THE ANALYSIS ON TECHNOLOGY AND METHOD OF GROUND THERMAL PROPERTY TEST

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Abstract: The ground thermal response test（TRT）is the major method to obtain the ground thermal properties before the design of ground coupled heat pump (GCHP). The reliability of the TRT results has a significant influence on the initial cost and operation stability. An analysis for the current conventional method to determine the soil thermal properties was made. Based on the probabilistic theory, a new analytical method to determine the uncertainty of ground thermal properties has been developed. The test data were counted and analyzed and a series of new data were produced by statistical method. On the basis of these new data, the ground thermal properties can be calculated, counted and analyzed and the results range, average value and standard deviation were obtained using this method. The sensitivity of the results of ground thermal properties was also investigated. The method improves the reliability of the results of TRT and can give more effective guidance for the design of GCHP system.

Keywords: Thermal response test; Ground coupled heat pump; Ground thermal properties; Uncertainty method

1 INTRODUCTION

The parameters of the ground thermal properties are the most important parameter in GCHP system design. In GCHP system, the parameters of the rock-soil thermal properties are the overall coefficient of thermal conductivity and specific thermal capacity. The deviation of the thermal conductivity and specific thermal capacity will result in the deflection of the ground thermal exchanger length, and thus causing the excessive initial cost or unqualified effect. Now the general test method of ground thermal properties is the thermal response test (TRT) which has been applied widely in projects (Mogensen 1983). The method is based on the line source or cylinder source theory. The parameters of ground thermal properties can be back

Nomenclature

d_i	inside diameter of the tube (m)
d_o	outside diameter of the tube (m)
D	distance between two legs of the U tube (m)
d_b	diameter of the borehole (m)
h	coefficient of heat exchange between fluid and inside of the pipe W/(m^2·K)
q_l	constant heat injection rate (W/m)
R_b	borehole thermal resistance (K·m/W)
Pr	prandtl number
T_f	mean fluid temperature in the borehole heat exchanger (℃)
T_{ff}	undisturbed ground temperature (℃)
V	flow rate in the tube (m^3/h)

Greek Letters

γ	*Euler's constant=0.5772*
λ_b	thermal conductivity of the backfill material W/ (m·K)
λ_p	thermal conductivity of the pipe W/ (m·K)
ν	viscosity of the fluid (m^2/s)
λ_s	ground thermal conductivity (W/ (m·K))
$\rho_s c_s$	volumetric specific heat (J/ (m^3·K))

calculated according to the inlet and outlet water temperatures of the ground heat exchanger, flow rate and injected heat power.

The TRT method was developed first in 1983 by Mogensen (1983) . Since its application in 1995 the
method has spread to many countries. Roth et al (2004) applied the TRT in Latin America and analyzed the results by slope determination method, two variable parameter fitting method and geothermal properties measurement data evaluation software based on numerical solution. Florides and Kalogirou (2008) found in TRT in Cyprus that the accuracy of the collected data could be affected mainly by two factors: the daily flux penetration through the ground which gradually increases the temperature of the top layers and a variation of the heating coil injection rate per active length of borehole. Austin et al. (2000) investigated the sensitivity of the estimated ground thermal conductivity to assess the uncertainties associated with the values of volumetric specific heat of the ground, the undisturbed far-field temperature, the borehole geometry and instrumentation.

Other researcher analyzed the effect of testing duration on the results of ground thermal conductivity. Gehlin (2002) and Austin et al. (2000) investigated the necessary duration and gave their recommendation value. Signorelli et al.(2007) analyzed the starting time and ending time of the calculation. Florides and Kalogirou (2008) found that the change of heat exerted on the liquid can affect the testing result on his thermal properties testing and analysis. Signild and Gehlin (2003) discussed the influence of the undisturbed temperature on the thermal properties. Beier (2005) developed an analytical method to shorten the duration of recovery measurement while a temporary power loss interrupts.

The uncertainty analysis of ground parameters, such as the coefficient of compressibility and liquidity index, has been conducted by a number of researchers (Baecher and Christian 2003, Zhang et al. 2008). However, the characteristic of ground thermal properties based on GCHP is different. There are many factors in the measuring process of TRT and the accuracy of the results of the ground thermal properties can be affected. Some researchers conducted studies.

Bernier (2002) analyzed the uncertainty factor in the design calculation for vertical ground heat exchangers. He found that a ±10% uncertainty on the ground thermal conductivity leads an uncertainty on the length of 7.1%.Martin and Kavanaugh (2002) analyzed the effect of some factors on the results of thermal conductivity, such as testing duration, power quality, etc. Roth et al (2004) found in the thermal response test that the ground thermal properties fluctuations are mainly governed by corresponding fluctuations of ambient temperature and by fluctuation of electric power supply. Beier and Smith (2003) presented a method to reduce the adverse effect due to the heating power fluctuation. With the method the instantaneous power and inlet ground loop fluid temperature were input and outlet ground loop fluid temperature was output. Marcotte and Pasquier (2008), Beier and Marvin (2005) and Bozdag et al. (2008) discussed the factors affecting the measuring process, but they generally limited in the error analysis of the measurement system, measuring process and model.

Sharqawy et al. (2009) analyzed the uncertainty on the TRT of a vertical U shaped ground heat exchanger. The total uncertainty of any measured parameter may be calculated by the uncertainty in the sensor reading, data acquisition system and calibration procedure, so the uncertainty arising in calculating any result due these independent variable uncertainties can be obtained.

All of the research above was based on the certain back analysis method. Ground is a complicated natural geologic body and a highly complex uncertain system, so the petrophysical parameter can not be determined exactly as a unique value. The existing method to determine the ground thermal properties is certain back analysis. It seeks the unique value that meets the specific condition. In fact, due to the limit of the testing technology and method, the disturbance of test environment, reading error and random fluctuation of boundary condition, etc, the flow temperature, rate of flow and heating power measured are random variables. So the ground parameters are also uncertain variables.

In this paper the current testing method of rock-soil thermal properties was discussed. A new method was developed in which the probabilistic method is combined with interval analysis method to solve the uncertainty problem of ground thermal properties. The internal and error boundary was obtained by interval analysis method and the probability distribution was calculated by probabilistic method.

2 THE PRINCIPLE AND EQUIPMENT OF THERMAL RESPONSE TEST

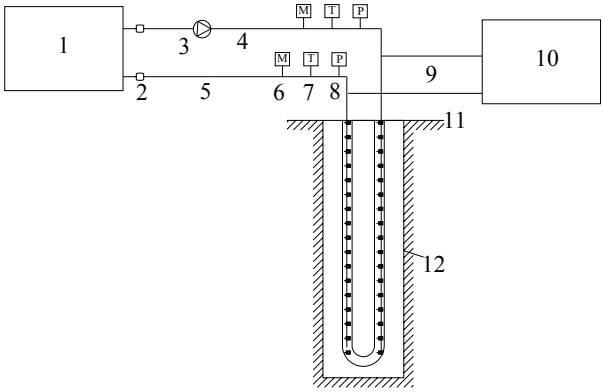
2.1 The Principle of the TRT

As an in situ measuring method to determine the ground thermal properties the principle of TRT is: Adding a constant heat injection to the ground through the fluid in the U tube，and measuring the electrical power, the inlet and outlet fluid temperatures and flow rate in the U tube. The change of fluid in the U tube is the response of the ground to the heat injection and the ground thermal conductivity and volumetric specific heat can be solved by the line source theory based on these measuring data.

2.2 The Measuring Device

The measuring device to determine the ground thermal properties is equipment we developed to conduct the in situ TRT. The equipment was calibrated by the meter calibration department. It includes mainly an electrical heater, a stainless steel temperature-holder box, a circulating pump, temperature sensors, flow rate probes and wattcmeters, and data acquisition system (Fig.1).

The measuring device is connected to the ground heat exchanger (GHE) to form a circulating system. Adding an electrical power and recording the electrical power, flow rate and fluid temperature at a constant interval, then the thermal conductivity and volumetric specific heat can be calculated.



1. electric heating water tank 2.hose 3. circulating pump 4. inlet tube 5. outlet tube 6. flow meter 7. temperature sensor 8. pressure gauge 9. data line 10.data acquisition system 11. ground 12. borehole wall

Figure 1: Ground thermal properties testing device

3 THE APPLICATION OF UNCEERTAINTY THEORY IN THE SOLUTION OF GROUND THERMAL PROPERTIES

3.1 Conventional Method

●Slope determination method

The convention TRT method relies on the conclusion of the LSM (line source Model). The average circulating fluid temperature is given as (Signild and Gehlin 2003)：

$$T_f = T_{ff} + \frac{Q}{H}\cdot R_b + \frac{Q}{4\pi\lambda_s H}\cdot\left[\ln\left(\frac{16\lambda_s\tau}{d_b^2\rho_s c_s}\right)-\gamma\right],\quad \tau \geq 1.25\frac{d_b^2\rho_s c_s}{\lambda_s} \qquad (1)$$

Equation1 can be re-written as:

$$T_f = k\cdot\ln(\tau) + m \qquad (2)$$

With

$$k = \frac{Q}{4\pi\lambda_s H} \tag{3}$$

$$m = T_{ff} + \frac{Q}{H} \cdot R_b + \frac{Q}{4\pi\lambda_s H}[\ln(\frac{16\lambda_s}{d_b^2 \rho_s c_s}) - \gamma] \tag{4}$$

$$\lambda_s = \frac{Q}{4\pi k H} \tag{5}$$

●two variable fitting method

The borehole thermal resistance of single U tube can be calculated as (Mogensen 1983, Signorelli et al.2007):

$$R_b = \frac{1}{2}\left\{\frac{1}{2\pi\lambda_b}\left[\ln\left(\frac{d_b^2}{2d_o D}\right) + \frac{\lambda_b - \lambda_s}{\lambda_b + \lambda_s} \cdot \ln\left(\frac{d_b^4}{d_b^4 - D^4}\right)\right] + \frac{1}{2\pi\lambda_p} \cdot \ln\left(\frac{d_o}{d_i}\right) + \frac{1}{\pi d_i h}\right\} \tag{6}$$

The borehole thermal resistance of double U tube can be calculated as (Mogensen 1983):

$$R_b = \frac{1}{4}\left\{\frac{1}{2\pi\lambda_b}\left[\ln\left(\frac{d_b^4}{4d_o D^3}\right) + \frac{\lambda_b - \lambda_s}{\lambda_b + \lambda_s} \cdot \ln\left(\frac{d_b^8}{d_b^8 - D^8}\right)\right] + \frac{1}{2\pi\lambda_p} \cdot \ln\left(\frac{d_o}{d_i}\right) + \frac{1}{\pi d_i h}\right\} \tag{7}$$

There is a turbulent heat transfer in the tube, so the convective heat transfer coefficient can be calculated by Dittus-Boelter correlation (Incopera and Dewitt 1996) :

$$h = \frac{0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}\,\lambda_f}{d_i} \tag{8}$$

where n=0.4 for heating and n=0.3 for cooling. n=0.3 in the TRT and the Equation 4 can be written as

$$h = 9.9617 \times 10^{-5} \cdot \left(\frac{V}{\pi\nu}\right)^{0.8} \frac{\mathrm{Pr}^{0.3}\,\lambda_f}{d_i^{1.8}} \tag{9}$$

There are two unknown parameters λs and $\rho_s c_s$ in Equation 1and 6 or 7. The parameters can be obtained by using the “two variable fitting” method.

3.2 Uncertainty Method

The current method to determine the ground thermal properties is certainty method described above. The result is an only solution of ground thermal conductivity and specific heat capacity on a certain condition. In the actual engineering, the parameters measured are random variable due to the variation of ground temperature, the limit of testing technique, the perturbation in the ambient environment, etc. The process of measuring parameters change is a Stochastic Process and the results of the TRT is also a random variable. So it is more proper to analyze and calculate the measuring results from the view of uncertainty method.

The uncertainty problem is evaluated by the probabilistic method combined with interval

analysis method in this paper. Different from the conventional method （certain method） which gives a certain value, the interval which include the exact solution of the ground thermal properties and a probability distribution in a error bound were given. So that the foundation to evaluate the results may be obtained. The analysis procedure on the uncertainty of ground thermal properties is as follows (shown in Fig. 2):

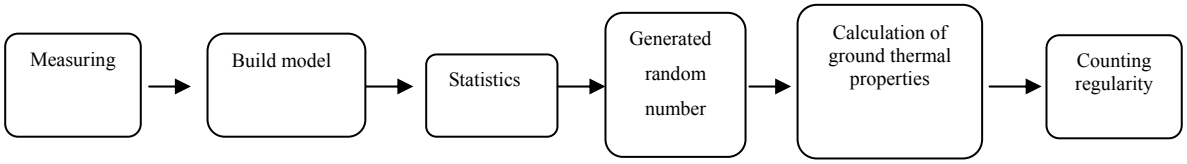


Figure 2: Flow chart on the analysis and calculation on the uncertainty of ground thermal properties.

● The measuring parameter flow rate, power in TRT is processed. The flow rate and power should be constant theoretically in TRT. In fact the flow rate and power are random variable which fluctuates near a constant value and generally the probability distribution can be represented by normal distribution. The mean value and Standard deviation of observing variables can be calculated by Equation 10 and 11.

$$\mu = \frac{1}{N}\sum_{i=1}^{N} X_i \tag{10}$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(X_i - \mu\right)^2} \tag{11}$$

where Xi is measuring data of observing variables, N is observed frequency.

● The measuring fluid temperature in the tube is processed. The average fluid temperature at the ith time point can be calculated as

$$T_{\exp,i} = \frac{T_{in,i} + T_{out,i}}{2} \tag{12}$$

where $T_{in,i}$ is the inlet fluid temperature at ith time, $T_{out,i}$ is the outlet fluid temperature at ith time.

● Based on the measuring data, the two variable parameter fitting method may be used to determine the thermal conductivity and specific heat as fitting Equation 1 and 6 and the theoretical value of the mean fluid temperature $T_{cal,i}$ can be obtained. The measuring value of the mean fluid temperature in the tube can be described as:

$$T_{\exp,i} = T_{cal,i} + \Delta T_i \tag{13}$$

where ΔTi is the measuring error of the average fluid temperature.

● Due to the uncertainty of the measuring instrument conditions, observation conditions and test model and planning, the measuring error is also a random variable and the probability distribution may be described as normal distribution.

● According to the statistics characteristics of the observations, M group of measuring error

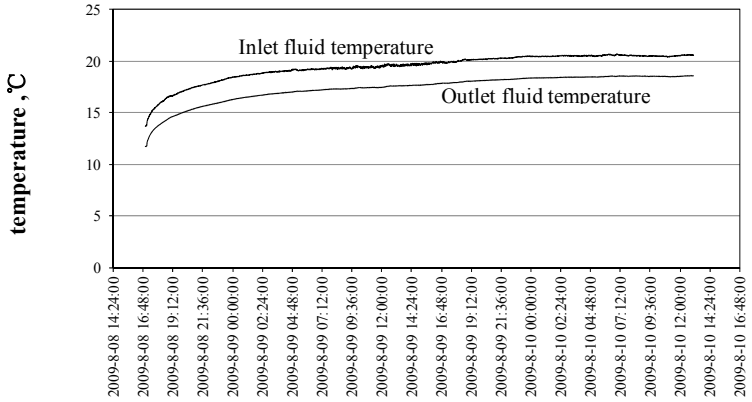
random number which has mean value μ and standard value σ are generated by means of Monte Carlo method. $T_{exp,i}$ can be obtained by the random measuring error and the theoretical value of fluid temperature calculated by Equation 1.

● M group thermal conductivity λs and specific heat ρscs can be calculated by Equation 1 and 6.
Statistic analysis of the thermal conductivity λs and specific heat $\rho_s c_s$ gives the mean value, standard deviation and the interval of the results.

4 EXPERIMENT TEST ANALYSIS

4.1 Experimental Configuration

The parameters of the testing hole in a ground source heat pump project are as follows: A borehole with a depth of 100 m and a diameter of 150 mm was drilled. The double U- pipe with diameter of 32 mm was installed in the borehole. 5% bentonite and yellow sand mixture were backfilled. The initial undisturbed ground temperature is 11.7°C. The inlet and outlet fluid temperature of the pipe is shown in Fig. 3. The inlet and outlet fluid temperature of the pipe increased remarkable in the initial hours and then the change is slowed down gradually. The electric power and flow rate remain constant with a little fluctuation.



4.2 The Results of Data Analysis

A model can be obtained by the measuring data and Equation 1 and 6.

$$T_f = 11.7 + Q(6.288387\times10^{-4} + \frac{1.313030\times10^{-5}}{V^{0.8}} + 7.786455\times10^{-7}\cdot\frac{2-\lambda_s}{2+\lambda_s}) + \frac{Q}{400\pi\lambda_s}\left[\ln\left(\frac{16\lambda_s\tau}{0.0225\rho_s c_s}\right) - 0.577216\right] \quad (14)$$

By using the uncertainty method described in Section 3, the mean value μ and Standard deviation σ can be calculated by Equation 6 and 7 and the results are shown in Table 1.

Table 1: The mean value and stand deviation of the measuring parameter

measuring parameter	μ	σ
Flow rate（m^3/h）	1.646187	0.007555
Electric power（W）	3631.409	102.3085
Measuring error of the mean fluid temperature（°C）	0.00001673	0.092431

To analyze the effect of number of random result on the result, 50 group of measuring parameter simulated were produced by Monte-Carlo technique. Therefore 50 groups of thermal conductivity and specific heat were obtained by two parameter fitting method. A summary of the conventional method (certainty method) results and uncertainty method is presented in Table 2. Their mean value and standard deviation versus the number of measuring parameter simulated are shown in Fig. 4~7.

If a confidence probability of thermal property parameter is given, the confidence interval can be obtained by statistical method. In this test, the confidence interval of thermal conductivity and specific heat are respectively

$2.194902<\lambda_s<2.198676$ and $1921607<\rho_s c_s<1930891$

Table 2: The distribution of thermal conductivity and specific heat (50 groups of simulated parameters, recording data at 1 minute interval)

Parameter	Conventional method results	Uncertainty method results		
		Initial value	Value range	Standard deviation
Thermal conductivity/ W/(m•K)	2.19679	2.19679	2.18467～2.21164	0.006572
Specific heat /J/(m^3•K)	1926249	1926249	1893287～1960368	16166

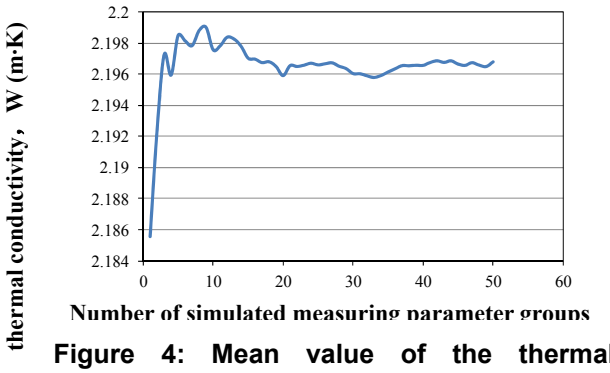


Figure 4: Mean value of the thermal conductivity versus the number of group

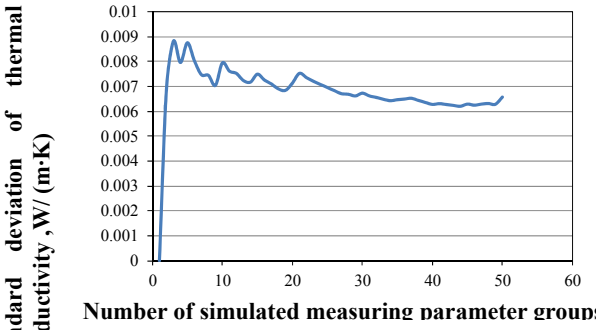


Figure 5: Standard deviation of the thermal conductivity versus the number of group

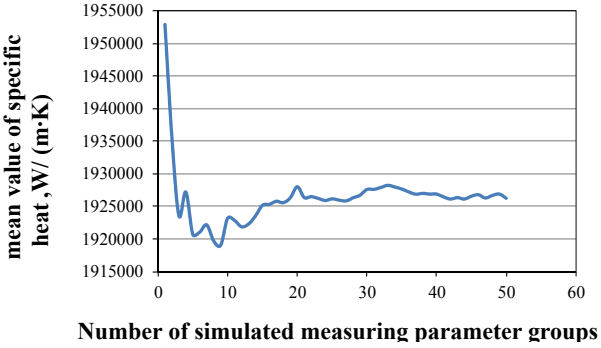


Figure 6: Mean value of the specific heat versus the number of group.

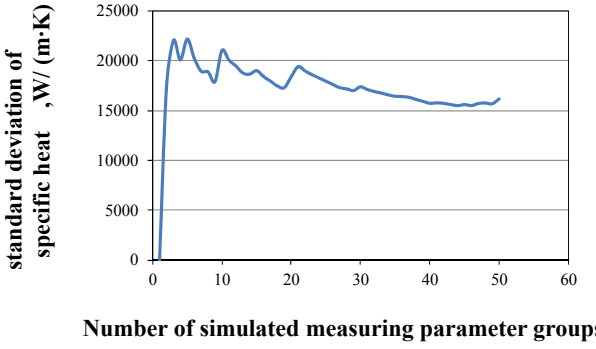


Figure 7: Standard deviation of the specific heat versus the number of group.

As shown in Fig.4~7, the number of measuring parameter simulated should reach a certain value to assure the stability and reliability of the results of thermal parameters. When the number of group comes to a certain quantity, about 35 in this test, the change of mean value and standard deviation of thermal conductivity and specific heat is small, and the effect of number of the group may be neglected. 50 group parameters were built here.

Record the measuring data, including fluid temperature, power and flow rate at different internals. The results of ground thermal properties are obtained by above steps and they are shown in Table 3.

Table 3: The results of ground thermal properties with recording data at different intervals

The results of ground thermal properties	Recording data at different intervals (min)			
	1	2	5	10
Number of measuring data	2880	1440	576	288
Standard deviation of measuring error of the mean fluid temperature (°C)	0.092431	0.092601	0.091469	0.092107
Standard deviation of flow rate (m3/h)	0.007555	0.007582	0.007242	0.007095
Standard deviation of electric power (W)	102.3085	102.1946	102.7203	104.4132
Mean value of the thermal conductivity W/(m·K)	2.196789	2.197122	2.199948	2.198371
Standard deviation of thermal conductivity	0.006572	0.009295	0.016288	0.019743
Mean value of specific heat J/(m3·K)	1926249	1926221	1921023	1925615
Standard deviation of specific heat	16165.73	23027.62	39533.81	48725.91

It can be seen from Table 3 that when the measuring time interval changes, parameters and their variance change. As a result, the ground thermal property parameters by inversion and their variance also change. What is more, the rate of change of the variance of the ground thermal property parameters is far more than that of measuring parameters. The results are shown in Table 4.

Table 4: The amplitude of variation of ground thermal properties and measuring parameters

Change of time interval (min.)	The variation rate of standard deviation of the parameters ((mi-mi-1)/mi-1)				
	Measuring error of temperature	Flow rate	Electric power	Thermal conductivity	Specific heat
1-2	0.001833	0.003675	-0.001113	0.414351	0.424471
2-10	-0.005331	-0.064259	0.021710	1.123977	1.115977

m_{i-1}: The value of the standard deviation of the parameters in Table 3 at time i-1.
m_i :The value of the standard deviation of the parameters in Table 3 at time i.

As shown in Table 4, when the time interval recording data changed from 1 minute to 2 minutes, the variation rate of standard deviation of the measuring parameters, including measuring error of temperature, flow rate and electric power were 0.11% to 0.36%. With corresponding the variation of standard deviation of the resulting thermal property parameters, namely thermal conductivity and specific heat, were 41% to 42%. The value of the former is significantly larger than that of the latter. Similar situation occurred when the time interval recording data changed from 2 minute to 10 minutes. The phenomenon showed the ill-posedness of the inverse problem.

Some recommended parameters in the testing are as follows: The flow velocity shall not be below 0.2m/s; parameter recording interval is 1 minute; heating power is about 50~70 W/m of borehole depth; the fluid temperature is determined mainly by heating power and ground thermal properties and the value is generally in the range of 22~30°C at inlet and 18~26°C at outlet.

5 CONCLUSIONS

The technology and method to test ground thermal properties was studied. Based on the line source theory of ground heat exchanger, a new uncertainty analysis method has been developed. It has different aspects with existing method which give a certain unique value of each thermal property. And the mean value, value range and standard deviation of each parameter of thermal properties are given.
The uncertainty method can reflect the random property of ground thermal properties. The practicability and reliability of the ground thermal properties may be improved by employing the method.

The number of measuring parameter simulated should reach a certain value to assure the stability and
reliability of the results of thermal property parameters. When the mean value and standard deviation of thermal conductivity and specific heat is relatively steady, we can consider the corresponding the number of measuring parameter simulated is suitable.

When the measuring parameters and their variance change, the resulting thermal conductivity and volumetric specific heat capacity change. The change range of the variance of the ground thermal property parameters is significantly larger than that of the measuring parameters.

Among the three measuring parameters, the error of heating power and mean fluid temperature has great influence on the results of thermal properties，while the ground thermal properties is insensitive to the error of flow rate in a certain range.

The effect of only three parameters (mean value of inlet and outlet fluid temperature, flow rate and electric power supplying to the circuit) on the ground thermal properties are discussed here. The comprehensive uncertainty problem in conjunction with other parameters, such as the borehole configuration parameter needs further research.

6 ACKNOWLEDGEMENT

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