REGRESSION ANALYSIS ON INFLUENCE OF VARIOUS FACTORS ON HEAT TRANSFER OF VERTICAL GROUND HEAT EXCHANGER

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Abstract: The heat transfer performance of Ground Heat Exchanger (GHE) is a key point for Ground Source Heat Pump system. Based on a coupled soil heat conduction and groundwater heat advection model for GHE, a series of simulations are implemented. Through these simulation results, we can see the influence of different factors such as soil thermal conductivity, groundwater flowrate, borehole parameters, operation schedule etc. on the heat transfer quantity per meter borehole and outlet water temperature from GHE. Then after that, through the Statistical Program for Social Sciences (SPSS) software, the linear and nonlinear regressions are used to arrive at the relationship between heat transfer quantity per meter borehole, outlet water temperature and various factors. For example, there are linear relationships between heat transfer quantity per meter borehole and soil thermal conduction, heat capacity; and nonlinear relationship between heat transfer quantity per meter borehole and soil porosity, groundwater flowrate. Thus it is easy and convenient for the researcher and designer to see the effect of different parameters choice, so as to save a lot of time in the initial stage of design.

Key Words: heat transfer quantity per meter borehole, outlet water temperature, single factors, regression analysis.

1 INTRODUCTION

The heat transfer quantity per meter borehole and outlet water temperature from underground pipes are two key indicators for the performance of ground heat exchanger (GHE) for ground source heat pump (GSHP) system. The GHE design capacity depends on the heat transfer quantity per meter borehole directly and the outlet water temperature from GHE has a big influence on operation efficiency of GSHP unit. In summer air-conditioning period, the coefficient of performance (COP) of heat pump unit will drop when the outlet water temperature increases and it is true conversely in winter. Various factors including soil thermal conductivity, pipe parameter, underground water table, groundwater flowrate, operation schedule etc. have close relationship with these two indicators. Therefore it is necessary to make clear the relationship between various factors and these two indicators. A lot of researches have implemented, whether in theoretical aspect (Wang, 2003; Sun, 2004) or experiment (V.C. et al.,1985; J.D. et al. 1991; Cenk et al., 1999). However, it is hard to apply the experimental data or results in one place to another place for design because of different geology situation, and time consuming numerical simulation is not easy to be used for practice either.

Therefore, a coupled heat conduction and heat advection numerical model of GHE is firstly introduced in the paper; and then a large quantity simulation for different cases are

Nomenclature

c_p	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)	***Subscripts***	
k	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	s	Soil
q	Internal heat source ($W \cdot m^{-3}$)	p	Pipe
T	Temperature (°C)	f	Groundwater
t	Time (s)	$f1$	Fluid inside pipe
u	velocity ($m \cdot s^{-1}$)	t	Total
x	Coordinate (m)	o	Initial
y	Coordinate (m)		
z	Coordinate (m)		
Greek symbols			
α	Convective heat transfer coefficient($W \cdot m^{-2} \cdot K^{-1}$)	σ	Volumetric specific heat ratio
ρ	Density ($kg \cdot m^{-3}$)	φ	Porosity

implemented further. Based on those simulation results, SPSS is used to analyze the relationship between various factors and heat transfer quantity per meter borehole & outlet water temperature. All the relationship equations here are helpful and convenient for research and practical application.

2 Coupled heat conduction and heat advection model for GHE

2.1 Assumptions

The heat transfer between the GHE and its surrounding soil was affected by a number of factors such as working fluid properties (e.g., 20% glycol) and its flow conditions, soil thermal properties, soil moisture content, and groundwater velocity and properties, etc. The following assumptions were made in developing the mathematical model of the GHE. Soil was a homogeneous porous medium, with its mass force, heat radiation effect and viscosity dissipation neglected. The thermal and physical properties of soil, and its temperature at the far-field boundary remained constant. An equivalent single straight pipe (Gu, 1998) was used to represent the actual U-shape pipe used in a GHE. Because the diameter of pipe was very small, only the temperature variation of the working fluid inside pipe along the pipe depth was considered.

2.2 Basic equations for the control volume

Both solid and liquid parts co-existed in one control volume of non-isothermal groundwater flow, it was therefore necessary to integrate the two parts into one energy equation. Accordingly, the governing equation (1) describing non-isothermal groundwater flow in a saturated porous medium was as follows:

$$\sigma \frac{\partial T}{\partial t} + (V \cdot \nabla)T = \alpha_t \nabla^2 T + \frac{q_t}{(\rho c_p)_f} \tag{1}$$

If a unidirectional groundwater field was assumed over the entire numerical domain along x direction with a velocity u_x, then Eq. (1) can be re-written as:

$$\sigma \frac{\partial T}{\partial t} + u_x \cdot \frac{\partial T_f}{\partial x} = \alpha_t \cdot \nabla^2 T + \frac{q_t}{(\rho c_p)_f} \tag{2}$$

The initial conditions were:

$$T_{f1}(z,t) = T_p(x,y,t) = T_s(x,y,t) = T_0 \quad (t = 0) \tag{3}$$

The far-field boundary condition was:

$$T_s(x,y,t)\big|_{farfield} = T_0 \tag{4}$$

The radius of the far-field boundary was set at 10m.
The inlet working fluid temperature to the GHE was:

$$T_{f1}(z=0,t) = T_{fin}(t) \tag{5}$$

In solving the GHE model by using the overall method, a home use program is used to solve the GHE mathematical model. An unstructured mesh was adopted. The partial differential equations were discretized spatially based on Finite Volume Method. In order to ensure the continuity of heat flux at the solid-fluid interface, the harmonic mean method (Tao, 2002) and the pseudo-density method (Chen, 2000) were adopted to calculate equivalent thermal diffusion coefficient in solid-fluid interface. The Gauss-Seidel point iteration method was employed to solve these equations. There were detailed descriptions including validation of mathematical model in literatures (Fan, 2006) and (Fan, 2007).

3 Regression analysis on single factor' impact

3.1 Various parameters

There are various parameters having impact on heat transfer performance of GHE such as soil and groundwater thermal conductivity, pipe thermal parameters, heat carrier fluid inside pipes flowrate and operation schedule etc.. In the paper, the author did analysis on influence of soil thermal conductivity and resistance, underground water flowrate, borehole depth, heat carrier fluid flowrate, inlet water temperature to GHE and operation schedule. The basic value and range of these parameters are decided according to practice and relevant literatures (Tang, 1985; A.C., 2000), as shown in Table 1.

Table. 1 Various parameters

Items	Parameters	Unit	Benchmark	Value number	minimum	maximum
Soil and underground water	Soil thermal conductivity	W/(m·°C)	1.55	8	0.75	2.25
	Soil volumetric heat capacity	kJ/(m3·°C)	1890	9	1270	3289
	Porosity	%	0.389	6	0.24	0.61
	Underground water flowrate initial temperature	m/a °C	30 17	9 6	5 9	800 19
GHE	Borehole depth	m	100	6	50	150
Heat carrier fluid	flowrate	m3/h	1.5	8	0.6	2
	Inlet water temperature	°C	35	6	30	40
Operation schedule	Operation hours	h/d	8	7	6	18

Note: 1.the initial soil temperature is 17.9 as in Shanghai ;

2.HDPE pipe material with inner & outer diameters DN32/DN26 ;

3.Water inside underground pipes without anti-freezing addition in summer air-conditioning;

4. According to the simulation, the system almost gets into steady state after 10 days operation. So the operation schedule with 8 hours per day and 10 days running is adopted in the paper.

3.2 The analysis on single factor's impact

3.2.1 Soil thermal conductivity

As shown in Fig.1, the heat transfer quantity per meter borehole increases linearly following the increase of soil thermal conductivity. And the outlet water temperature decreases when the soil thermal conductivity increases which is better for the system. Further, the heat transfer quantity per meter borehole has a increase by 85.47% and outlet water temperature drops by 8.91% when thermal conductivity changes from 0.75 W/(m•°C) to 2.25 W/(m•°C).

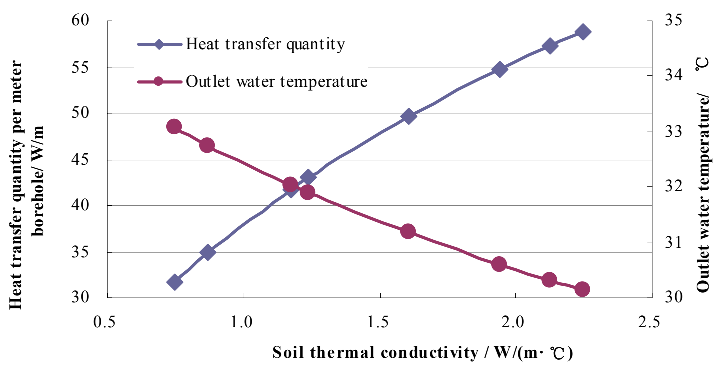

Figure 1 The influence of thermal conductivity

3.2.2 Soil volumetric heat capacity

The volumetric heat capacity is an indicator for thermal storage capability of soil. The heat transfer quantity of soil per unit volume with higher volumetric heat capacity is more than that with lower volumetric heat capacity. Therefore, the heat impact radius is much less when the volumetric heat capacity increases.
As shown in Fig.2, following the increase of soil volumetric heat capacity, the heat transfer quantity per meter borehole increases linearly and outlet water temperature drops gradually. For example, the heat transfer quantity per meter borehole changes by 5.7% with soil volumetric heat capacity from 1270 kJ/(m^3· °C) to 2754 kJ/(m^3· °C). However, the outlet water temperature decreases by 0.6% only which means subtle influence of volumetric heat capacity.

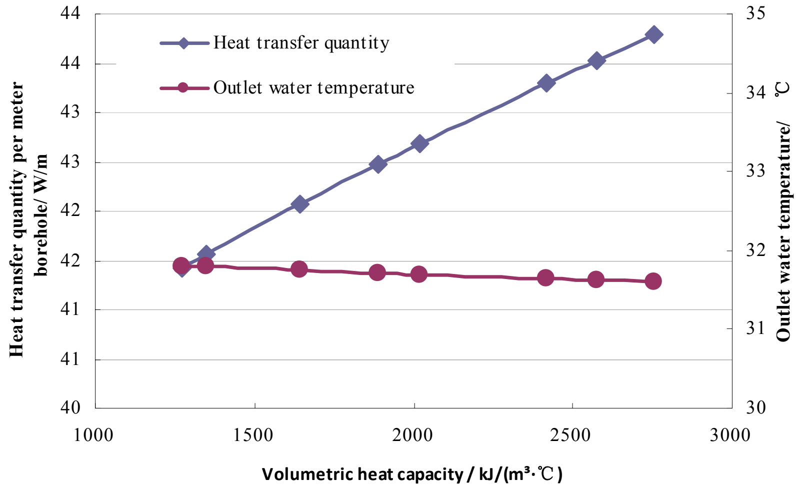

Figure 2 The influence of soil volumetric heat capacity

3.2.3 Soil porosity

The thermal properties of soil and rock depend on mineral substance contents, porosity and water saturation. Among which, porosity is the most important parameter as the result of formation mechanism and essence of soil and rock. Further, rock has a higher thermal conductivity than soil, which is because rock comes into being under much higher temperature and pressure with lower porosity.
Porosity also has big impact on hydraulic conductivity. The higher the soil porosity, the higher the hydraulic conductivity is. As shown in Fig.3, the heat transfer quantity per meter borehole decreases gradually when the soil porosity becomes more and more. For unsaturated soil, big porosity indicates big air volume among soil grains. As the result of less touch area among soil grains, the soil thermal conductivity drops, which leads to degrade of heat transfer ability. For saturated soil, it is full of water among the soil grains. The water thermal conductivity is more than that of air, but less than the soil's which also leads to decrease of overall thermal conductivity (considering soil and water together). However, this result comes from without considering the increase of hydraulic conductivity which will be researched in later work. The outlet water temperature has a slow increase with increasing porosity only.

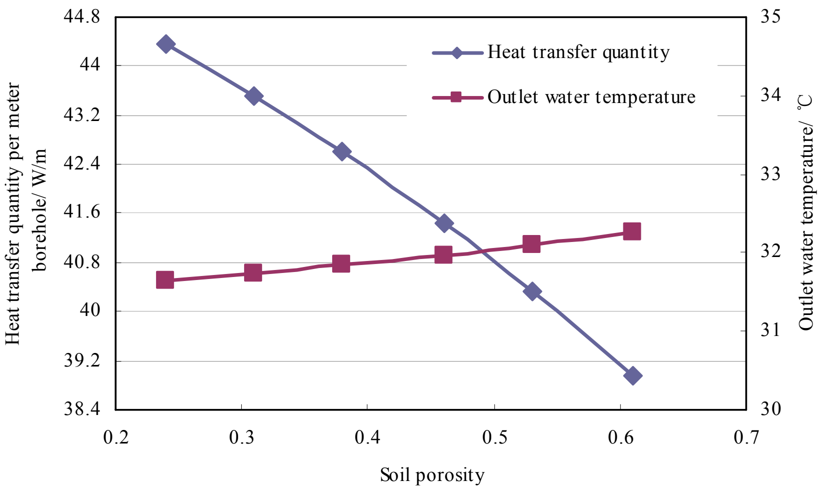

Figure 3 The influence of soil porosity

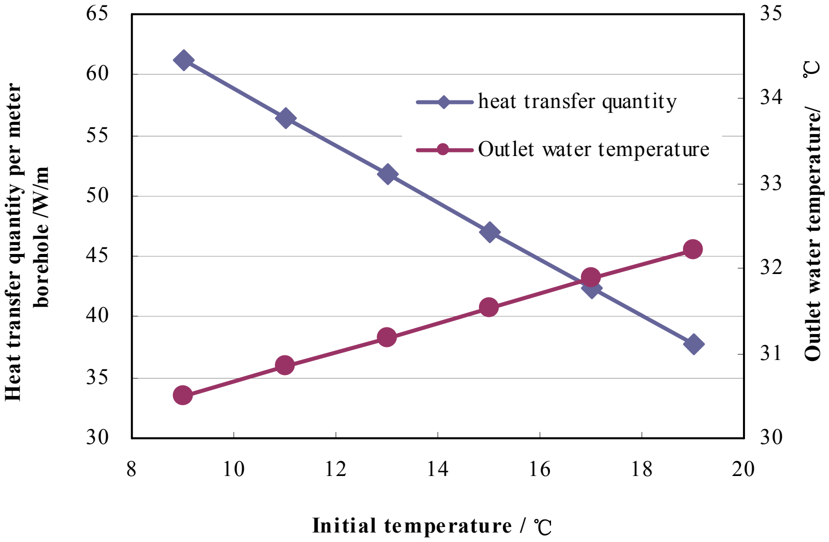

Figure 4 The influence of initial soil temperature

3.2.4 The initial soil temperature

Just as shown in Fig. 4, the higher soil temperature will decrease heat transfer of GHE and further impact the system operation efficiency.

3.2.5 Underground water flowrate

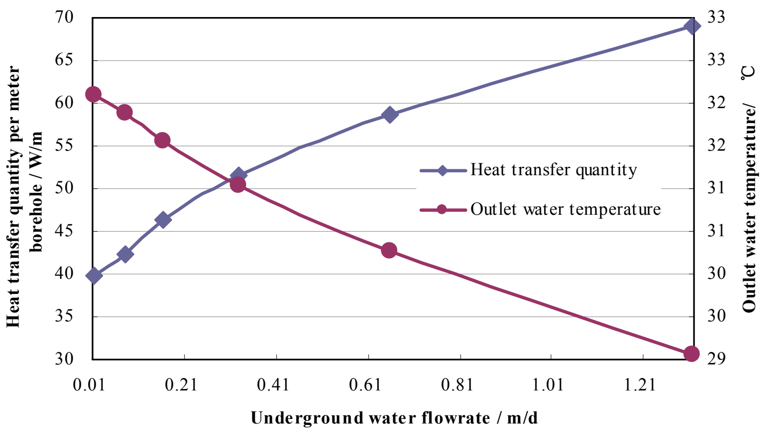

Figure 5 The influence of underground water flowrate

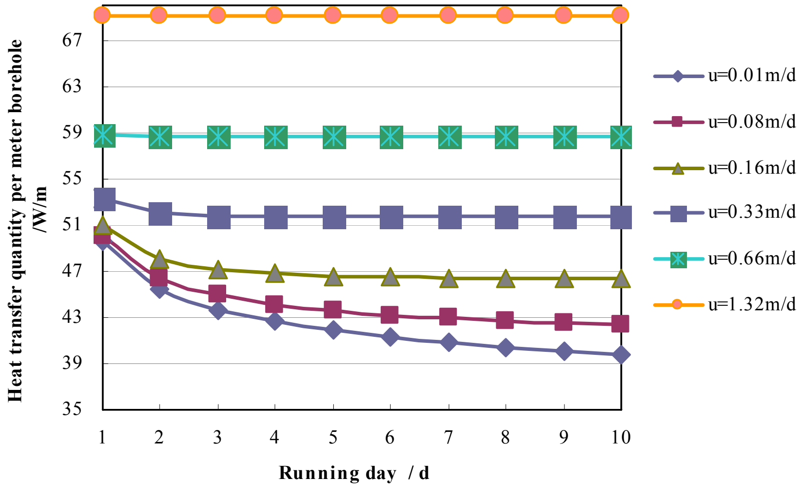

Figure 6 The influence of running days under different groundwater flowrate

The groundwater flow can improve the heat transfer between soil and ground heat exchanger which is better for the mitigation of thermal accumulation effect. As shown in Fig.5 and Fig.6, the heat transfer is strengthened and the outlet water temperature decreases. Taking the data on 10th day as an example, the heat transfer quantity per meter borehole increases by 47.5% and the outlet water temperature drops from 32°C to 29°C when the groundwater flowrate changes from 0.01m/d to 0.066m/d. Furthermore, it shortens the time for the system to be in steady state which can be seen in Fig. 6. And when the groundwater flowrate amounts to 0.66m/d, the heat transfer quantity per meter borehole keeps in a constant value about 58.69W/m. Thus we can conclude that the groundwater flow is beneficial to heat transfer of GHE. It is important to make sure the groundwater flowrate during the initial design stage of GSHP system.

3.2.6 Borehole depth

As shown in Fig.7, the heat transfer quantity per meter borehole decreases with increasing borehole depth. That is because the temperature difference between underground pipes and soil is less and less when the borehole becomes deeper and deeper. While the overall heat transfer per borehole is still strengthened, although the increase is in lower speed. Furthermore, the decrease of outlet water temperature in summer air-conditioning period following the borehole depth increase is better for the improve of GSHP unit efficiency. For example, the outlet water temperature changes from 33.45°C to 30.15°C by 9.87% when the borehole depth is from 50m to 150m.

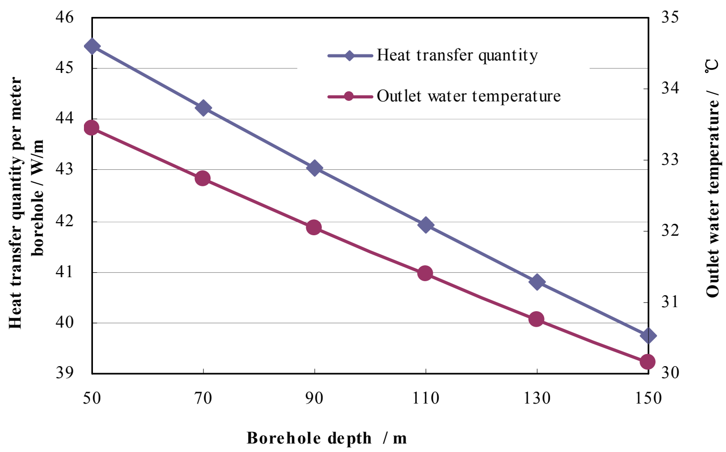

Figure 7 The influence of borehole depth

3.2.7 Heat carrier fluid flowrate

As shown in Fig.8, the heat transfer quantity per meter borehole and outlet water temperature both increase with increasing fluid flowrate inside pipe. The heat transfer quantity per meter borehole increases by 26.4% and outlet water temperature changes from 27.81°C to 32.94°C when the fluid flowrate changes from 0.6 m^3/h to 2.0m^3/h. Thus we can see more fluid flowrate inside pipe is better for the heat transfer, but not for outlet water temperature because higher outlet water temperature from GHE leads to decrease of heat pump unit efficiency. And water circulation pump consumed more with higher fluid flowrate too. Therefore, it is necessary to keep fluid flowrate in a certain value range, which can not only make the fluid in turbulent state for good heat transfer, but also prevent the outlet water temperature and water pump consumption from getting higher.

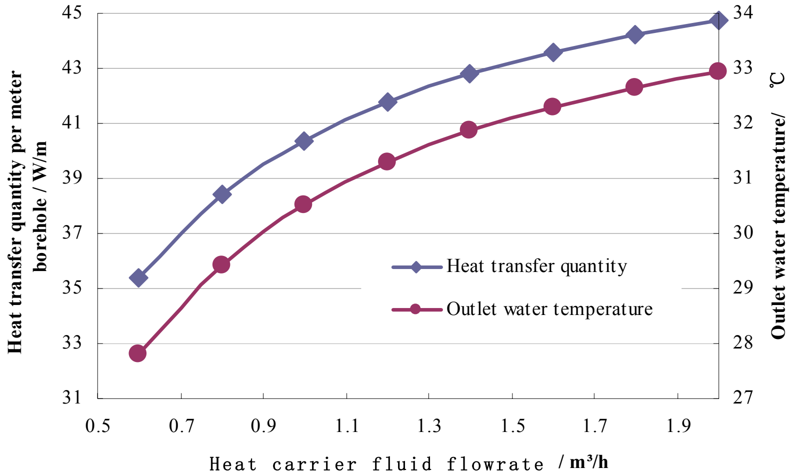

Figure 8 The influence of heat carrier fluid flowrate

3.2.8 Inlet water temperature to GHE

The outlet water temperature from heat pump unit condenser is changeable as the result of unsteady load. As shown in Fig.9, the heat transfer quantity per meter borehole and outlet water temperature both increase with increasing inlet water temperature to GHE. And the heat transfer quantity per meter borehole increases by 76.9% when the inlet water to GHE changes from 30°C to 40°C. Thus we can see the heat transfer between soil and GHE is strengthened as the result of big temperature difference. However, the outlet water temperature also increases from 27.81°C to 35.93°C which results into the lowering efficiency of heat pump unit. And when the outlet water temperature amounts to a certain degree, the heat pump unit will stop running for protection.

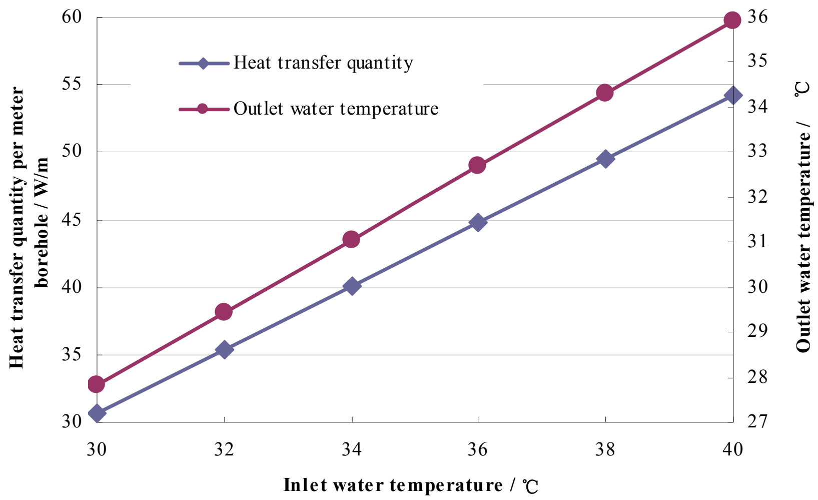

Figure 9 The influence of inlet water temperature

3.2.9 Operation schedule

Operation schedule for a GSHP system is very important for the better running. Ten days simulation under different running hours has been done and the results in 10th day are shown in Fig.10. Less operation hour per day is better for heat transfer and outlet water temperature. When operation hours per day change from 6h/d to 16h/d, we can see that heat transfer quantity per meter borehole decreases by 30.6% and outlet water temperature increases by 2.5%. So it is better for GSHP system to be used for office building with intermittent schedule. However, when it is used continuously such as for residential building, almost 24 hours operation will make the coefficient of performance of GSHP system decrease quickly. So it is better to use another cooling source as auxiliary to make the GHE area or even large area GHE have time to recovery.

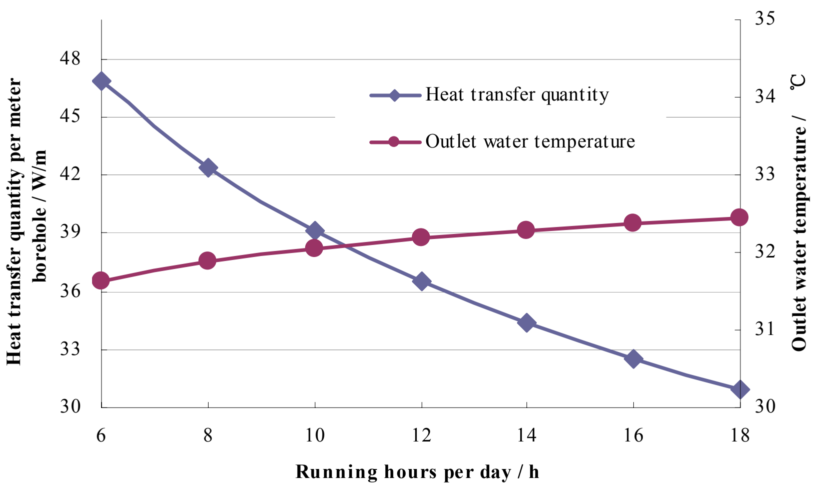

Figure 10 The influence of running hours per day

4 Regression analysis of single factor

Based on all simulation results under different parameters, the SPSS software is used for analysis to get the relationships between heat transfer quantity per meter borehole & outlet water temperature and various factors, as shown in Table 2. All regression equations and coefficients passed the significance test. And it can be seen in Table 2 that heat transfer quantity per meter borehole & outlet water temperature have almost linear relationship with soil thermal conductivity, volumetric heat capacity, inlet water temperature and borehole depth; they have conic relationship with soil porosity and groundwater flowrate.

Table. 2 Summary of relationships between single factor & heat transfer quantity per meter borehole

Parameters	Unit	Value range	Regression equations	R2
k	W/(m•℃)	0.75-2.25	ql=19.835+17.821k Tout=34.403-1.944k	0.990 0.993
c	kJ/(m^3•℃)	1270-3289	ql=39.508+0.002c Tout=31.966-0.0001c	0.998 0.999
φ	%	0.24-0.61	ql =46.531-6.917φ-9.013φ2 Tout=31.384+0.847φ+0.942$φ^2$	1.000 1.000
U	m/a	5-800	ql =48.691+0.046U-(9.801E-6)U2 Tout=32.095-0.008U-(4.293E-6)U2	0.998 0.999
To	℃	9-19	ql=82.213-2.342To Tout=28.947+0.172To	1.000 1.000
Tin	℃	30-40	ql =-40.062+2.358Tin Tout=3.441+0.812Tin	1.000 1.000
V	m^3/h	0.6-2	ql =exp(3.9-0.201/V) Tout=exp(3.566-0.146/ V)	1.000 0.999
L	m	50-150	ql =48.233-0.057L Tout=35.05-0.033 L	0.999 0.999
T	h/d	6-18	ql =72.562-14.455ln(T) Tout=30.356+0.728ln(T)	0.999 0.995

4 Conclusions

After a large quantity simulation, we can see the influence of various factors on heat transfer of ground heat exchanger; and then based on SPSS analysis, we can make sure further the relationships between them.

1) There are linear relationships between heat transfer quantity per meter borehole & outlet water temperature and soil thermal conductivity, soil volumetric heat capacity, initial soil temperature, inlet water temperature to GHE; while there are nonlinear relationships between two indicators and groundwater flowrate, soil porosity, heat carrier fluid flowrate and operation schedule.

2) The heat transfer quantity per meter borehole decreases following the increase of soil porosity, initial soil temperature, borehole depth and operation hours; while increases following the increase of soil thermal conductivity, soil volumetric heat capacity, inlet water temperature to GHE and groundwater flowrate.

5 Acknowledgement

The project was supported by National Natural Science Foundation of China（50806052）.

6 REFERENCES

Wang Yong, Liu Xianying, Fu Xiangzhao. Experiment of ground-source heat pump and underground energy storage system. HV&AC. 2003, 33(5): 2l-23.

Sun Henghu, Cui Jianqiang, Mao Xinli. The Mechanism of the ground-source heat pump for energy co nservation. Acta Energiae Solaris Sinica. 2004, 25(1): 24-27.

V.C. Mei, C.J. Emerson. New approach for analysis of ground-coil design for applied heat pump systems. ASHRAE Transactions, 1985, 91 (2B): 1216-1224.

J.D. Deerman, S.P.Kavanaugh. Simulation of Vertical U-Tube Ground-Coupled Heat Pump Systems Using the Cylindrical Heat Source Solution. ASHRAE Transactions, 1991, 97(1): 287-295

Cenk Yavuzturk, J. D.Spitler, S. J.Rees. A Transient Two-Dimensional Finite Volume Model for the Simulation of Vertical U-Tube Ground Heat Exchangers[J]. ASHRAE Transactions, 1999, 105(Part 2): 465-474

Fan Rui. Theoretical and experimental research on geothermal heat exchanger in the integrated soil cool thermal storage and ground source heat pump system under coupled heat conduction and groundwater advection. Harbin Institute of Technology, 2006: 25-38

Fan R, Jiang Y Q, Yao Y, Deng S M and Ma Z L. A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection. Energy 2007; 32(11) : 2199-2209

Yian Gu, Dennis LO'Neal. Development of an equivalent diameter expression for vertical U-tube used in ground-coupled heat pumps[J]. ASHARE Transactions, 1998, 104: 347-355

Tao W. Numerical Heat Transfer (Second Edition, in Chinese). Xi'an Jiao Tong University Publication, 2002, 81, 483-487

Chen X, Han P. A note on the solution of conjugate heat transfer problems using SIMPLE-like algorithms. International Journal of Heat and Fluid Flow, 2000, 21: 463-467.

Tang D., Sun S.. Rock and Soil in engineering. Geology publication, 1985: 10-15

A.C.Chiasson, S.J.Rees, J.D.SPitler. A Preliminary Assessment Of The Effects Of Ground-Water V On Closed-Loop Ground-Source Heat Pump Systems[J]. ASHRAE Transactions, 2000, 106(I): 380-393.