Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Analysis of influencing factors of thermal response test of deep borehole heat exchanger

Changlong Wang, Qiang Fu, Xin Wang

School of Civil Engineering and Architecture, Anhui University of Technology,

Ma'anshan, Anhui 243002, China

Keywords: Deep borehole heat exchanger (DBHE); Soil thermal conductivity; Volumetric heat capacity of soil; Thermal response test (TRT)

ABSTRACT

As a new kind of ground heat exchanger (GHE), deep borehole heat exchanger (DBHE) has a great potential to exploit medium-deep geothermal energy. Soil thermal properties are very important parameters for designing GHE, and they are normally measured by thermal response test (TRT). TRT of shallow GHE has been studied widely, however, there are only a few researches to study the TRT of DBHE. In this paper, TRT of DBHE is simulated based on a 3D numerical model, and the simulated TRT data are used to estimate the thermal conductivity and volumetric heat capacity of soil based on a parameter estimation method, and then the influences of different factors (including the test duration, soil thermal conductivity, volumetric heat capacity of soil, geothermal gradient, mass flow rate and heat output rate per depth) on the estimated soil thermal properties of TRT are studied. The results are follows: the TRT results of DBHE are greatly influenced by the test duration and heat output rate per depth, and are also influenced by the mass flow rate and geothermal gradient, and are slightly influenced by the soil thermal properties; longer test duration, higher heat output rate per depth, lower mass flow rate and lower geothermal gradient would improve the accuracy of the TRT results of DBHE. The results of this paper can offer some suggestions to improve the accuracy of TRT of DBHE.

1. INTRODUCTION

Ground-source heat pump (GSHP) is an important form of geothermal energy utilization [1]. GSHP normally uses ground heat exchanger (GHE) to extract geothermal energy, and traditional GHE usually has a depth of less than 200 m. Deep borehole heat exchanger (DBHE) is a new kind of GHE, which has a depth ranging from several hundred meters to several thousand meters [2]. DBHE can be used to efficiently exploit medium-deep geothermal energy, and GSHP using DBHE has much higher coefficient of performance than that using traditional GHE [3,4]. As key parameters for DBHE design, soil thermal properties are normally measured by thermal response test (TRT) [5].

There are lots of researches conducted on the TRT of shallow GHE [5,6], and the influencing factors of TRT are widely investigated [7]. Heat transfer model for TRT data evaluation is found to have a great influence on the estimated soil thermal properties, and it seems that the infinite line source (ILS) model has enough accuracy for parameter estimation based on TRT data [8,9], but more accurate heat transfer model can lead to more accurate parameter estimation [10-12]. Parameter estimation method can also influence the accuracy of TRT, and some researchers conducted sensitivity analysis of soil thermal properties and other unknown parameters on the GHE performance, and then proposed two-step or multi-step parameter estimation method based on the results of sensitivity analysis to further improve the estimation accuracy [11-14]. Measurement errors and calculation errors of TRT would lead to a theoretical error of 5% for soil thermal conductivity [15]. TRT data (including the first data point and test duration) used for parameter estimation can severely influence the estimation results of TRT, and it is suggested that the first 10-hour data should be ignored and that the test duration should be larger than 50 hours [8,16-20]. When there exists groundwater flow in the soil, the estimated soil thermal conductivity of TRT is probably much higher than the actual value, and the results of TRT are questionable if ignoring the groundwater flow [16,21]. Besides, other influencing factors of TRT include GHE length [16], borehole radius [18], grout thermal properties [18], GHE type [18] and different test conditions (including fluid velocity, fluid thermal properties and heat input rate etc.) [22,23].

Because there are only a few field tests conducted on DBHE [1], there exist a few researches on the TRT of DBHE [24-27]. For DBHE, the initial soil temperature probably varies greatly along the borehole, and geothermal gradient should be considered when establishing the heat transfer models of DBHE [25], and geothermal gradient has important influence on the TRT results of DBHE [24-27]. For higher geothermal gradient, the estimated soil thermal conductivity of TRT has a larger error when using the annular inlet configuration, and has a smaller error when using the center inlet configuration [24,25]. For longer DBHE length, the estimated soil thermal conductivity of TRT has a larger error when using the center inlet configuration, and has a smaller error when using the annular inlet configuration [24]. Errors of TRT for coaxial DBHE are larger than those for U-tube DBHE, and for coaxial DBHE, errors of TRT using the annular inlet configuration are smaller than those using the center inlet configuration [26], and it should be mentioned that DBHE normally uses the coaxial type. The soil thermal properties probably have a wide range along the borehole of DBHE, and multiple soil layers also have some influence on the TRT results [27].

There are only a few researches about the TRT of DBHE, which needs further detailed investigation. Based on TRT data of DBHE simulated by a 3D numerical model [28], this paper uses a semi-analytical heat transfer model and a parameter estimation method developed in our previous work [29,30] to estimate the soil thermal properties (including thermal conductivity and volumetric heat capacity), and makes detailed analysis on the influencing factors of the TRT of DBHE, including the test duration, starting time, soil thermal conductivity, volumetric heat capacity of soil, geothermal gradient, mass flow rate and heat output rate per depth.

2. SIMULATION OF TRT OF DBHE

The 3D numerical model developed and verified by the authors [28] is used to simulate the TRT of a DBHE shown in Fig. 1, and the default parameters of the DBHE are shown in Table 1. However, different from Ref. [28], this paper considers no groundwater flow, and sets the inlet of annular fluid as the mass flow rate boundary with the following temperature:

$$T_a = T_i - \frac{LQ_L}{Mc_f}, (z = 0, t > 0) \qquad (1)$$

where T_a is the temperature of annular fluid, ℃; T_i is the temperature of internal fluid, ℃; L is the DBHE length, m; Q_L is the heat output rate per depth, W m^{-1}; M is the mass flow rate, kg s^{-1}; c_f is the specific heat capacity of fluid, J kg^{-1} K^{-1}; z is the depth, m; t is the time, s. The 3D numerical model is based on FLUENT software to solve the mathematical equations of DBHE, and Eq. (1) can be applied to the boundary based on a User Defined Function of FLUENT software.

Table 1. Parameters of a DBHE.

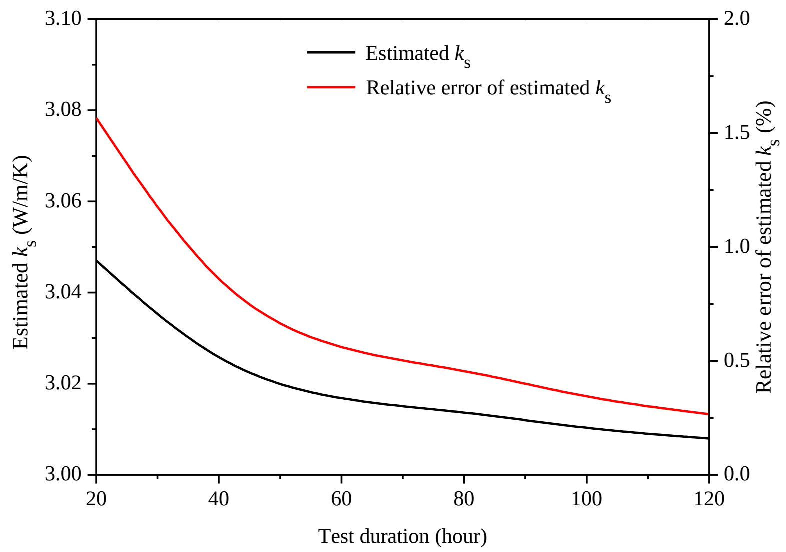
Parameter	Value
DBHE length L (m)	2000
Inner radius of internal pipe r_{ii} (m)	0.03766
Outer radius of internal pipe r_{io} (m)	0.045
Inner radius of external pipe r_{ei} (m)	0.08263
Outer radius of external pipe r_{eo} (m)	0.0885
Borehole radius r_b (m)	0.10
Fluid thermal conductivity k_f (W m^{-1} K^{-1})	0.59
Volumetric heat capacity of fluid $(\rho c)_f$ (J m^{-3} K^{-1})	4.19×10^6
Specific heat capacity of fluid c_f (J kg^{-1} K^{-1})	4197
Prandtl number of fluid Pr	8.11
Thermal conductivity of internal pipe k_{ip} (W m^{-1} K^{-1})	0.05
Volumetric heat capacity of internal pipe $(\rho c)_{ip}$ (J m^{-3} K^{-1})	1.8×10^6
Thermal conductivity of external pipe k_{ep} (W m^{-1} K^{-1})	10
Volumetric heat capacity of external pipe $(\rho c)_{ep}$ (J m^{-3} K^{-1})	1.8×10^6

Grout thermal conductivity k_g (W m^{-1} K^{-1})	0.73
Volumetric heat capacity of grout $(\rho c)_g$ (J m^{-3} K^{-1})	3.8×10^6
Soil thermal conductivity k_s (W m^{-1} K^{-1})	3.0
Volumetric heat capacity of soil $(\rho c)_s$ (J m^{-3} K^{-1})	2.0×10^6
Ground surface temperature T_{sur} (℃)	20
Geothermal gradient a (K m^{-1})	0.03
Mass flow rate of fluid M (kg s^{-1})	15
Heat output rate per depth Q_L (W m^{-1})	150

3. ANALYSIS OF THE INFLUENCING FACTORS OF THE TRT OF DBHE

Based on the above 3D numerical model, TRT of DBHE can be simulated. For actual TRT, the measured inlet and outlet fluid temperatures have some errors. Therefore, the simulated TRT data are added with an error of -0.1 K, which are then used as input data of parameter estimation method to estimate the thermal conductivity and volumetric heat capacity of soil. Then, different influencing factors (including the test duration, soil thermal conductivity, volumetric heat capacity of soil, geothermal gradient, mass flow rate and heat output rate per depth) of TRT can be investigated.

Fig. 2 shows the influences of test duration on the TRT results of DBHE. When the test duration increases, the relative errors of the estimated thermal conductivity and volumetric heat capacity of soil firstly decreases quickly and then decreases slowly. The relative error of estimated soil thermal conductivity is much smaller than that of estimated volumetric heat capacity of soil, which is caused by the fact that the DBHE performance is much more sensitive to the soil thermal conductivity than to the volumetric heat capacity of soil [30]. The results indicate that the test duration of TRT should be long enough to improve the precision of estimated soil thermal properties. Since the results of TRT for the test durations longer than 80 hours are accurate enough, the test duration is set as 80 hours in the following studies. It should be mentioned that the first 10-hour TRT data are ignored, and that the TRT data from 10 hours to the test duration are used to estimate the soil thermal properties.



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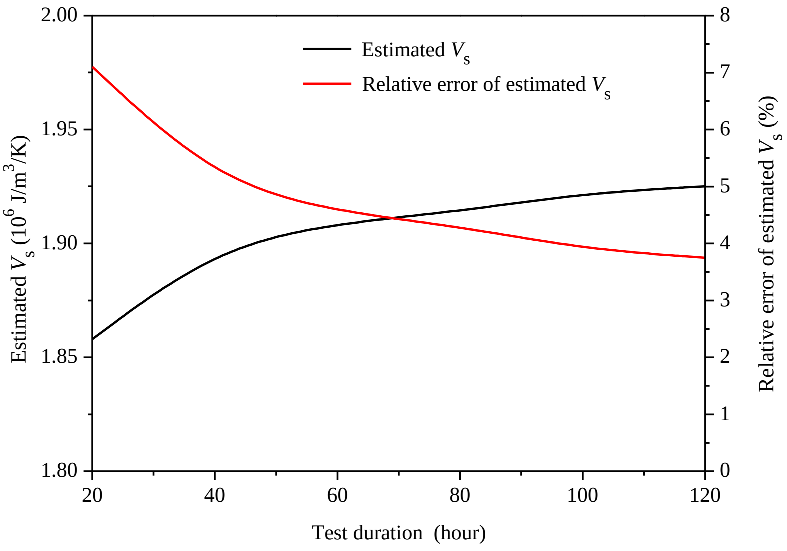

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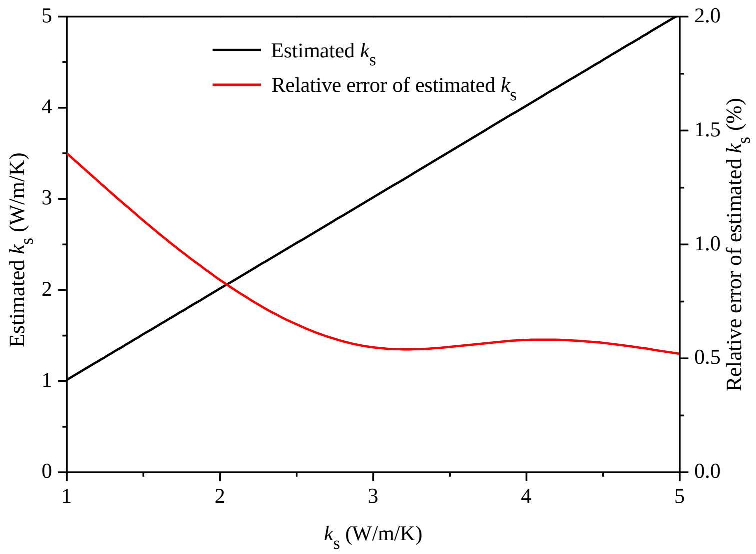
Fig. 2. Influences of test duration on the TRT results of DBHE. (a) estimated soil thermal conductivity; (b) estimated volumetric heat capacity of soil.

Fig. 3 shows the influences of soil thermal conductivity on the TRT results of DBHE. For higher soil thermal conductivity, the relative error of estimated soil thermal conductivity is basically a little smaller, and the relative error of estimated volumetric heat capacity of soil is basically unchanged. The results show that higher soil thermal conductivity can lead to a little higher accuracy of estimated soil thermal properties and has little influence on the estimated volumetric heat capacity of soil.



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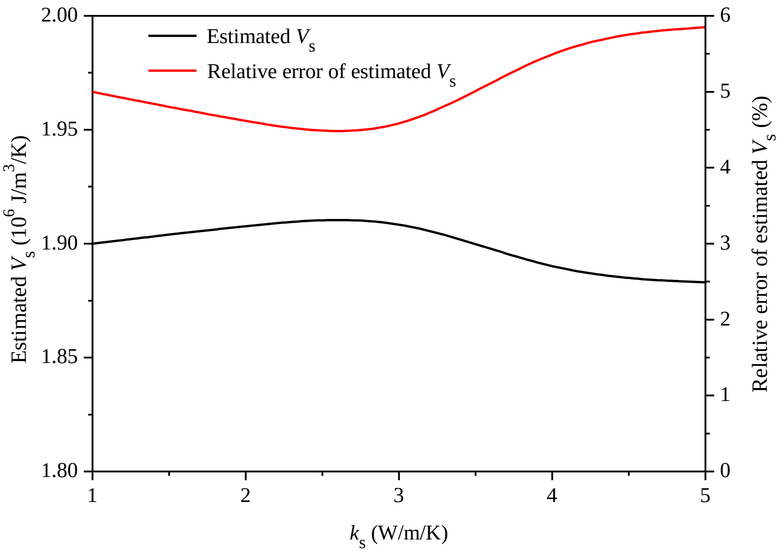

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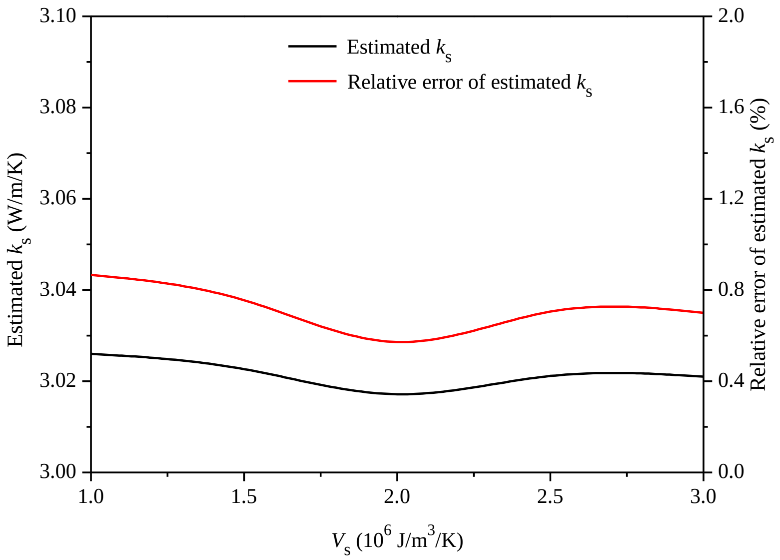
Fig. 3. Influences of soil thermal conductivity on the TRT results of DBHE. (a) estimated soil thermal conductivity; (b) estimated volumetric heat capacity of soil.

Fig. 4 shows the influences of volumetric heat capacity of soil on the results of TRT of DBHE. For higher volumetric heat capacity of soil, the estimated soil thermal conductivity is nearly unchanged, and the relative error of estimated volumetric heat capacity of soil is basically a little smaller. The results show that the volumetric heat capacity of soil only has little influence on the TRT results.



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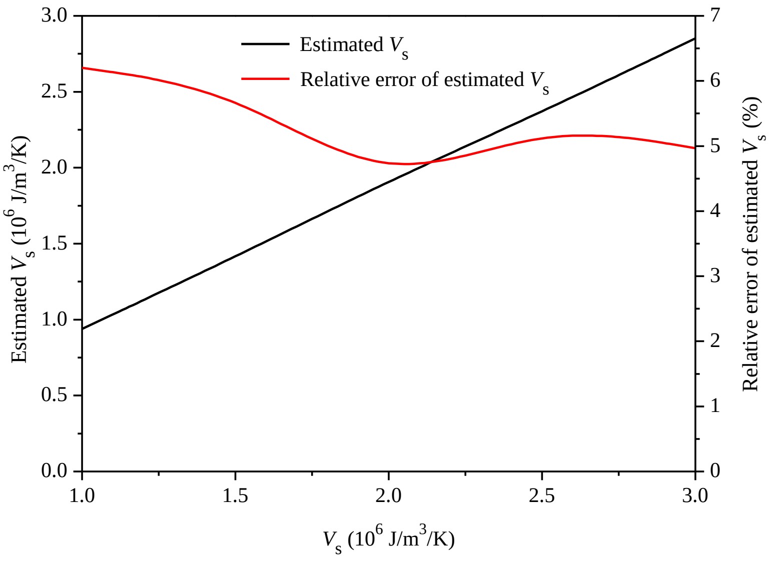

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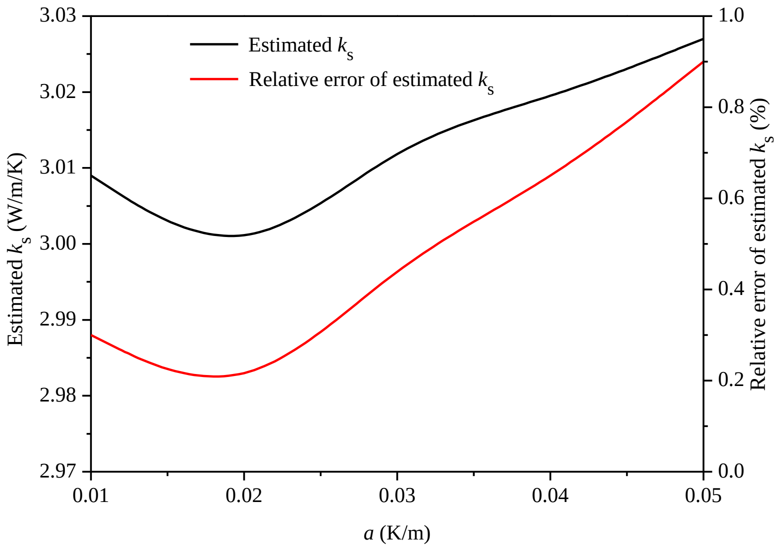
Fig. 4. Influences of volumetric heat capacity of soil on the TRT results of DBHE. (a) estimated soil thermal conductivity; (b) estimated volumetric heat capacity of soil.

Fig. 5 shows the influences of geothermal gradient on the TRT results of DBHE. Basically, for higher geothermal gradient, the relative error of estimated soil thermal conductivity is a little larger, and the relative error of estimated volumetric heat capacity of soil is larger, showing that higher geothermal gradient would lead to a little larger error of the TRT results.



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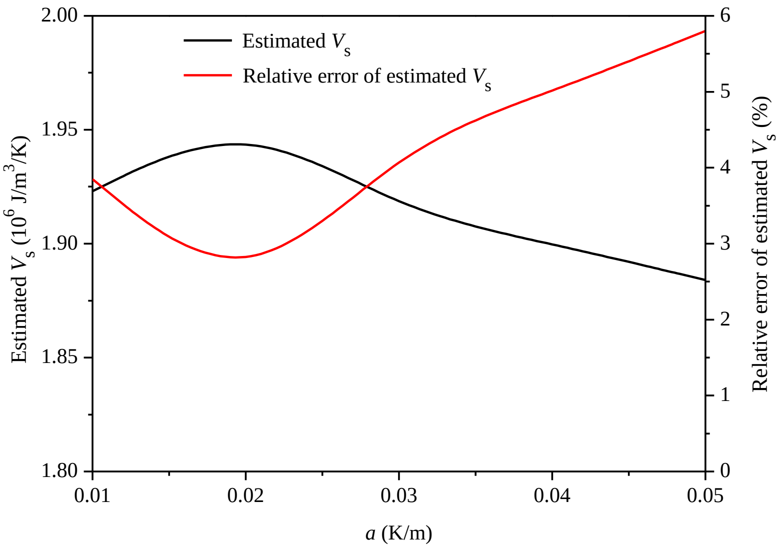

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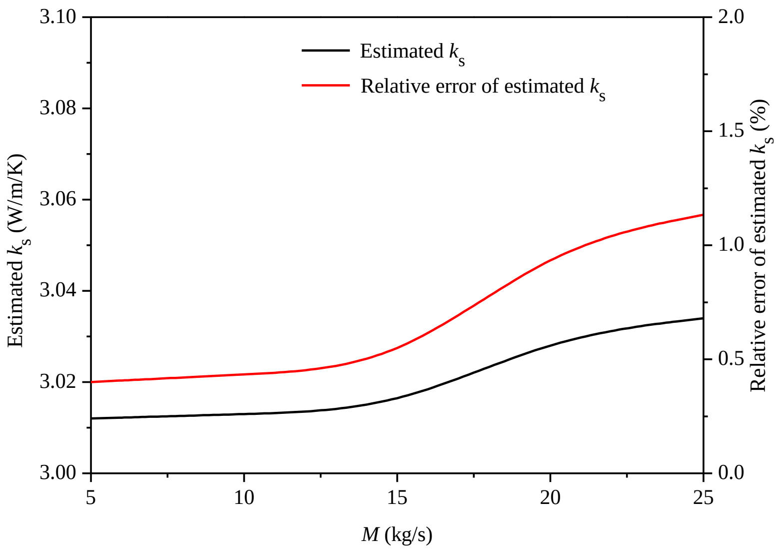
Fig. 5. Influences of geothermal gradient on the TRT results of DBHE. (a) estimated soil thermal conductivity; (b) estimated volumetric heat capacity of soil.

Fig. 6 shows the influences of mass flow rate on the TRT results of DBHE. For higher mass flow rate, the relative error of estimated soil thermal conductivity is a little larger, and the relative error of estimated volumetric heat capacity of soil is larger. It should be mentioned that the heat output rate per depth is kept constant, which means smaller temperature difference between the outlet and inlet fluids for higher mass flow rate. The results show that the mass flow rate has some influence on the TRT results, and that lower mass flow rate can improve the accuracy of the TRT results.



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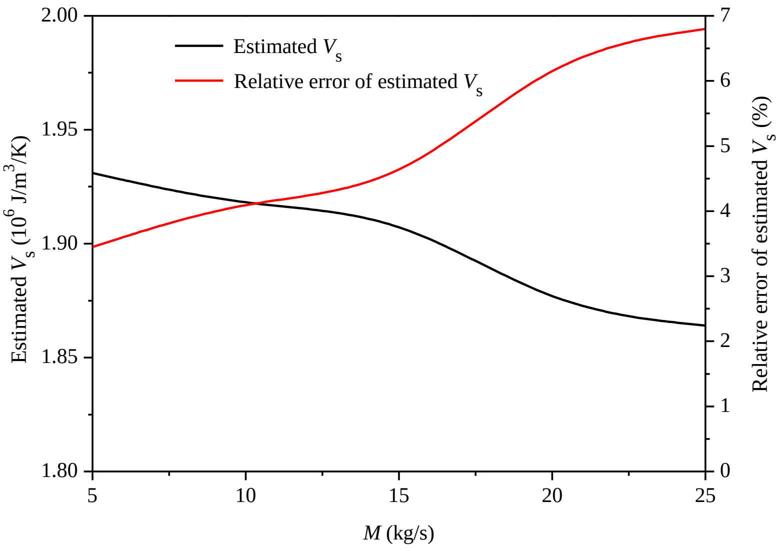
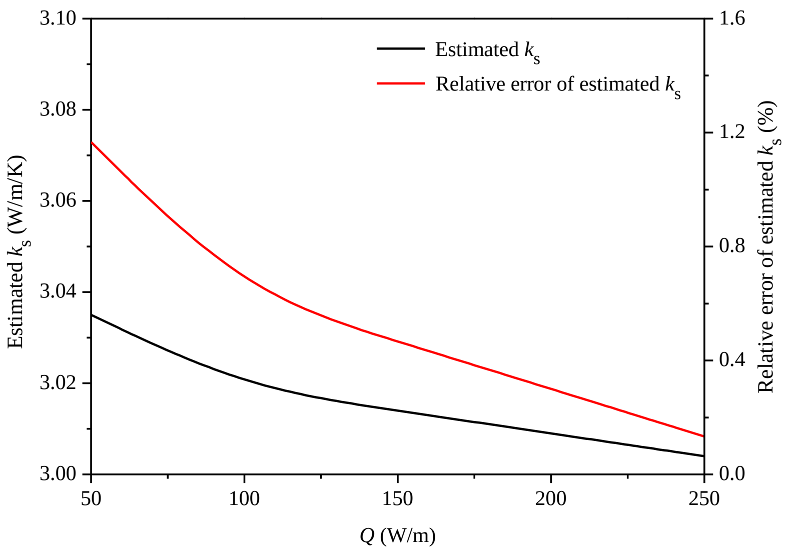


(b)

Fig. 6. Influences of mass flow rate on the TRT results of DBHE. (a) estimated soil thermal conductivity; (b) estimated volumetric heat capacity of soil.

Fig. 7 shows the influences of heat output rate per depth on the TRT results of DBHE. For higher heat output rate per depth, the relative error of estimated soil thermal conductivity is a little smaller, and the relative error of estimated volumetric heat capacity of soil is much smaller, which are explained as follows: higher heat output rate per depth means larger fluid temperature variance, which can reduce the influence of temperature measurement error. The results indicate that heat output rate per depth has a great influence on the TRT results, and that higher heat output rate per depth can improve the accuracy of TRT results.



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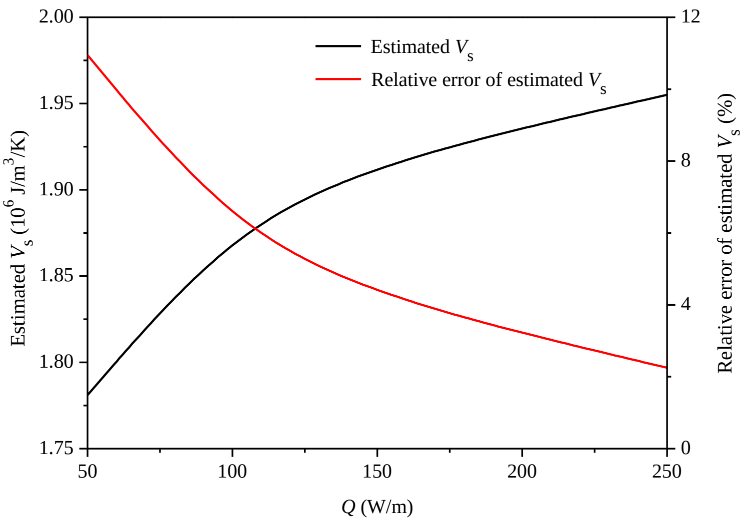

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Fig. 7. Influences of heat output rate per depth on the TRT results of DBHE. (a) estimated soil thermal conductivity; (b) estimated volumetric heat capacity of soil.

To sum up, the TRT results of DBHE are greatly influenced by the test duration and heat output rate per depth, and are also influenced by the mass flow rate and geothermal gradient, and are slightly influenced by the thermal conductivity and volumetric heat capacity of soil.

4. CONCLUSIONS

In this paper, a 3D numerical model is used to simulate the TRT of DBHE, a semi-analytical heat transfer model and a parameter estimation method are used to estimate the thermal conductivity and volumetric heat capacity of soil based on the simulated TRT data, and then detailed analysis are made on the influencing factors of the TRT of DBHE. The conclusions are summarized as follows:

(1) Both the test duration and heat output rate per depth have a great influence on the TRT results of DBHE, and longer test duration and higher heat output rate per depth would improve the accuracy of soil thermal properties estimated by TRT.

(2) Both the mass flow rate and geothermal gradient have some influence on the TRT results of DBHE. For higher mass flow rate or geothermal gradient, the relative error of estimated soil thermal conductivity is a little larger, and the relative error of estimated volumetric heat capacity of soil is larger.

(3) The thermal conductivity and volumetric heat capacity of soil only have slight influence on the TRT results of DBHE.

The results of this paper can offer some suggestions to improve the accuracy of TRT of DBHE.

ACKNOWLEDGMENTS

The authors would like to thank the Natural Science Foundation of Anhui Province (Grant No. 1808085QE178) for the financial support.

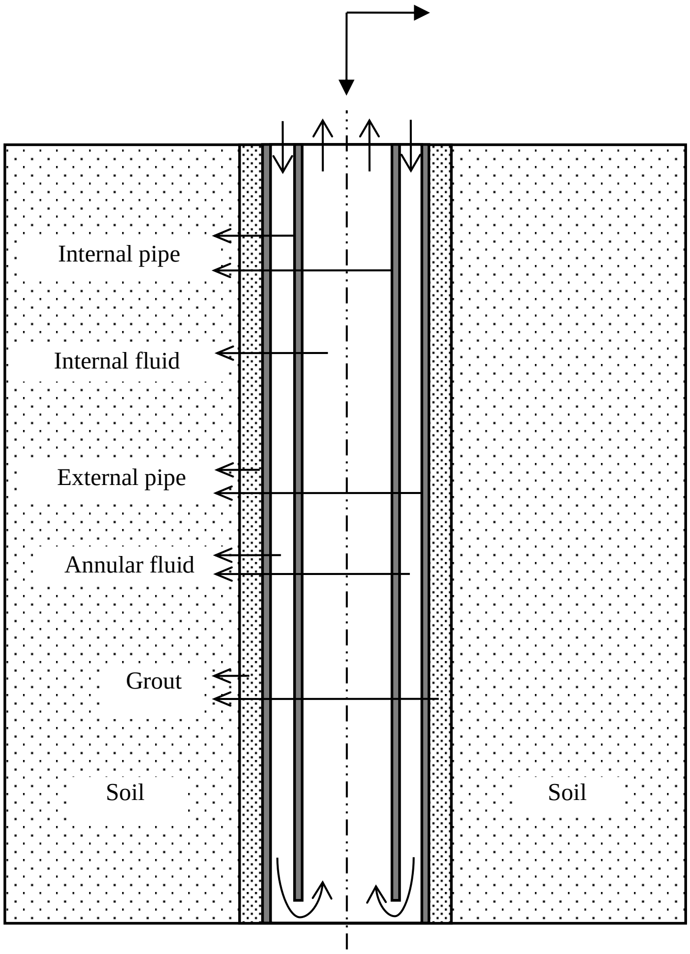

Fig. 1. Schematic diagram of a DBHE [28].

REFERENCES

[1] Lund, J.W., and Toth, A.N.: Direct utilization of geothermal energy 2020 worldwide review, *Geothermics*, **90**, (2021), 101915.

[2] Sapinska-Sliwa, A., and Rosen, M.A.: Deep borehole heat exchangers — A conceptual and comparative review, *Int. J. Air-Cond. Refri*, **24**, (2016), 1630001.

[3] Wang, Z., and Wang, F.: Field test and numerical investigation on the heat transfer characteristics and optimal design of the heat exchangers of a deep borehole ground source heat pump system, *Energy Convers. Manage*, **153**, (2017), 603-615.

[4] Nian, Y.L., and Cheng, W.L.: Evaluation of geothermal heating from abandoned oil wells, *Energy*, **142**, (2018), 592-607.

[5] Zhang, C., and Guo, Z.: A review on thermal response test of ground-coupled heat pump systems, *Renew. Sustain. Energy Rev*, **40**, (2014), 851-867.

[6] Wilke, S., and Menberg, K.: Advanced thermal response tests: A review, *Renew. Sustain. Energy Rev*, **119**, (2020), 109575.

[7] Zhang, X., and Han, Z.: Thermal response tests for the identification of soil thermal parameters: A review, *Renew. Energy*, **173**, (2021), 1123-1135.

[8] Gehlin, S.E.A., and Hellström, G.: Comparison of four models for thermal response test evaluation, *ASHRAE Trans*, **109**, (2003), 131-142.

[9] Lamarche, L.: Short-term behavior of classical analytic solutions for the design of ground-source heat pumps, *Renew. Energy*, **57**, (2013), 171-180.

[10] Zhang, L.F., and Zhang, Q.: A p(t)-linear average method to estimate the thermal parameters of the borehole heat exchangers for in situ thermal response test, *Appl. Energy*, **131**, (2014), 211-221.

[11] Bozzoli, F., and Pagliarini, G.: Estimation of soil and grout thermal properties through a TSPEP (two-step parameter

estimation procedure) applied to TRT (thermal response test) data, *Renew. Energy*, **36**, (2011), 839-846.

[12] Li, M., and Zhang, L.: Step-wise algorithm for estimating multi-parameter of the ground and geothermal heat exchangers from thermal response test, *Renew. Energy*, **150**, (2020), 435-442.

[13] Nian, Y.L., and Wang, X.Y.: Estimation of ground thermal properties for coaxial BHE through distributed thermal response test, *Renew. Energy*, **152**, (2020), 1209-1219.

[14] Zhang, C., and Xu, H.: The coupled two-step parameter estimation procedure for borehole thermal resistance in thermal response test, *Renew. Energy*, **154**, (2020), 672-683.

[15] Witte, H.J.L.: Error analysis of thermal response tests, *Applied Energy*, **109**, (2013), 302-311.

[16] Signorelli, S., and Bassetti, S.: Numerical evaluation of thermal response tests, *Geothermics*, **36**, (2007), 141-166.

[17] Beier, R.A.: Analysis of thermal response tests on boreholes with controlled inlet temperature versus controlled heat input rate, *Geothermics*, **94**, (2021), 102099.

[18] Cai, Y., And Xu, H.: Testing and analysis of the influence factors for the ground thermal parameters, *Applied Thermal Engineering*, **107**, (2016), 662–671.

[19] Urchueguía, J.F., and Lemus-Zúñiga, L.G.: How reliable are standard thermal response tests? An assessment based on long-term thermal response tests under different operational conditions, *Energies*, **11**, (2018), 3347.

[20] Wei, A., and Gu, K.: Experimental investigation on the influencing factors of the thermal response test using actively heated fiber optics, *IOP Conference Series: Earth and Environmental Science*, **861**, (2021), 062103.

[21] Tiwari, A.K., and Basu, P.: Interpretation of TRT data in the presence of natural convection and groundwater flow in saturated ground, *Computers and Geotechnics*, **140**, (2021), 104426.

[22] Zhang, X., and Zhang, T.: A new correcting algorithm for thermal response test data evaluation, Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019), *Environmental Science and Engineering*.

[23] Han, Z., And Zhang, X.: Study on the influence factors of short-time thermal response test based on artificial neural network, *Geothermics*, **95**, (2021), 102171.

[24] Morchio, S., and Fossa, M.: On the ground thermal conductivity estimation with coaxial borehole heat exchangers according to different undisturbed ground temperature profiles, *Applied Thermal Engineering*, **173**, (2020), 115198.

[25] Beier, R.A.: Thermal response tests on deep borehole heat exchangers with geothermal gradient, *Applied Thermal Engineering*, **178**, (2020), 115447.

[26] Morchio, S., and Fossa, M.: Study on the best heat transfer rate in thermal response test experiments with coaxial and U-pipe borehole heat exchangers, *Applied Thermal Engineering*, **200**, (2022), 117621.

[27] Beier, R.A., and Fossa, M.: Models of thermal response tests on deep coaxial borehole heat exchangers through multiple ground layers, *Applied Thermal Engineering*, **184**, (2021), 116241.

[28] Wang, C., and Wang, X.: A semi-analytical heat transfer model for deep borehole heat exchanger considering groundwater seepage, *International Journal of Thermal Sciences*, **175**, (2022), 107465.

[29] Wang, C., and Lu, Y.: A semi-analytical model for heat transfer in coaxial borehole heat exchangers, *Geothermics*, **89**, (2021), 101952.

[30] Wang, C., and Fang, H.: A two-step parameter estimation method for estimating soil thermal properties of coaxial ground heat exchangers, *Geothermics*, **96**, (2021), 102229.