A TRNSYS-Based Thermal Response Test Parameter Estimation Method

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***Abstract*—Thermal Response Test (TRT) has become a very popular method of estimating ground thermal properties for ground-coupled heat pump systems. This technique relies on the fact that required best-fit parameters can be identified by inverse modeling of heat transfer equations with the help of optimization algorithms. In this paper, a TRNSYS-based model that can automatically realize TRT parameter estimation is proposed and validated. Besides, the method is applied to a case study, and different optimization algorithms are employed and analyzed. Finally, the results calculated by the TRNSYS-based method and that of conventional methods are compared. It shows that the deviations of the estimated parameters between different models are obvious, which should be paid great attention by researchers and engineers.**

***Index Terms*—Ground Heat Exchanger (GHE), TRNSYS, parameter estimation, optimization algorithm**

I. Introduction

Over the past few decades, Ground-Coupled Heat Pump (GCHP) systems have received increasing attention throughout the world. These systems have been installed for space heating and cooling in various buildings, as well as for some other special applications such as water heating, crop drying, agricultural greenhouses, due to their obvious advantages of high efficiency, low maintenance cost and environmental friendliness. As an essential part of a GHCP system, Ground Heat Exchangers (GHEs) are mostly responsible for the high initial cost and affect the operating performance of the entire system. For the design and analysis of GHEs, accurate and reliable thermal properties of the ground at the vicinity of borehole field must be obtained when sizing the exchanger and deciding the number of boreholes. Thermal Response Test (TRT) is one of such technologies to determine ground thermal properties. In this paper, a TRNSYS-based model that can serve for TRT parameter estimation is introduced, and different optimization algorithms used for searching best-fit parameter sets are compared, and finally, the difference between the proposed method and conventional method is analyzed, which provides reference for practical engineering applications.

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II. Thermal Response Test Parameter Estimation

Nowadays TRT becomes a routine method to determine required parameters for large BHE design. During a conventional TRT [1], a defined thermal load is applied to a pilot borehole by circulating heat carrier fluid through tubing and the inlet and outlet temperatures are continuously measured and recorded. This approach is virtually to simulate a real GCHP system and, more details of this approach including test equipment development and modeling approaches can be found in reference [2]. The temperature response serves as an indicator of the thermal behavior of the ground in future time. The test provides a better understanding of geothermal properties, including undisturbed ground temperature, effective ground thermal conductivity, thermal diffusivity and borehole thermal resistance, etc. In some cases, the test is also suitable for evaluating grout materials or groundwater movements.

In the data evaluation process, inverse modeling approach is adopted for parameter identification. A number of mathematical models for GHE in TRT have been reported, most of which were based on either analytical approaches or numerical methods. For analytical ones, Infinite Line Source model (ILS), was first introduced to simulate heat transfer of BHE by Ingersoll [3], and then their findings were further enhanced to apply the model to estimate the ground thermal properties by Mogensen [4]. Another significant contribution is Infinite Cylindrical Source model (ICS), which is solved by Ingersoll [5]. Subsequent analytical models are more or less derived from these two most widely used models. A few models were developed based the combination of analytical and numerical solutions, such as Eskilson's model [6]. However, they are seldom applied in the field of TRT data evaluation and parameter estimation field owing much to failure to capture short period thermal response. There is also a bulk of numerical models capable of improving the interpretation of TRT, and more reference can be found in [2]. Due to

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their complexity and time consuming characters, these numerical models are used exclusively in research settings, except for a well-known duct storage system model (DST).

DST was proposed by Hellstrom [7] and then packed into TRNSYS software and included in the geothermal heat pump library. In TRT, Witte *et al.* [8] first adopted DST to calculate borehole thermal response. In their simulation, type557a was used and a number of parameters concerning borehole geometry and configuration are required to compute borehole thermal resistance. The estimated parameters were thermal conductivities of soil and grout λs and λg. Based on DST, Zhang *et al.* [9] presented a simulation-optimization approach for determining optimal thermal conductivity λs and heat capacity cs of soil. Both of the above simulations were employing Hooke-Jeeves algorithm (HJ). Unlike their models, a TRNSYS component type557b with thermal resistance known will be applied in this paper. This type doesn't need so many input parameters like thermal properties of grout and buried pipes, and it can be used to obtain best-fit thermal conductivity of soil λs and thermal resistance of borehole Rb. The parameter set λs and Rb is also what common TRT interpretation will give. Moreover, different algorithms such as Simplex Method (SM), Coordinate Search Method (CSM), and Particle Swarm Optimization Method (PSOM) are introduced and compared.

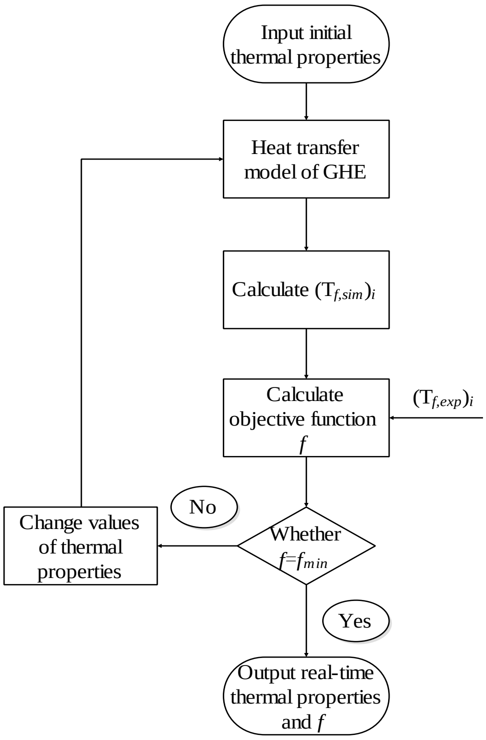

Figure 1. Schematic diagram of the proposed model employing optimization algorithm

Fig. 1 shows the schematic diagram of the proposed model employing optimization algorithm. Modelling approach specifies the Root Mean Square Error (RMSE) of measured mean fluid temperature and that of simulated data as objective function; the optimization algorithm will keep changing the values of estimated parameters until it finds the optimal one subject to specified tolerance.

$$f = \sqrt{\frac{\sum_{i=1}^{n}[(T_{f,sim})_i - (T_{f,\exp})_i]^2}{n}}$$

$(T_{f,sim})_i$: Calculated fluid temperature, ℃;
$(T_{f,exp})_i$: Experimental fluid temperature, ℃ ;
n: Number of sets of data.

This parameter estimation utilizes an existing TRT data set, collected from open literature [10]. The GHE used for the test have a standard configuration, with a single U-pipe of 0.034m in diameter inserted in a borehole with a diameter of 0.152m. The piping of the GHE is installed to a depth of 140m, and the average undisturbed subsurface temperature, measured with a vertical temperature profile, was equal to 7.5 ℃. The first 168.03 hours data, with a heat injection rate of 66.49 (W/m), are selected. Besides, to exclude the influence of unsteady heat transfer at the beginning of the test, only 1860 data sets from 13h to 168h are applied to conduct parameter estimation.

III. Modeling Approach

A. *TRNSYS Component Introduction*

Apart from the standard utility components of the program, the following standard TRNSYS component models (Types) were employed in the simulation:

- Type557b, Vertical ground heat exchanger
- Type583, TRNOPT Optimization Program
- Type55, Periodic integrator
- Type9, Data Reader

Type557 is one of the most important models in GHP library of TRNSYS. This subroutine models a vertical heat exchanger that interacts thermally with the ground. This GHE model is most commonly used in GCHP applications.

Type583, this component will launch the TRNOPT optimization program. Ii is a stand-alone utility that can optimize any TRNSYS input file. This subprogram links TRNSYS with a packed generic optimization program GenOpt. GenOpt package comes with its own optimization algorithms, while the following ones are suitable for multiple continuous variables:

- Simplex Method (SM)
- Coordinate Search Method (CSM)
- Hooke-Jeeves Method (HJM)
- Particle Swarm Optimization with Inertia Weight Method (PSOIWM)
- Particle Swarm Optimization with Constriction Coefficient Method (PSOCCM)
- Particle Swarm Optimization Restricted to Mesh Method (PSORMM)

Type55, during a transient simulation, it is often desirable to know some basic statistics of an input over a specified time range. This component will calculate the integral of the input with respect to time or alternatively, the sum of the input over the specified time range.

Type9, this component serves the purpose of reading data at regular time intervals from a data file, converting it to a desired system of units, and making it available to other TRNSYS components as time-varying forcing functions. This component is very general in nature and can read many different types of files. In this case, it is mainly used to read experimental data of TRT from a user-defined external txt format file.

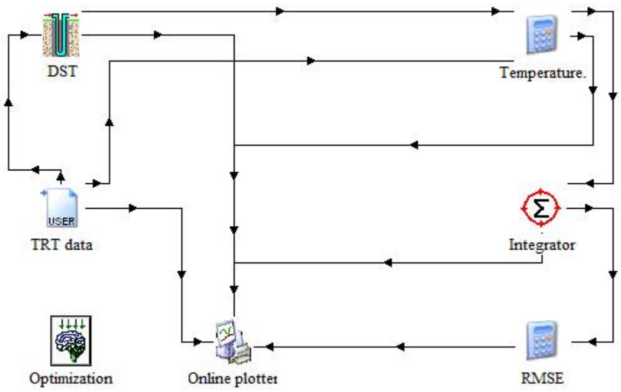

Figure 2. Layout of the proposed TRNSYS-based parameter estimation model

The layout of the proposed model is shown in Fig. 2. Using this model, auto automatic optimum searching that specifies RMSE of simulated and experimental mean fluid temperature as objective function can be realized.

B. *Parameter Settings*

In this model, the following assumptions are made:

- Ground is regarded as an infinite medium distributed homogeneously and isotropically.
- Initial surface temperature is assumed to be well-distributed without thermal gradient.
- No insulation measures are taken around the storage volume, that is to say, none of the surfaces of the cylindrical storage volume are covered with thermal insulation.
- The ground keeps the initial state before the simulation starts, thus no preheating calculations are needed.
- And, no groundwater exists at the vicinity of the borehole.

TABLE I. MAIN PARAMETERS OF TYPE557B

Parameter No.	Description	Unit	Value
1	Borehole depth	m	140
2	Header depth	m	0
3	Borehole radius	mm	76
4	Soil heat capacity	$kJ/m^3/K$	2250
5	Fluid specific heat	kJ/kg/K	4.2
6	Fluid density	kg/m^3	1000
7	Initial surface temperature	℃	7.5
8	Initial thermal gradient	--	0
9	Number of ground layers	--	1
10	Average air temperature	℃	-1.84
11	Inlet flowrate	kg/s	0.434

As DST model (Type557b) is the most important part in this simulation, so the values of parameters and inputs are set in strict accordance with that of a real TRT, as shown in Table I. When simulation is called upon, thermal conductivity of soil and thermal resistance of borehole will be regarded as unknown parameters, and the initial values are κ_s=4W/m/K and R_b=0.001K•m/W; meanwhile, optimization range is [1, 5] and [1e-4, 1], respectively. Other parameters concerning optimization algorithm keep default value except for PSOM, where the particles and generations are set to 10 and 200, respectively.

IV. SIMULATION RESULTS AND DISCUSSION

A. *Parameter Estimation Results*

At the beginning, a simulation using HJM was conducted to see whether the proposed method can find an optimal parameter set for TRT. As Fig. 3 shown, the difference between simulated temperature and experimental data is rather small, around ±0.2℃ except for the first 8 evaluation hours. The final RMSE is as small as 0.115. The result shows that the proposed model can successfully realized parameter estimation and obtain required ground thermal properties.

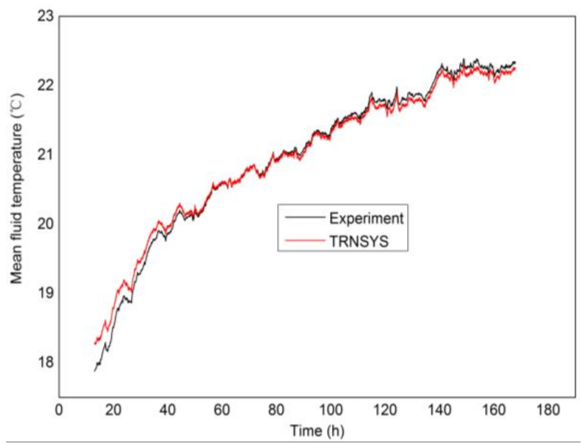

Figure 3. Comparison of simulated mean fluid temperature corresponding to optimal parameter set and experimental data

B. *Comparison of Different Optimization Algorithms*

It is known that generalized pattern search algorithms (the Nelder and Mead's Simplex, the Hooke-Jeeves and the coordinate search algorithm), which can be run using multiple starting points. Besides, particle swarm optimization algorithms, with inertia weight or constriction coefficient, and with a modification that constricts the continuous independent variables to a mesh to reduce computation time, are also capable of dealing with optimization problem for continuous variables. Seen from Table II, we can see that all the algorithms have the ability to find an optimal parameter set. Generalized pattern search algorithms are faster than PSOMs, however, the accuracy is less satisfactory. The best one is the modified PSORMM, which has higher accuracy and faster convergence rate. The best-fit parameter set for this TRT parameter estimation process is R_b=0.020K•m/W and κ_s=3.85W/m/K, which will be further used in the next section.

TABLE II. Comparison of Different Optimization Algorithms

Algorithm	Fits	SSE	R_b^*	κ_s
SM	272	23.93	0.0038	3.94
CSM	33	24.69	0.0039	3.99
HJM	38	24.66	0.0039	3.99
PSOIWM	1904	25.53	0.0055	4.07
PSOCCM	1916	23.08	0.0025	3.87
PSORMM	152	23.06	0.0020	3.85

C. Comparison of Parameter Estimation Results

Usually, the purpose of a TRT is to provide design parameters into software or some design method, mainly including soil thermal conductivity and borehole thermal resistance. The basic heat transfer models should be the same both in the test analysis and the design process. Otherwise, calculation deviations may occur due to different assumptions, initial and boundary conditions of different models. To prove it, ILS and ICS are used to conduct TRT parameter estimation according to the same experimental data mentioned above, the best-fit parameter sets compared with the TRNSYS-based model are given in Table III.

TABLE III. Comparison of TRT Parameter Estimation Results Using Different Models

Algorithm	SSE	R_b	κ_s
ILS	18.43	0.0685	2.94
ICS	18.97	0.0642	2.87
TRNSYS	23.06	0.0020	3.85

Although the SSEs are similar, the best-fit parameter set determined by the TRNSYS-based model using Type557b and that by conventional analytical ILS and ICS models do vary significantly. This presents important implications for design calculations that the approach should be consistent with the test analysis in order to eliminate these avoidable calculation errors.

V. Conclusion

A TRNSYS-based TRT parameter estimation method is proposed in this paper. It can realize automatic optimization searching with the help of GenOpt package embedded in the software. Different from previous work, this model utilizes type557b component to do the simulation. It is proved that the proposed model is successful in the TRT data interpretation and parameter estimation. Moreover, different optimization algorithms suitable for searching best-fit parameter set are compared; a modified PSORMM with high accuracy and faster speed is demonstrated to be better than generalized pattern searching algorithms. By applying the proposed method and conventional methods to the same TRT data, the authors find that parameter estimation results can vary significantly because of the discrepancies in assumptions, initial and boundary conditions between different heat transfer models.

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References

[1] W. A. Austin III, "Development of an in-situ system for measuring ground thermal properties," MS thesis, Oklahoma State University, Oklahoma State, USA, 1998.

[2] C. Zhang, Z. Guo, Y. Liu, X. Cong, and D. Peng, "A review on thermal response test of ground-coupled heat pump systems," *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 851-867, 2014.

[3] L. R. Ingersoll and H. J. Plass, "Theory of the ground pipe heat source for the heat pump," *Heating, Piping and Air conditioning*, vol. 20, pp. 119-122, 1948.

[4] P. Mogensen, "Fluid to duct wall heat transfer in duct system heat storages," in *Proc. International Conference on Subsurface Heat Storage in Theory and Practice*, Swedish Council for Building Research, 1983.

[5] L. R. Ingersoll, O. J. Zobel, and A. C. Ingersoll, *Heat Conduction with Engineering Geological and Other Applications*, New York: Mc Graw-Hill, 1954.

[6] P. Eskilson, "Thermal analysis of heat extraction boreholes," PhD dissertation, University of Lund, Lund, Sweden, 1987.

[7] D. Pahud and G. Hellstrom, "The new duct ground heat model for TRNSYS," in *Proc. Eurotherm Seminar 49*, Eindhoven, 1996, pp. 127-136.

[8] H. J. L. Witte, "Advances in geothermal response testing," *Thermal Energy Storage for Sustainable Energy Consumption*, *NATO Science Series*, vol. 234, pp. 177-192, 2007.

[9] C. Zhang, *et al.*, "Determination method for rock-soil thermal properties based on system optimization," *J. Zhejiang Univ. (Eng. Sci.)*, vol. 46, no. 12, pp. 2237-2242, 2012.

[10] J. Raymond, *et al.*, "A review of thermal response test analysis using pumping test concepts," *Ground Water*, vol. 49, no. 6, pp. 932-945, 2011.

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