A TOWER BASED DESIGN METHOD FOR GROUND SOURCE HEAT PUMP SYSTEMS

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Abstract: An optimal ground source heat pump (GSHP) system assures a problem-free operation over the entire life cycle, proper design method for the GSHP system is crucial. Different from traditional design methods, the presented method is modified by the long-term performance of a practical GSHP system, which is directly reflected by continuous temperature change of the ground, the ground thermal properties and other influential factors. Theoretically the operation of designed GSHP is simulated based on degree-day boundary conditions and building loads during the periods of ten years. Continuous experiment validation on the practical GCHP system has been carried out among the years of 2003 to 2007, using a computer data acquisition system. Through the comparison between experimental data and simulated results, the tower-based design method of GSHP system is verified in practice.

Key Words：***Ground source heat pump (GSHP); ground coupled heat exchangers (GCHE); system design; tower-based method; long-term performance***

1 INTRODUCTION

Being an effective energy-saving technology of buildings, ground source heat pump (GSHP) has been used increasingly for space heating and cooling in the world. However, in many GSHP applications, due to the unbalance between heat injection and extraction from and to the ground, the ground temperature surrounding ground coupled heat exchangers (GCHE) may potentially rise over a number of years, resulting in a lowering of performance of the heat pump as the fluid temperature rises. Therefore, it is necessary to understand the long-term performance of GCHE during the design of GSHP system. Such a problem has been paid great concern by researchers and designers. In this paper, a novel Tower Method is presented to design and predict the long-term performance of GCHE. In order to verify the validation, the comparison between experimental data and simulated results is carried out.

2 TOWER BASED METHOD

2.1 Design principle

A correct design of ground source heat pump (GSHP) system assures a problem-free operation over the entire life cycle, which takes into the following real local conditions, including real petrophysical conditions (e.g. thermal conductivity), real climatic conditions (e.g. temperature, operation time), real operation conditions (e.g. heating & cooling, DHW, swimming pool). Also the design should take into account the real geometry of the BHE, that is, the diameter, the distance between BHEs, depth of BHEs and the layout (line, rectangle etc.)

At present, a usual design method for the GSHE system can be summarized as the following simple formula: the length of GCHE = required load/ thermal power. As to thermal power (W/m), it is often determined by individual experience or steady-state calculation. This method, however, is invalid in many cases, when it is difficult to obtain accurate value of thermal power because of insufficient design information or dynamic variation of thermal power with cooling or heating load of buildings, operating mode, layout of GCHE, climate conditions, thermo-physical properties of the soil, etc. Besides, as is well known, the criterion to determine the success of GSHP system is not transient performance, but the long-term stability. Considering this, a Tower Method for the design of GSHP system is presented.

Fig 1 shows the design principle of Tower Method. It can be seen that, different from traditional methods, the design objective at the tower top is the long-term performance of GCHE, which is directly reflected by continuous temperature change of the ground and the fluid inside the GCHE base on hourly simulation. At the tower bottom is basic information, including the structure of buildings, meteorological conditions, thermo-physical properties of the soils and single-borehole testing (if necessary). Based on the above information, modeling on the GCHE is carried out. Then, preliminary design of GCHE can be obtained through steady-state and transient-state analysis. Between preliminary design and long-term performance is repeatedly optimal process until design requirements are met.

Some key factors for Tower Method are analyzed as follows, including thermo-physical properties of the soil, hourly simulation, etc.

2.2 Thermo-physical properties of the soil

In the design of GSHP system, natural ground temperature and thermal conductivity are two important parameters. For determination of the thermal interaction between the GCHE and the ground, precise knowledge of the natural ground temperature is required. From the point of view of the temperature distribution, we can distinguish the following ground zone:

· *Surface zone* reaching a depth of about 1m, where the ground temperature is very sensitive to short-time change of weather conditions;

· *Shallow zone* extending from the depth of about 1-10m, where the ground temperature is close to the average annual air temperature;

· *Deep zone* (below about 10-20m), where the ground temperature is practically constant or very slowly rising with depth according to the geothermal gradient.

Considering that heat transfer of GCHE occurs mainly in the deeper soils, average temperature of deep zone is to be treated as initial ground temperature at the infinite boundary. In theory, through the solution for transient heat conduction in a semi-infinite solid, where the temperature of exposed surface is varying periodically with time, the formula of Eq. (1) can be obtained:

$$T(x,t) = (T_m \pm \Delta T_m) - 1.07 K_v A_s \exp\left(-0.00031552 x a^{-0.5}\right) \cos\left[\frac{2\pi}{365}\left(t - t_o + 0.018335 x a^{-0.5}\right)\right] \quad (1)$$

As an example, Fig 2 shows the variation of the ground temperature under different depths in Tianjin, China. Average temperature at the depth of 20-30m is about 13.8 ^{o}C.

As to thermal conductivity, typical methods include the table of constants and sample testing in the laboratory. However, considering the variation of thermal conductivity with heat and moist transfer of the soil during the heat injection and extraction, the above methods are not accurate enough. In the Tower Method, an in-situ measurement method is developed based on the condition of constant heating-flux. Fig 3 shows the measured result of thermal conductivity of saturated sandy soil in Tianjin area, with the testing period of 40 hours. Generally, effective thermal conductivity can be obtained within 20-30 hours.

2.3 Hourly simulation

In the Tower Method, the objective of hourly simulation includes the load of buildings, the temperature of the ground and fluid. As to the load of buildings, hourly cooling and heating load can be simulated using the program Energy Plus. In some cases, an alternative DEST program developed by Tsinghua University is also used. Then according to COP of heat pump units, heat injection or extraction from and to the ground can be derived. Thus, we can give a preliminary overview of the operating conditions of GCHE, which can be useful for the later design and adjustment.

With the description of the ground temperature, a two-dimensional, homogeneous, constant physical property, unsteady heat conduction model without inner heat source is present. Further, a Transient Solver based on User Defined Functions is developed to meet the required accuracy of practical GCHE. Short-time Step Response Model is used to simulate the temperature change of the fluid inside the GCHE. In fact, it is a model integrated G-functions with Dimensionless Temperature Response Factors. Different from traditional Linear Model by Kelvin and Cylindrical Model by Kavanaugh, it takes into full account limited G-functions under different layout of boreholes, the choice of calculation time step, transient effective of boreholes, etc. In the Tower Method, average temperature of boreholes is obtained based on hourly load of buildings and natural ground temperature:

$$T_b(\tau) = T_g + \sum_{i=1}^{n} \frac{(q_i - q_{i-1})}{2\pi\lambda} G\left(\frac{\tau_n - \tau_{n-1}}{\tau_s}, \frac{r_b}{H}\right) \quad (2)$$

3 EXPERIMENTAL VALIDATION

3.1 Experimental system

In order to verify the validation of Tower Method, continuous experiments on a demonstrated GSHP system have been made since the year of 2003. The schematic diagram of the experimental system is shown in Fig 4. It is composed of three parts: the GCHE system under the surface, the heat pump/air-conditioning system by using the screw compressor above the surface and the terminal heat radiators inside the houses. The total floor area is 3715 m2. Based on the simulation of hourly load of buildings using Energy Plus (Fig 5), U shaped borehole heat exchanger and U shaped pipe buried in the foundation piles are constructed. Totally, 61 foundation piles have U shaped loop inside, and their depths are 20 meters. The depth of borehole heat exchanger is 90 meters, and 21 boreholes are used. All these pipes are made of high-density polyethylene, and have a diameter of 32 mm. As shown in Fig.5, the maximum heating load in winter is 148 kW, while in summer the load of cooling is 300 kW. That means the unbalanced load ratio is very large, reaching about 2.0 that merit our attention.

Besides, a data acquisition system SCADA is designed, in which all of the measured data are collected and processed through a personal computer. The collected data are the ground temperatures surrounding a borehole, the water flow rates through the loops and the consumed electric power. The typical positions of those measuring instruments used in this study are shown in Fig 6.

3.2 Experimental results and analyses

By September 2005, the measured data including three cooling operation (July 2003-September 2003, June 2004-September 2004 and June2005-September 2005) and two heating operation (November 2003-March 2004 and November 2004-March 2005) has been collected.

Fig 7 shows the average fluid temperature and the soil temperatures surrounding the GCHE at locations of typical thermocouples (2#, 5#, 7# and 9#). Fig.8 and Fig.9 show the simulated results of the temperature variation of the ground and the fluid inside the GCHE during the 10-year operation respectively, based on the Tower Method mentioned above.

As shown in Figs 7-9, both the ground temperature and the fluid temperature vary periodically. However, according to different cooling and heating load as well as climate conditions each year, the temperature rise of both the ground and the fluid is changing. On average, for a complete cycle (totally 8760 hours), the average temperature rise of the ground and the fluid is about 1.4 oC (amplitude: 8-15 ^oC) and 1.0 ^oC (amplitude: 12-24 ^oC), respectively. In contrast, simulated results show that the average temperature rise of the ground and the fluid is lower, reaching about 1.2 ^oC (amplitude: about 10 ^oC) and 0.8 ^oC (amplitude: 14 ^oC), respectively. Despite the difference, the relative error of about 14-20% is within the required accuracy of practical GCHE. Therefore, according to the comparison above, the validation of Tower Method in practical GSHP system is verified. It should be noted that, due to the limitation of measured data, only two-year tested results are compared and the further validation for longer running period will be done in our next study.

4 CONCLUSION

An integrated Tower Method for the design of GSHP system is presented, which modified by the long-term performance of GCHE system. Combined the simulation of hourly boundary conditions of the ground temperature and the load of design buildings, continuous temperature variation of the ground and the fluid inside the GCHE system is used to evaluate the long-term performance, which is different from other typical methods. Using a computer data acquisition system, continuous experiments on a demonstrated GSHP system have been made among the years of 2003 to 2007. Through the comparison between experimental data and simulated results, the validation of Tower Method in the design of GCHE system is verified.

NOMENCLATURE

a	average thermal diffusivity of ground, m^2/s
A_s	amplitude of annual air temperature wave, ^oC
G	temperature response factor, dimensionless
H	depth of borehole, m
i	time step, s
K_v	vegetation coefficient, dimensionless
q	load, W/m
r	radius, m
t, τ	time, day
T	temperature, ^oC
T_m	average annual air temperature, ^oC
ΔT_m	ground temperature differential, ^oC
t_o	phase of air temperature wave, day
x	depth below the ground, m
λ	thermal conductivity, W/m/K

SUBSCRIPTS

b	borehole
g	ground
i	time
n	number

5 Acknowledgement

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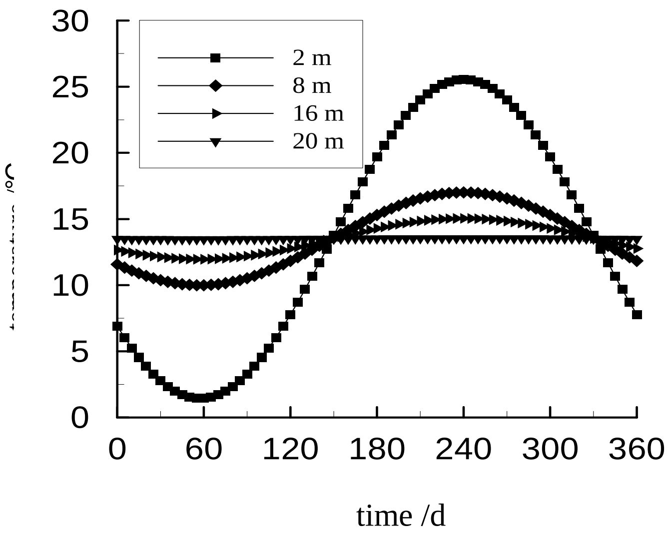

Fig 1: Design structure of Tower Method

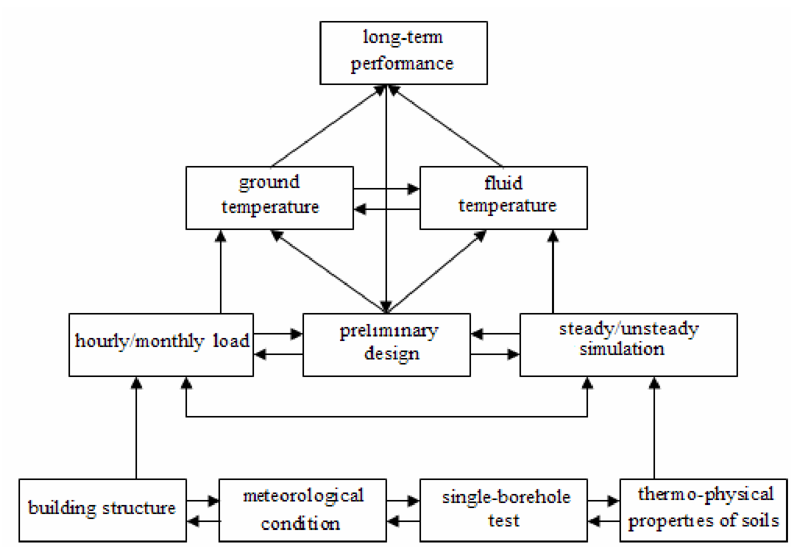

Fig 2: Variation of the ground temperature under different depths in Tianjin

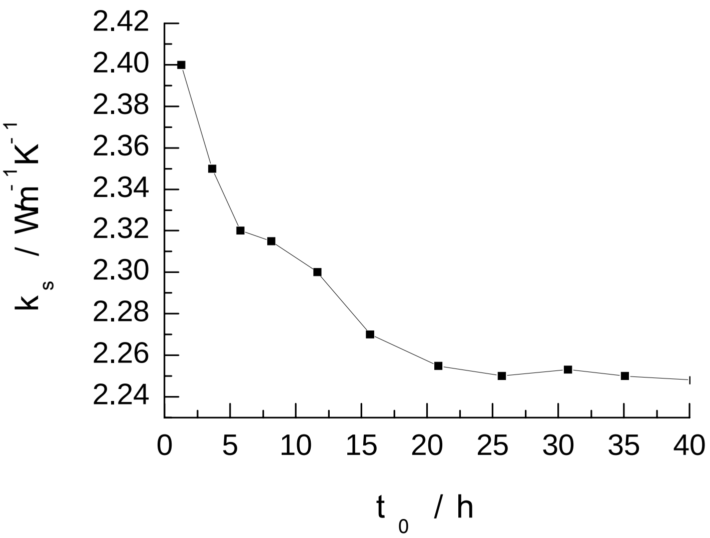

Fig 3: Thermal conductivity of saturated sandy soil in Tianjin

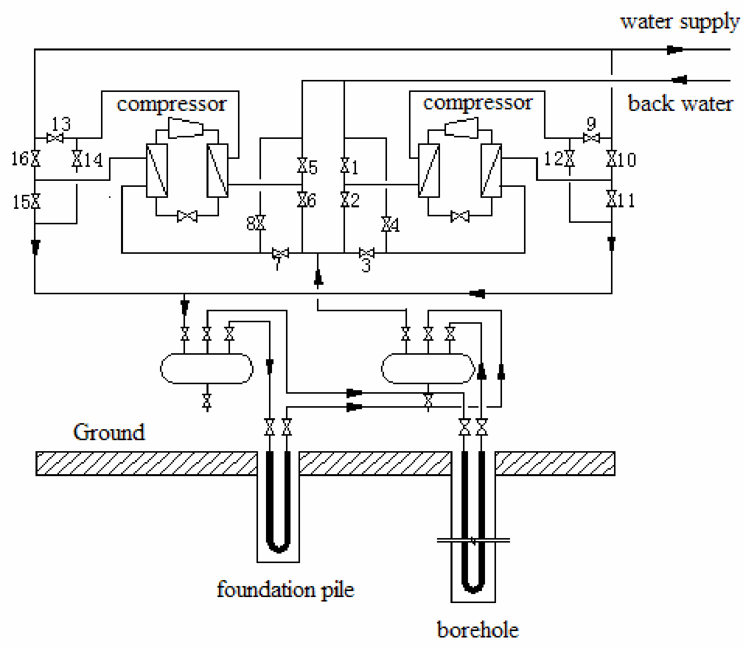

Fig 4: Schematic diagram of the experimental GSHP system

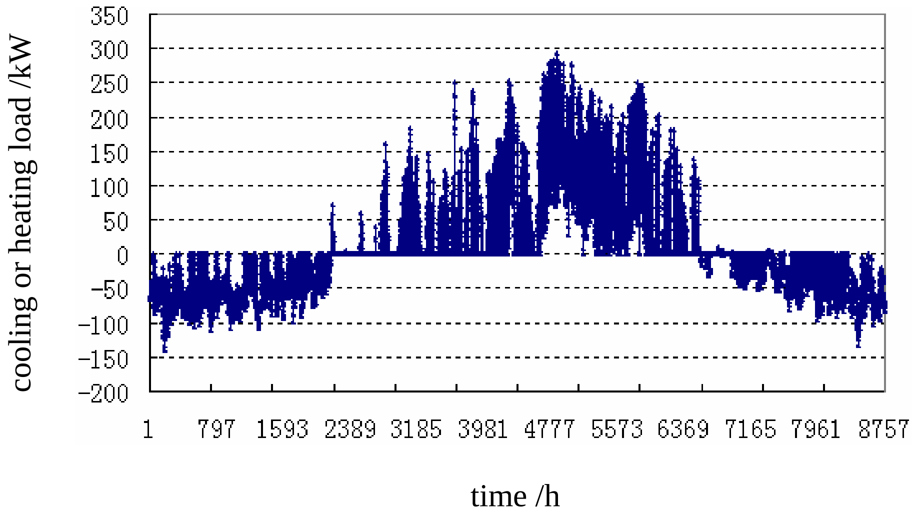

Fig 5: Hourly load of office buildings at Meijiang GSHP system

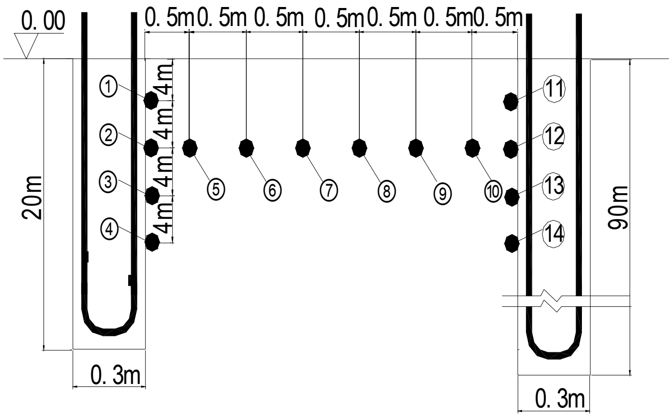

Fig 6: Layout of underground Temperature monitoring points

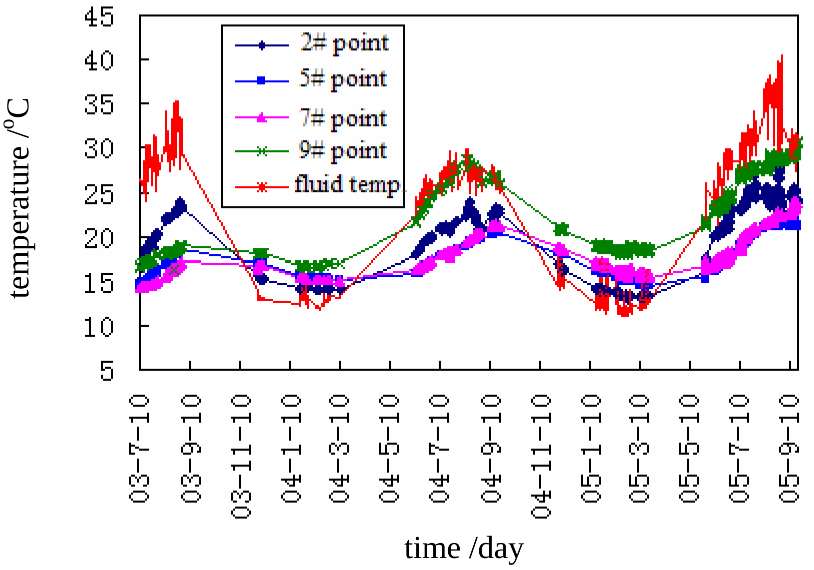

Fig 7: Measured temperature of the ground and the fluid

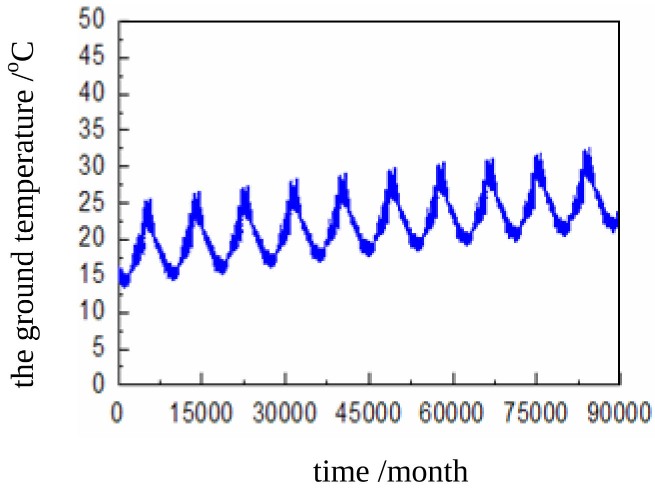

Fig 8: Simulated results on the ground temperature

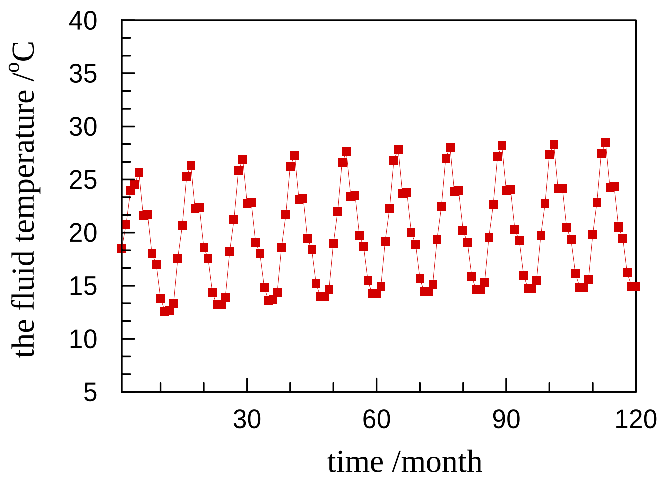

Fig 9: Simulated results on the fluid temperature