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A Comprehensive Study on Ground Source Heat Pump Applicability

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Abstract. Ground coupled heat pump (GCHP) technology has the energy saving potential, but closely related to the building ambient conditions. This paper studied the effect of climatic condition on the ground heat flow balance. A 4603 m^2 floor area building was used as the base building and EnergyPlus software was used as the simulation platform. 73 cities from 5 climate zones in the great China region were selected to study the effect of climatic condition diversity on the ground heat balance. Based on the ground heat flow ratios 73 cities were grouped into 5 categories with different GCHP applicability. This paper provided a strategic assessment method on GCHP applicability study.

Introduction

GCHP technology has a selective applicability associated with the building ambient climatic conditions [1]. Differing from a house scale application the use of GCHP for large size buildings will encounter more serious problem of ground heat accumulation/depletion if the ground heat flows are not balanced [2,3]. Currently more and more large buildings have designed with GCHP systems, but some of them have not addressed the ground heat flow balance issue properly. Fail to solve the ground heat flow imbalance problem will face the consequences of cooling/heating performance degrade or operation failure.

As the ground heat flow balance issue is concerned the climatic condition is the dominant factor. This paper provided an in depth study of GCHP applicability, by analyzing the effect of climatic condition on the magnitude of the ground heat flow imbalance.

The Ground Heat Flow Imbalance Issue

A large GCHP system will use large piece ground mass as energy storage media to achieve energy saving operation, storing heat to the ground during summer cooling operation, and withdrawing heat from the ground during winter heating operation. To achieve sustainable energy saving operation it is required to maintain the ground temperature field in favorable range and to be sustainable during the GCHP lifetime [4]. This will demand the GCHE ground to have a balanced annual heat flow, keeping the inlet heat flux equalized with the outlet heat flux.

Most GCHPs have a certain degree of ground heat flow imbalance, depends on their location, scale and ground geological condition. A stand alone house GCHP project may not demonstrate any obvious ground heat flow imbalance problem, because it has an infinite volume of ground mass as heat source/sink. For a large scale GCHP project with a large number of GCHEs the effect of ground heat imbalance can not be tolerated. Caused by the heat transfer barrier from their neighbors majority of the GCHEs can only use the section ground volume in their loci as heat source/sink mass. Therefore heat accumulation/depletion will happen if a ground heat flow is imbalanced.

To examine the ground heat accumulation effect a GCHP (longitude 118.8°, latitude 32.0°), designed with cooling capacity 1960 kW and heating capacity 1590 kW, was investigated experimentally. The GCHP had designed 1180 GCHEs and an alternative cooling tower. The GCHP was put on operational test using GCHE only for one year. Recorded temperature profile revealed that there was a temperature rise 2K due to the ground heat accumulation. For the case of GCHE caused ground heat flow deficit, a ground temperature drop of 4K in one year operation was reported [5].

Ground heat flow imbalance will have some detrimental effect to the GCHP performance. For cooling operation a 1K rise in condensing temperature will cause the cooling COP drop by 2.5%. A 10K rise in condensing temperature will result in COP drop by 20.8%, for a GCHP with an evaporating temperature 2℃ and a condensing temperature 40℃. For heating operation, 1K drop in evaporating temperature will cause COP drop 2.1%, and 10K drop in evaporating temperature will cause COP drop 17.3%.

If a GCHP has imbalanced ground heat flows the system performance will degrade year by year. In short term it will cause GCHP COP drop, in long term it will cause GCHP malfunction.

Modeling Heat Flows for a Gchp System

A GCHP equipped HVAC system normally consists of three sub-systems: the building site end user sub-system, the heat pump sub-system, and the GCHE sub-system.

In cooling mode the amount heat dissipated to the soil *GHo* is bigger than the amount of heat removed from the building. The building side will add a heat gain from the circulation pumps, as well as a heat gain from the pipeline heat leaking. The heat pump sub-system will add a heat gain from the compressor. The GCHE subsystem will add a heat gain from its circulation pumps and a heat gain from the pipeline heat leaking.

In heating mode the amount of heat absorbed from the soil *GHi* is less than the amount heat supplied to the building. On its way from the soil to the building it will be joined by a heat gain from GCHE pumps, a heat gain from heat pump compressors, and a heat gain from the building side pumps.

The magnitude of a ground heat flow balance for a GCHP system can be determined by *GHio*, the ratio of the ground inlet heat flow *GHi* to the ground outlet heat flow *GHo* in one year cycle, defined as:

$$GHio = \frac{GH_i}{GH_o} = \frac{\int Q_{GCHE}(cooling)}{\int Q_{GCHE}(heating)} . \tag{1}$$

With $Q_{GCHE}(cooling)$ designated as heat inlet flow to the soil in cooling mode, and $Q_{GCHE}(heating)$ as the heat outlet flow from the soil in heating mode.

A Base Envelope Building for the Gchp Simulation

To study the impact of different climate condition on GCHP ground heat flow imbalance, a factory building was used as the base envelope with the predetermined internal heat gains and settings.

It is located in Nanjing of China, with a floor area of 4603 m^2, equipped with GCHP. It has the main section developed as one story assembly area and about 20% of the section in North side developed as two story area used for office, canteen, and toilets. The wall consisted of 12.7 mm external sheathing + 50 mm air gap + 60 mm isulation + 102 mm bricks + 12.7 mm internal sheathing. The roof consisted of a layer of 12.7 mm RG01 + 80 mm insulation board + 203 mm concrete block. The floor was made of 180 mm concrete + 60 mm insulation board + 203 mm concrete block + 51 mm perlite concrete.

To reduce heat transfer through glasses triple glazing low-E windows were used.

The building internal heat gains were set as below: 95 occupants, with human heat gain rate of 117 W/person, total lighting heat gain of 54.4 kW, total equipment heat gain of 62.7 kW, and total amount of fresh air supply 4125 m^3/h.

The EnergyPlus software [6] was used as the building energy flow simulation platform. The GCHP system was scheduled to operation between 06:00 hours to 22:00 hours and switched off during rest of the night hours for weekdays. The GCHP was set in off mode during weekends and public holidays. The indoor air temperature settings were 20℃ for heating operation and 26℃ for cooling operation.

The base building GCHP system consisted of following items during operation:

- 2 off heat pumps, each with nominal cooling capacity 216kW; heating capacity 240.7kW
- 2 off circulating pumps for GCHE water circuit and each with power input 7.5kW;
- 2 off circulation pumps for the building side water circuit each with 7.5kW power input.

Base Building Energy Flow Simulation and Results Analyses for the Selected 73 Cities

To thoroughly investigate the magnitude of ground heat flow imbalance influence by the climatic condition, 73 cities within the great China were carefully selected to represent various ambient conditions in 5 climatic zones.

Using the data from the base building envelope, the internal heat gains and settings specified in Section 4, the required building annual HVAC heat flows were simulated city by city for the selected 73 cities by applying the typical metrological year weather file for each city. The ratio of the ground inlet heat flow to the outlet heat flow GHio was evaluated accordingly, and summarized in a colored GCHP map in Fig. 1. Based on the calculated GHio values, the 73 cities were grouped into 5 categories of GCHP applicability scenarios. Principally the value GHio close to 1 represents ground heat flow balanced applications, GHio>1 represents ground inlet heat flow (cooling operation) dominated applications, GHio<1 represents ground outlet heat flow (heating operation) dominated applications.

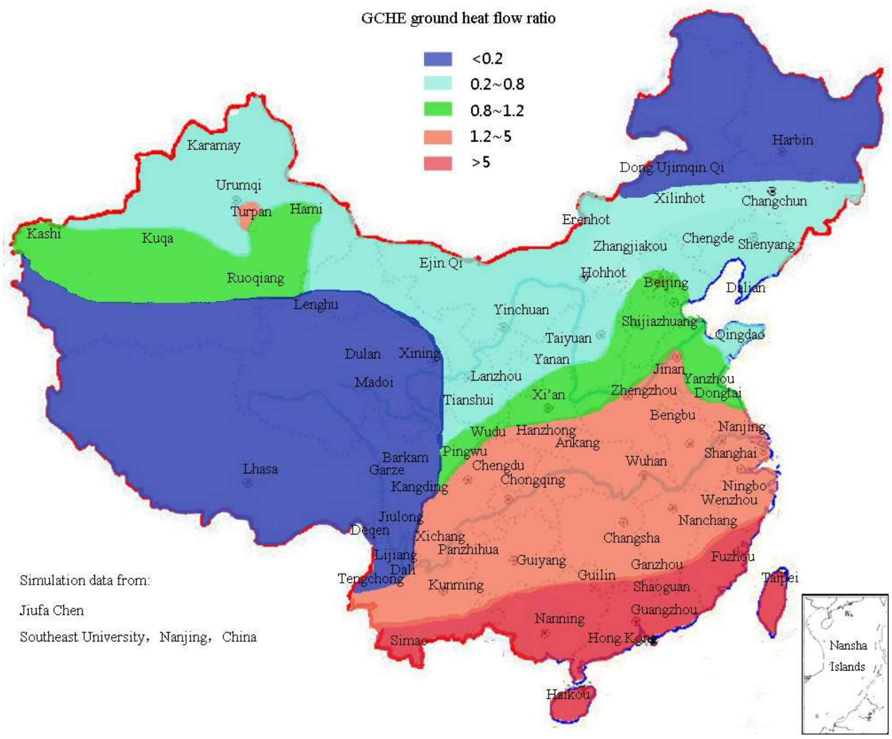

Fig. 1. A map of GCHP applicability referenced to the base building.

Those cities with the GHio values in the range 0.8 to 1.2 were considered in the ground heat best balanced category, the green area in Fig. 1. Here the balanced category has been given a ±20% offset to take into account that a perfect balance with GHio=1 is rare in reality. In the GHio coloring map the balance category consisted two long green stripes, one in central region including Beijing, and another in the northwest region including Hami.

Those cities with the GHio values in the range of 1.2 to 5 were considered in the ground inlet heat flow dominated (or as ground heat accumulation) category, 20 cities of this group were collected, colored in pink in Fig. 1. With the ground annually receiving 20% to 400% more inlet heat flow, heat accumulation is inevitable if operated with GCHE alone. This category is considered as GCHP applicable, provided that auxiliary heat sink technology is made available for cooling season. So far there are a number of auxiliary heat sink technologies are available, for instance, introducing parallel cooling tower, retrieving heat from the GCHP condensers for swimming pool or hot water supply, etc. For this category it is clear that ignoring the ground heat flow imbalance will pay the penalty in GCHP performance degradation.

Those cities with the GHio values in the range of 0.2~0.8 were considered in the outlet heat flow dominated (or as ground heat depletion) category, market in light blue in Fig. 2. This category is considered as another GCHP applicable zone. Since using GCHP alone will make the ground outlet heat flow exceeding the inlet heat flow by 25%~400%, it requires to design additional solar heater or biomass heater, summer time charging ambient heat to the ground, etc.

Those cities with the GHio values greater than 5 were considered as a GCHP non-applicable category, 8 cities from the simulation, marked in dark red in Fig. 2. This category is dominated by cooling operation, with very little heating operation demand. The use of GCHP will result in ground heat deposit rate 5 times or greater than the heat withdrew rate. Hence drastic heat accumulation will be encountered and fast ground temperature up shifting effect will make the GCHP non-operative in few years time. Considering some area has occasional heating requirement, using air source or water source AC/chiller will be favorable.

Those cities with the GHio values less than 0.2 were considered as a GCHP non-applicable category, marked in dark blue in Fig. 1. Owing to its cold climate condition, cooling is scarcely required. Unless a geothermal heat resource is found the use of a GCHP will cause the ground heat depleted year by year, making the use of GCHP unjustified in terms of performance degradation and finance burden.

To summarize the simulated GHio values Fig. 1 was created to provide a strategic and fast assessment on energy saving potential and applicability for GCHP technology. All the GHio values from the selected 73 cities were plotted on the map and 5 coloring bands were used to group the cities with similar GHio values. As describe above, 5 categories of GCHP applicability scenarios were designated for the base building:

- GHio $\in[0.8, 1.2]$, marked in green color, recommended as the best applicable region using GCHP.
- GHio $\in(1.2, 5]$, marked in pink color, recommended as GCHP applicable region. Owing to its cooling dominated operation requirement, alternative heat sink technology needs to be designed to avoid ground heat accumulation.
- GHio$\in[0.2, 0.8)$, marked in light blue color, recommended as GCHP applicable region. Owing to its heating dominated operation requirement, alternative heat source technology needs to be provided to avoid the ground heat depletion.
- GHio > 5, marked in dark red color, recommended as GCHP non-applicable region. Owing to its cooling only requirement, alternative AC technology other than GCHP shall be beneficial.
- GHio < 0.2, marked in dark blue color, recommended as GCHP non-applicable region. Owing to its heating only requirement, alternative heating technology other than GCHP shall be beneficial.

Summary

Focused on GCHP applicability strategy this paper presented a simulation study about the effect of climatic condition on the ground heat flow balance.

Various research works have confirmed that the use of GCHP can often have ground temperature shift problem. An experimental work of a GCHP found a ground temperature up shifting by 2K in one year operation due to heat accumulation. Simulations also demonstrated that heat flow surplus or overdrew to and from the ground can cause the ground temperature field shift. The effect of ground heat imbalance can cause performance degradation. Theoretical analysis predicted a cooling COP drop by 2.5%/K caused by ground heat accumulation during cooling operation; and a heating COP drop by 2.1%/K caused by ground heat depletion during heating operation. It was concluded that keeping the ground heat flow balanced is an important measure to maintain a GCHP in sustainable energy saving operation.

It was concluded that the climatic condition is one of the dominant factors affecting the ground heat flow balance, which in turn predicting the GCHP applicability magnitude. Models for evaluating GCHP ground heat flows were proposed. A newly built GCHP equipped factory building was used as the simulation base building. To cover a diversity of climatic conditions 73 cities from 5 climatic zones in the great China region were selected as the simulation sites. The EnergyPlus software was used to calculate the building required annual heat flows in cooling operation and in heating operation. The climatic variation simulations were carried out by applying the annual weather file from each of those 73 cities to the base envelope with the predetermined internal heat gains and settings. Based on the simulation results the values of ground heat flow ratio GHio (defined as the ratio of ground inlet heat flow to the ground outlet heat flow) for all the 73 cities were evaluated. Using the GHio value as the criterion the 73 cities were grouped in 5 categories, the GCHP applicability level for each city was visually illustrated in a 5 color band map for the whole great China region.

The conclusions from this paper were referenced to the selected base building envelope under the assumed internal settings and operation schedules.

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