 % (from 4.59 to 4.18). It should also be noticed that with 4 m spacing, the ground loop temperatures have exceeded 38 °C, indicating a potential risk of heat pump shut-down. Zhang et al. [1] concluded in their work that the 4 m spacing will produce an optimal $\mathrm{COP_{all}}$ value. However, their model was simulated for only one year period. In comparison, similar simulations over 20 years in this work indicate that 4 m spacing is no longer optimal. When the effect of heat accumulation and elevated ground loop temperature is considered, larger borehole spacing (e.g. 6 m) will lead to better system performance and also lower operational costs over time.

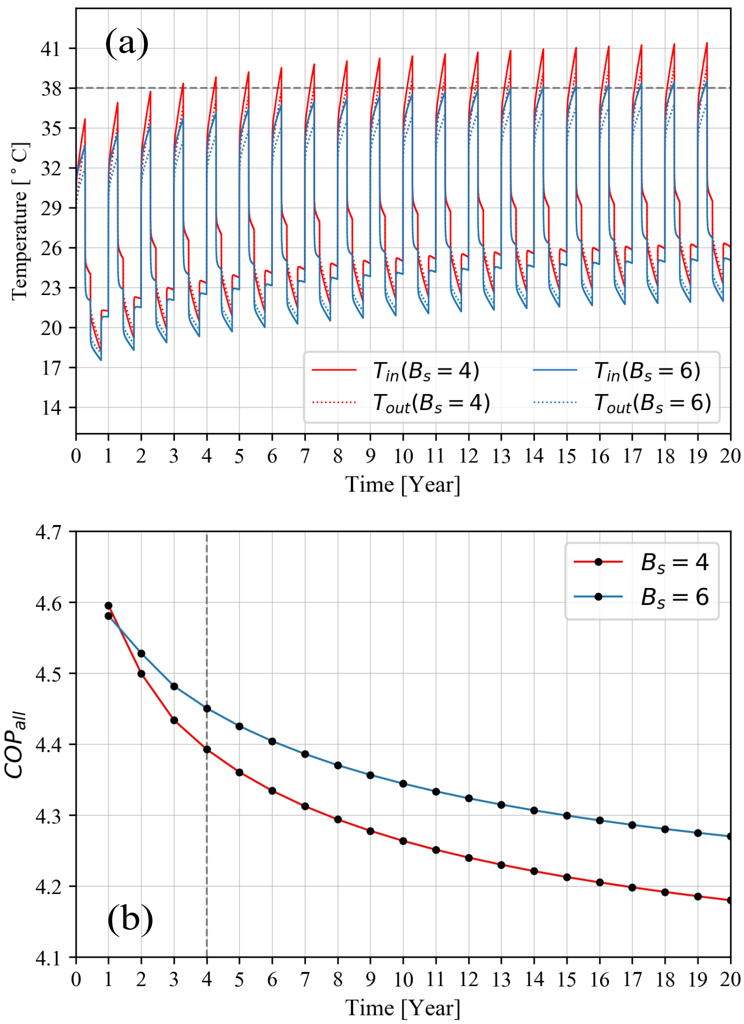

Figure 6: (a) Ground loop inlet and outlet temperature and (b) $\mathrm{COP_{all}}$ values simulated by TRNSYS with two different borehole spacing settings

5. Discussion

In a real-world project, the building thermal load does not equal the load on the ground loop. In the cooling scenario of GSHP projects, the electricity consumed by the heat pump will be added on top of the building cooling load and passed on to the ground loop. With the decrease in heat pump COP, the ground-loop thermal load will actually increase, because more electricity is consumed by the heat pump to move heat from the hot side to the cold side. This behavior can already be predicted by OGS-TESPy as in Hein et al. [2]. However, Zhang et al. [1] did not provide the performance curve of heat pump that was adopted in their simulation to calculate the heat pump COP. To make a fair comparison, it is decided to impose the same ground-loop thermal load in both the TRNSYS and OGS-TESPy models, and the interaction between building and ground-loop is neglected in this study.

Despite of this simplification, the heat accumulation in the subsurface and ascending trend in ground-loop circulation temperature are predicted by both models in a similar manner. This allows us to adopt the same performance curve as in Hein et al. [2] in this study to produce the resulting COP_{all} value in Fig. 3 and Fig. 6(b). Assuming that the dynamic shifting of the ground-loop thermal loop has to be considered, the subsurface temperature will drop even further, as more thermal load will be applied on the ground side, when the heat pump COP values are dropping. Overall, the assumption taken in the current simulations is conservative and it will not change the trend of COP over long-term operation.

6. Conclusion

In a recent article published in this journal [1], an optimal design method for the ground source heat pump system was presented considering both the hydraulic characteristics and soil thermal balance of the buried pipe network. The researchers concluded that an optimum COP_{all} value will be reached with the minimum borehole spacing, and higher spacing will bring lower COP_{all} after one year.

In this short communication, similar scenarios were simulated by both TRNSYS and OpenGeoSys-TESPy for 20 years. The temperature variation of buried pipe network calculated by two software is very similar, which verifies the accuracy of both simulation tools. The new results show that the predicted COP_{all} value with the 4.0 m spacing decreases from 4.59 after one year to 4.18 after 20 years, along with a ground-loop temperature rise from

24.93 °C to 30.61 °C over the same period. If the borehole spacing increase to 6.0 m, a similar trend is also predicted by the numerical modeling. Due to the smaller increase of ground-loop temperature and lower electricity consumption by the heat pumps, the larger borehole spacing of 6 m brings better COP_{all}, and thus should be recommended in the system design.

To answer the question raised in the introduction part, the circulation temperature in the ground loop, which is affected by the heat accumulation over the long term, is the most critical factor determining the performance of GSHP systems. As a result, the variation of long-term ground-loop temperature needs to be quantitatively evaluated in advance, and any optimization of GSHP system should be conducted over its entire life span.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Zhang, G. Gong, L. Zeng, Investigation for a novel optimization design method of ground source heat pump based on hydraulic characteristics of buried pipe network, Applied Thermal Engineering 182 (2021) 116069.

[2] P. Hein, O. Kolditz, U.-J. Görke, A. Bucher, H. Shao, A numerical study on the sustainability and efficiency of borehole heat exchanger coupled ground source heat pump systems, Applied Thermal Engineering 100 (2016) 421–433.

[3] Z. Liu, W. Xu, C. Qian, X. Chen, G. Jin, Investigation on the feasibility and performance of ground source heat pump (gshp) in three cities in cold climate zone, china, Renewable Energy 84 (2015) 89–96.

[4] J. Deng, Q. Wei, M. Liang, S. He, H. Zhang, Does heat pumps perform energy efficiently as we expected: Field tests and evaluations on various kinds of heat pump systems for space heating, Energy and Buildings 182 (2019) 172–186.

[5] Z. Liu, Y. Li, W. Xu, H. Yin, J. Gao, G. Jin, L. Lun, G. Jin, Performance and feasibility study of hybrid ground source heat pump system assisted with cooling tower for one office building based on one shanghai case, Energy 173 (2019) 28–37.

[6] G. Teza, A. Galgaro, M. De Carli, Long-term performance of an irregular shaped borehole heat exchanger system: Analysis of real pattern and regular grid approximation, Geothermics 43 (2012) 45–56.

[7] S. Chen, W. Cai, F. Witte, X. Wang, F. Wang, O. Kolditz, et al, Long-term thermal imbalance in large borehole heat exchangers array-a numerical study based on the leicester project, Energy and Buildings (2020) 110518.

[8] M. Beck, P. Bayer, M. de Paly, J. Hecht-Méndez, A. Zell, Geometric arrangement and operation mode adjustment in low-enthalpy geothermal borehole fields for heating, Energy 49 (2013) 434–443.

[9] W. Yang, Y. Chen, M. Shi, J. D. Spitler, Numerical investigation on the underground thermal imbalance of ground-coupled heat pump operated in cooling-dominated district, Applied Thermal Engineering 58 (2013) 626–637.

[10] J. Luo, H. Zhao, J. Jia, W. Xiang, J. Rohn, P. Blum, Study on operation management of borehole heat exchangers for a large-scale hybrid ground source heat pump system in china, Energy 123 (2017) 340–352.

[11] W. Li, X. Li, Y. Wang, J. Tu, An integrated predictive model of the long-term performance of ground source heat pump (gshp) systems, Energy and Buildings 159 (2018) 309–318.

[12] G. Hellström, Duct ground heat storage model, manual for computer code, Department of Mathematical Physics, University of Lund, Sweden (1989).

[13] M. A. Bernier, Ground-coupled heat pump system simulation/discussion, ASHRAE transactions 107 (2001) 605.

[14] D. Garber, R. Choudhary, K. Soga, Risk based lifetime costs assessment of a ground source heat pump (gshp) system design: Methodology and case study, Building and Environment 60 (2013) 66–80.

[15] S. Kavian, C. Aghanajafi, H. J. Mosleh, A. Nazari, A. Nazari, Exergy, economic and environmental evaluation of an optimized hybrid photovoltaic-geothermal heat pump system, Applied Energy 276 (2020) 115469.

[16] O. Kolditz, S. Bauer, L. Bilke, N. Böttcher, J.-O. Delfs, T. Fischer, et al, Opengeosys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (thm/c) processes in porous media, Environmental Earth Sciences 67 (2012) 589–599.

[17] F. Parisio, V. Vilarrasa, W. Wang, O. Kolditz, T. Nagel, The risks of long-term re-injection in supercritical geothermal systems, Nature communications 10 (2019) 1–11.

[18] J. Nordbeck, S. Bauer, A. Dahmke, J.-O. Delfs, H. Gomes, H. Hailemariam, C. Kinias, K. M. zu Beerentrup, T. Nagel, C. Smirr, et al., A modular cement-based subsurface heat storage: Performance test, model development and thermal impacts, Applied Energy 279 (2020) 115823.

[19] Y. Huang, H. Shao, E. Wieland, O. Kolditz, G. Kosakowski, Two-phase transport in a cemented waste package considering spatio-temporal evolution of chemical conditions, npj Materials Degradation 5 (2021) 1–14.

[20] R. Al-Khoury, T. Kölbel, R. Schramedei, Efficient numerical modeling of borehole heat exchangers, Computers & Geosciences 36 (2010) 1301–1315.

[21] H.-J. Diersch, D. Bauer, W. Heidemann, W. Rühaak, P. Schätzl, Finite element modeling of borehole heat exchanger systems: Part 1. fundamentals, Computers & Geosciences 37 (2011) 1122–1135. doi:10.1016/j.cageo.2010.08.003.

[22] H.-J. Diersch, D. Bauer, W. Heidemann, W. Rühaak, P. Schätzl, Finite element modeling of borehole heat exchanger systems: Part 2. numerical simulation, Computers & Geosciences 37 (2011) 1136–1147. doi:10.1016/j.cageo.2010.08.002.

[23] F. Witte, I. Tuschy, Tespy: Thermal engineering systems in python, Journal of Open Source Software 5 (2020) 2178.

[24] S. Chen, F. Witte, O. Kolditz, H. Shao, Shifted thermal extraction rates in large borehole heat exchanger array–a numerical experiment, Applied Thermal Engineering 167 (2020) 114750.

[25] W. Cai, F. Wang, S. Chen, C. Chen, J. Liu, J. Deng, O. Kolditz, H. Shao, Analysis of heat extraction performance and long-term sustainability for multiple deep borehole heat exchanger array: A project-based study, Applied Energy 289 (2021) 116590.

[26] C. Chen, W. Cai, D. Naumov, K. Tu, H. Zhou, Y. Zhang, O. Kolditz, H. Shao, Numerical investigation on the capacity and efficiency of a deep enhanced u-tube borehole heat exchanger system for building heating, Renewable Energy 169 (2021) 557–572.

[27] B. Meng, T. Vienken, O. Kolditz, H. Shao, Evaluating the thermal impacts and sustainability of intensive shallow geothermal utilization on a neighborhood scale: Lessons learned from a case study, Energy Conversion and Management 199 (2019) 111913.

[28] P. Hein, K. Zhu, A. Bucher, O. Kolditz, Z. Pang, H. Shao, Quantification of exploitable shallow geothermal energy by using borehole heat exchanger coupled ground source heat pump systems, Energy Conversion and Management 127 (2016) 80–89.

[29] M. A. Bernier, Closed-loop ground-coupled heat pump systems, Ashrae Journal 48 (2006) 12–25.