NUMERICAL INVESTIGATION ON FREE COOLING PERFORMANCE OF GROUND-SOURCE HEAT PUMP IN A SOLAR GREENHOUSE

by

Zhao HOU, Yuqiu HU, Xiaojie LIU, Jianhua WANG, Mei YANG, and Jun FAN *

College of Water Conservancy and Civil Engineering, Shandong Agricultural University, Tai'an, China

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This paper presents the numerical study of a ground source heat pump with borehole free cooling in a solar greenhouse. The system is mainly composed of a solar greenhouse with a water-water heat pump, a ground heat exchanger, and several pipes for free cooling. Thermal performances of ground source heat pump with and without borehole free cooling are investigated. The cooling time of the solar greenhouse is divided into transitional seasons (May and September) and summer seasons (from June to August). The mixed mode, including the free cooling mode and the ground source heat pump cooling mode, runs in summer seasons. During the entire transition seasons, the free cooling mode consumes 33.6% of the electricity in the ground source heat pump cooling mode and the soil thermal storage in free cooling mode is 76.3% of that in ground source heat pump cooling mode. Throughout the summer seasons, the power consumption of the mixed mode is 4.3% lower than that of the ground source heat pump cooling mode, and mixed mode soil thermal storage is 19.5% lower than that of ground source heat pump cooling mode. The results indicate that borehole free cooling system has better energy-saving performance during whole cooling period. In addition, a borehole free cooling system can also reduce the thermal imbalance in the soil.

Key words: *ground source heat pump, borehole free cooling, solar greenhouse, ENERGYPLUS*

Introduction

Solar greenhouses have been used extensively in China. It covered an area of more than 57.7 million square meters (Facilities Horticultural Information Center, http://www.sheshiyuanyi.com/). Due to its energy intensive nature, the rapid growth of greenhouse has resulted in a rapid increase in energy use. The greenhouse has a high potential to reduce carbon emissions [1].

Ground source heat pump (GSHP) systems can achieve heating and cooling by using renewable geothermal energy efficiently. The system also has lower CO_2 emissions and energy use due to its high efficiency, which is beneficial to the environment [2-7]. Greenhouse heating using geothermal energy was universal [8]. The results of the study have

* Corresponding author, e-mail: fanjuu@163.com

proved the feasibility of heating a greenhouse using a GSHP system [9-11]. The efficiency and energy-saving performance of the GSHP system for greenhouse heating has been confirmed by researchers. The COP of GSHP systems reached 3.5 and higher [12-15]. Borehole free cooling is particularly effective and energy efficient in the GSHP system according to a large group of researchers. Study results revealed that the COP of free cooling reached above 15.0, while the electrical energy was greatly saved [16-20]. The majority of borehole free cooling studies were applied to residential and commercial buildings in the last few years, and the efficiency of borehole free cooling has been also revealed, however, research on solar greenhouse cooling by borehole free cooling has not been previously explored.

The mismatch between annual heating and cooling loads leads to an imbalance of geothermal energy. Thermal disequilibrium has emerged as a major impediment to stable and efficient operation in regions dominated by either heating or cooling [21, 22]. Several solutions were proposed to solve the problem. There have been a few studies of hybrid ground source heat pump systems that provided supplemental power through auxiliary heating or cooling source equipment [23-27]. It was also common for GSHP systems to be operated with a variety of strategies [28, 29]. Much of the research has been focused on the GSHP system for use in residential buildings, research on greenhouse should receive more attention.

Dynamic simulations of greenhouse are complicated because there are so many factors that affect simulation outcomes. The TRNSYS has been used in a number of studies to simulate solar greenhouse thermal performance [30-32]. A regression model was developed by Ali Pakari and Saud Ghani who used ENERGYPLUS to calculate the maximum cooling load of a greenhouse [33]. Another work created the ENERGYPLUS dynamical model and carried out its validation using experimental data obtained in a greenhouse [34].

Researches on the application of ground source heat pumps in solar greenhouse have been discussed in the aforementioned studies. Among which, few studies focused on borehole free cooling performance for solar greenhouse. Up to now, no research has been reported on the use of borehole free cooling for solar greenhouse based on the ENERGYPLUS platform. The objective of this work is to develop borehole free cooling of GSHP in a solar greenhouse with ENERGYPLUS and to numerically investigate its thermal performance, which forms the basis of further research into underground soil thermal equilibrium.

Simulating models for solar greenhouse

Model of solar greenhouse

The simulated greenhouse is 60 m long, 15 m wide and 5.8 m high, with the northern wall 4.3 m high. The south roof is made of EVA film and covered by a removable thermal blanket. Tables 1 and 2 show the composition of the wall as well as the dimensions and thermal parameters of the materials. Figure 1 shows the operation principle of the solar greenhouse heating or cooling by the coupled GSHP system.

The solar greenhouse simulation is performed using ENERGYPLUS software. Greenhouse geometric model is established using the SKETCHUP software and the model is fed into ENERGYPLUS to determine the parameters and numerical models of the GSHP system with borehole free cooling.

Weifang City, Shandong Province, China is chosen as the site for the solar greenhouse simulation. The meteorological data used by ENERGYPLUS is available on the official software website (www.energyplus.net).

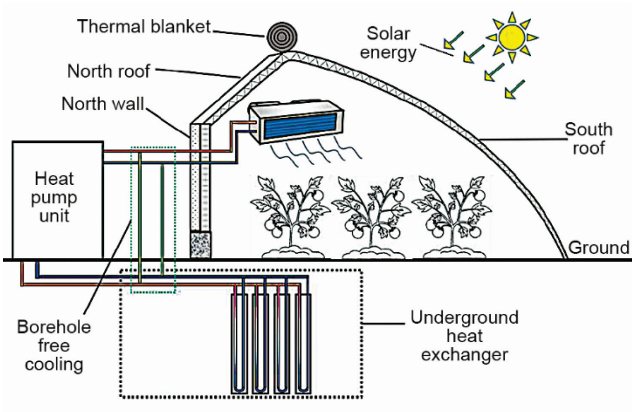

Figure 1. Operating principle of solar greenhouse cooling by GSHP or borehole free cooling

Table 1. Envelope parameters

Construction	Materials	Thickness [mm]
East wall	1 Polyurethane board 2 Slag bricks	100 370
West wall	1 Polyurethane board 2 Slag bricks	100 370
North wall	1 Polyurethane board 2 Slag bricks	100 500
South roof	1 Thermal blanket (movable) 2 EVA film	100 0.1
North roof	1 Pitch whirl material 2 Cement mortar 3 Polyurethane board	4 20 100

Notes: The sequence of materials of walls is from outside to inside

Table 2. Thermal property parameters of materials

Materials	Density [kgm^{-3}]	Thermal conductivity [Wm^{-1}K^{-1}]	Special heat capacity [Jkg^{-1}K^{-1}]
Slag brick	1700	0.87	1050
Cement mortar	1800	0.93	1050
Pitch whirl	2000	0.23	1500
Polyurethane board	35	0.024	1380
EVA film	950	0.04	2010
Thermal blanket	100	0.1	1200

Weifang is located in the eastern part of Shandong Province, at location 35°42'33"-37°26'00" N and 118°10'00"-120°01'00" E. Weifang has a semi-humid continental climate with a warm temperate monsoon climate type of climate, with a mean annual temperature of

12.3 °C and mean annual rainfall of approximately 650 mm. There are four distinct seasons, which are cold in winter and warm in summer.

Thermal load simulation

Depending on the characteristics of tomato growth, the temperature of the tomato crop in the solar greenhouse is controlled between 16 °C and 29 °C.

In an effort to reduce the daily operational energy consumption of solar greenhouses, outdoor shading and natural ventilation are chosen as additional cooling measures, while thermal blanket is chosen as insulation measures. The schedule of cooling and insulation measures is determined based on the temperature in Weifang, which is provided by ENERGYPLUS.

Monthly and hourly heating and cooling loads over a year are simulated by ENERGYPLUS. The result of the simulation is shown in fig. 2. The peak cooling load is in July and January is the month with the highest heating load. The maximum cooling load per hour is 3.04×10^5 kJ, which occurred at 10:00 on 15 August. The maximum hourly heating load is 2.8×10^5 kJ at 10:00 on January 9. The cooling load appears in April and ends October.

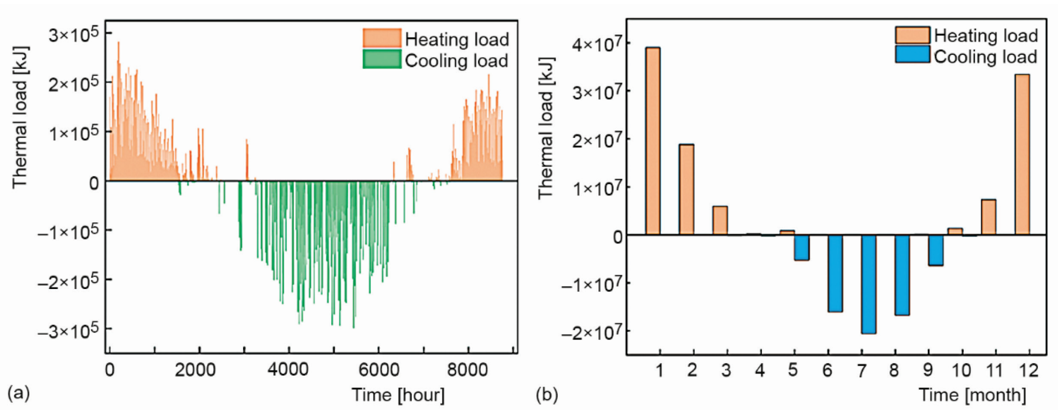

Figure 2. Thermal load of the solar greenhouse; (a) hourly load and (b) monthly load

The GSHP system model

The GLHEPRO software (https://hvac.okstate.edu/glhepro.html) is used to design the heat pump units and the ground heat exchanger (GHE). In GLHEPRO, the number of boreholes and performance curve of the GSHP unit can be simulated through the input of the monthly thermal load, the soil, the fluid and the fluid flow rate. The GLHEPRO then generates IDF documents for ENERGYPLUS.

Ground heat exchanger design

The design results presented by GLHEPRO are shown in tabs. 3-5. Table 3 gives the borehole number as 12, each borehole length as 100 m, the borehole interval as 5 m. Table 4 shows that the specific heat capacity and conductivity of the materials. Working fluid parameters are given by tab. 5.

Table 3. Parameters of GHE

Program	Value	Program	Value
Borehole length [m]	100	*U*-tube outer diameter [mm]	25
Borehole number	12	Thickness of *U*-tube	3.6
Borehole interval [m]	5	Volume flow rate [Ls^{-1}]	0.19
Diameter [mm]	110		

Table 4. Thermal parameters of materials

Materials	Specific heat capacity [$kJK^{-1}m^{-3}$]	Conductivity [$Wm^{-1}K^{-1}$]
Soil	2343.48	2.423
Grout	2300	1.5
Pipes of *U*-tube	1541.985	0.389

Table 5. Working fluid (ethylene glycol/water)

Project	Value	Project	Value
Mixing ratio [%]	15%	Volumetric heat capacity [$kJK^{-1}m^{-3}$]	3968.89
Freezing temperature [°C]	–4.56	Conductivity [$Wm^{-1}K^{-1}$]	0.518
Specific gravity [kgm^{-3}]	1023.88	Viscosity [Pa·s]	0.00131

Heat pump system design

McQuay's RWD 300 at 44GPM_10000CFM model is selected from models supplied by GLHEPRO on the basis of previously simulated monthly cooling and heating loadings, as shown in fig. 2.

It can be seen from fig. 3 that under the refrigeration condition of the heat pump unit, the power consumption and heat rejection of the heat pump increase with the temperature of the circulating fluid of the GHE.

It can be seen from fig. 4 that with the increase of circulating liquid temperature of GHE, the ratio of power consumption to heat supply is decreasing. The ratio of heat of absorption to heat supply increases with increasing of circulating liquid temperature of GHE.

The GSHP cooling mode and borehole free cooling mode

During the summer months, there is an alternative to the GSHP cooling (GC) model known as free cooling (FC). In FC mode, the liquid exits the GHE and flows directly into fan-coils in the greenhouse through additional pipes, instead of flowing through the condenser. Similarly, when fluid exits a greenhouse and flows directly into the GHE.

The FC mode requires only a single circulating pump. In GC mode the entire system requires two circulating pumps and one heat pump. Therefore, the FC mode can potentially save more electricity than the GC cooling mode.

In the case of FC, the model is based on GSHP. A schematic of the GSHP system and free borehole cooling is shown in fig. 5.

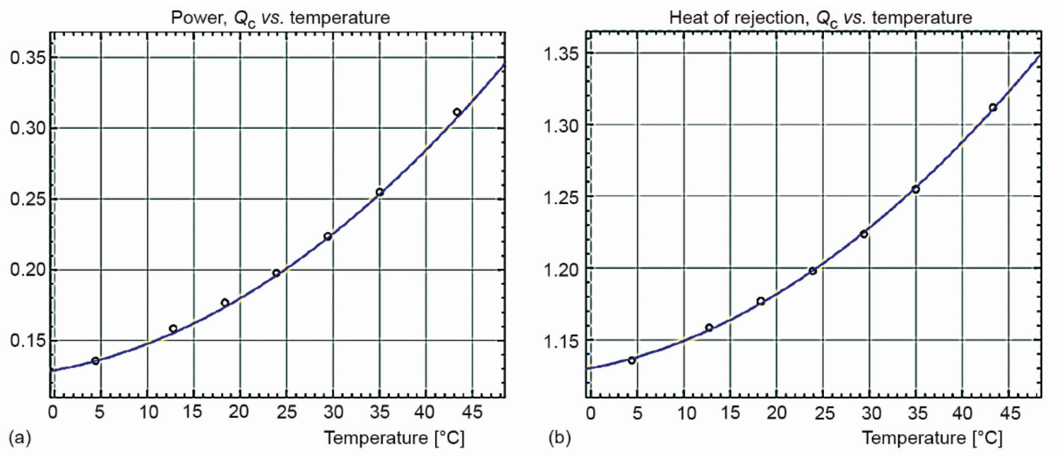

Figure 3. Cooling performance curve of the heat pump unit

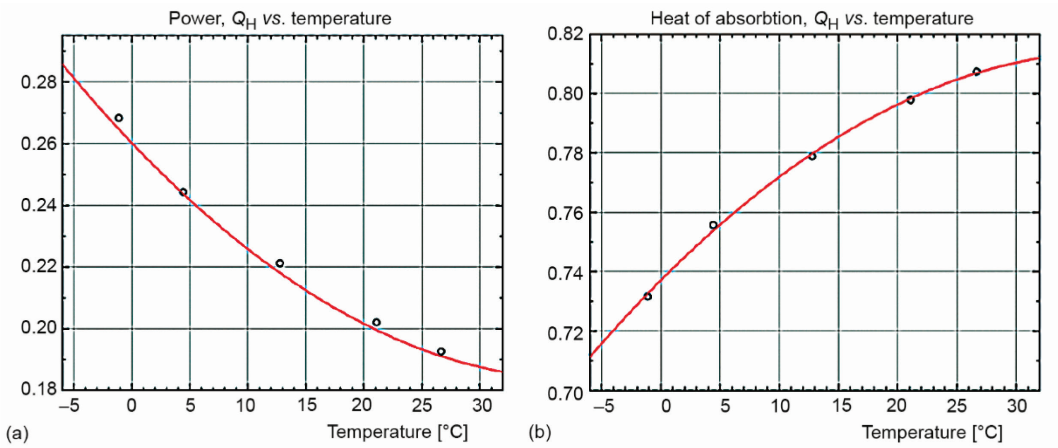

Figure 4. Heating performance curve of the heat pump unit

Three branches of the ENERGYPLUS simulation

There are three branches of the ENERGYPLUS simulation, which are fan coil branch, free cooling and GSHP cooling branch and condenser branch. Figures 6-8 show three branches of the numerical model in this case. All data in this case is evaluated at the node (connecting lines in the figures).

Figures 6-8 show three branches of the numerical model in this case. Where the fan coil is the air loop, fan coil is zone equipment for greenhouse cooling. Free cooling and GSHP cooling branch mean chilled water circling branch. Condenser branch means vertical ground heat exchanger branch.

Calculation basis for relevant parameters

The amount of soil thermal storage in the FC mode and GC mode are similarly, which is defined as follows:

$$Q_s = \sum GC_p (T_{\text{ghe,in}} - T_{\text{ghe,out}})\tau \quad (1)$$

where Q_s [kJ] is the soil thermal storage, G [kgs^{-1}] – the flow rate of circulating fluid, C_p [kJkg^{-1}°C^{-1}] – the specific heat of circulating fluid, $T_{ghe,\text{in}}$ [°C] – the fluid temperature entering the GHE, $T_{\text{ghe,out}}$ [°C] – the fluid temperature leaving the GHE, and τ [s] – the running time.

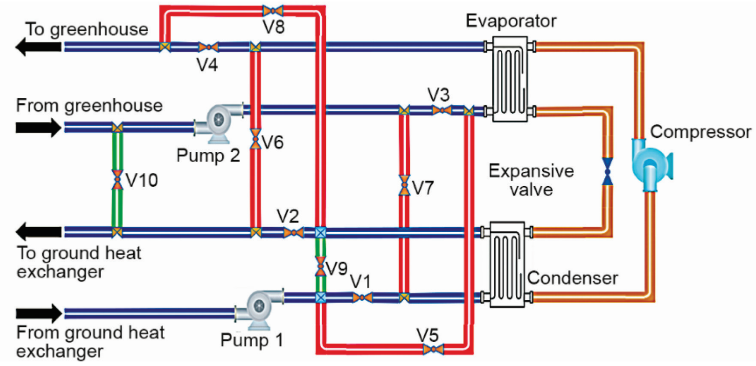

Figure 5. Schematic diagram of the GSHP with free cooling; Notes: GSHP cooling mode, V1, V2, V3, V4 on, others off; the GSHP heating mode, V5, V6, V7, V8 on, others off; free cooling mode, V8, V9, V10 on, others off

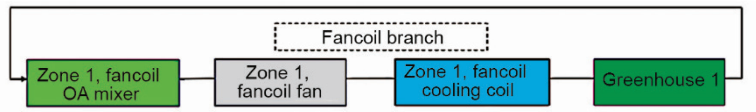

Figure 6. Fan coil branch diagram

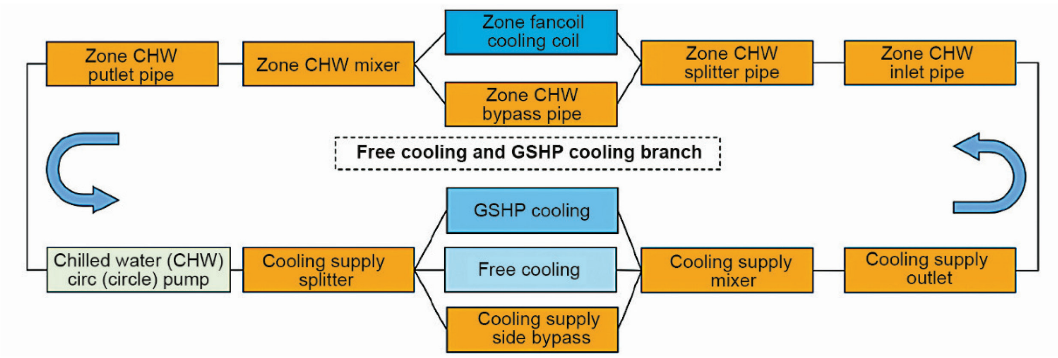

Figure 7. Free cooling and GSHP cooling branch diagram

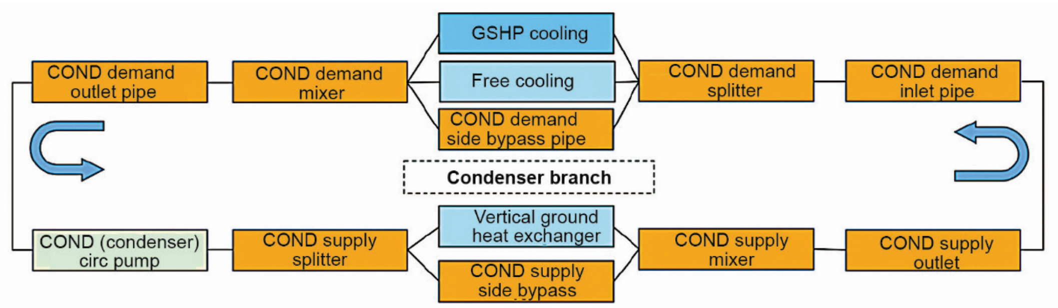

Figure 8. Condenser branch diagram

Electricity consumption in the FC mode is composed of the consumption of pump and fan-coil:

$$E_{\mathrm{fc}} = E_{\mathrm{p1}} + E_{\mathrm{f}} \tag{2}$$

where E_{fc} [kWh] is the electricity consumption of FC mode, E_{p1} [kWh] – the electricity consumption of pump 1, and E_{f} [kWh] – the electricity consumption of fan-coils in greenhouse.

Electricity consumption in the GC mode has two more components, one pump and one heat pump, than FC mode. The components of power consumption are:

$$E_{\mathrm{gc}} = E_{\mathrm{p1}} + E_{\mathrm{p2}} + E_{\mathrm{hp}} + E_{\mathrm{f}} \tag{3}$$

where E_{gc} [kWh] is the electricity consumption of GC mode, E_{p2} [kWh] – the electricity consumption of pump 2, E_{hp} [kWh] – the electricity consumption of heat pump, and E_{f} [kWh] – the electricity consumption of fan-coils in greenhouse.

Energy efficiency ratio (EER) is used to describe cooling capacity per unit power consumption:

$$EER = \frac{\text{cooling load}}{\text{electricity consumption}} \tag{4}$$

where cooling load refers to the excess heat that needs to be discharged from the greenhouse, and electricity consumption refers to E_{fc} or E_{gc}.

Control strategy

The FC mode runs from April to October as fig. 2. The FC mode starts when the internal temperature exceeded 29 °C during the day. Table 8 lists the operating schedule for the greenhouse temperature control methods. The FC mode and the mixed mode running time are given in tab. 9. Mixed mode means that FC mode started first then GC mode took place of FC mode to realize temperature control. That is, FC mode runs first until temperature in greenhouse exceeds 29 °C. Then GC mode starts (FC mode stops meanwhile) to cool down the greenhouse.

Table 8. Running period of facilities according to temperature in solar greenhouse

Running time	Temperature control range	Shading	Natural ventilation	Thermal blanket
4.1-4.30 10.13-11.30	16 °C-29 °C	On, from 9:00 to 17:00	On, above 29 °C	On, from 19:00 to the next day 8:00
5.1-5.30 9.1-10.12	16 °C-29 °C	On, from 9:00 to 17:00	On, above 26 °C from 9:00 to 18:00 Off in other time	Off
6.1-8.31	16 °C-29 °C	On, from 9:00 to 17:00	On, above 26 °C from 9:00 to 18:00 Off in other time	Off

Table 9. Running time of FC mode and mixed mode according to temperature in solar greenhouse

Running time	FC mode	Mixed mode
5.1-5.30 / 9.1-9.30	On, above 29 °C	Off
6.1-8.31	Off	On, running time of FC mode or GC mode depending on temperature control

Analysis of simulation results

Comparison of FC mode and GC mode of transition seasons

Comparison of typical day

In transition seasons (May and September), with the aid of shading and natural ventilation, FC mode can fully control the greenhouse temperature. In order to compare the differences between FC mode and GC mode in transition seasons, May 1 is selected as typical day. The calculation for the rest of the transition seasons is similar to that of May 1. Figure 9 shows the typical day comparison results.

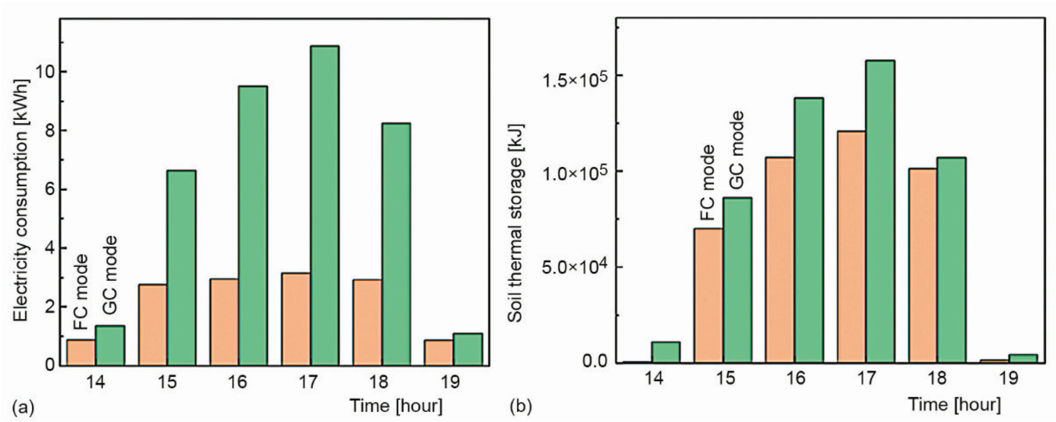

Figure 9. Comparison of simulation results on May 1; (a) electricity consumption in FC mode and GC mode and (b) soil thermal storage in FC mode and GC mode

As can be seen in fig. 9(a), from 14:00 to 19:00, the hourly electricity consumption of the FC mode is lower than that of the GC mode. Total electricity consumption is 13 kWh of FC mode and 37.7 kWh of GC mode, with 35.9% of the power consumed by the FC mode compared to the GC mode. There is no electricity consumption during the rest of May 1 because the FC mode or GC mode is not started.

From fig. 9(b), the soil obtains 4×10^5 kJ for FC mode and 5×10^5 kJ for GC mode. Soil thermal storage is more in GC mode than FC mode. With the exception of the 14:00 to 19:00, the temperature in the greenhouse is well controlled by shading and (or) natural ventilation during the other period. So, there is no soil thermal storage.

The EER comparison of GC mode than FC mode is shown in fig. 10.

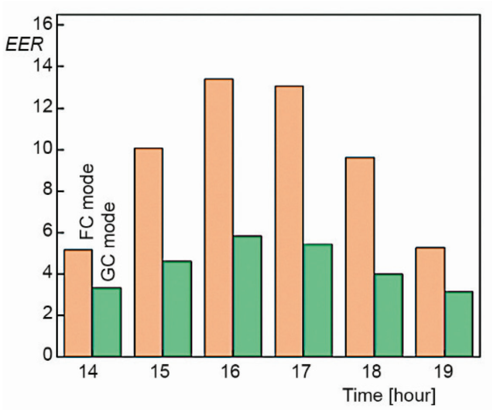

Figure 10. Comparison of EER on May 1

As fig. 10 shows, between 14:00 and 19:00, the EER of GC mode first increases and then decreases. The peak EER appears at 16:00, which corresponds to 13.8. The EER value of GC mode also changes according to the same rule, and the maximum value is 5.8 at 16:00. The FC mode has more energy saving potential than GC mode.

Comparison of transition seasons

During the transition seasons, *i.e.*, May and September, the cooling load is relatively low. The FC mode fully meets solar greenhouse cooling requirements during the transition seasons. Therefore, the simulation considers only the months of May and September. The monthly simulation results are shown in fig. 11.

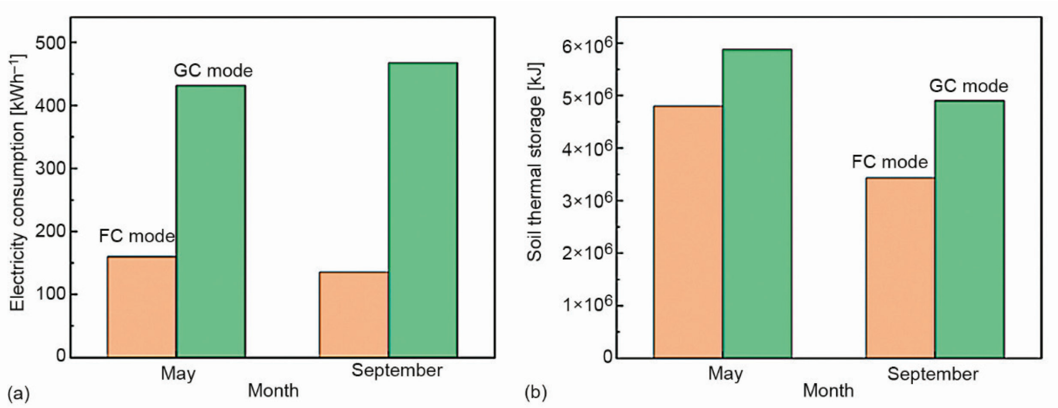

Figure 11. Comparison of monthly simulation results; (a) electricity consumption in FC mode and GC mode and (b) soil thermal storage in FC mode and GC mode

As shown in fig. 11, in May and September, the FC mode power consumption is 165.4 kWh and 135.7 kWh, respectively, while the GC mode uses 435.7 kWh and 461.5 kWh, respectively. Compared to the GC mode, the FC mode consumes 62% less electricity in May and 71% less electricity in September. In other words, the FC mode consumes 33.6% of the electricity in the GC mode during the entire transition seasons. The power consumption of the FC mode is significantly less than that of the GC mode under similar internal temperature conditions. The cooling capability of the FC mode can meet the cooling requirements of the transition seasons.

The FC mode has the potential to cool the solar greenhouse throughout the entire transition seasons. This results in a total soil thermal storage of 8.24×10^6 kJ in FC mode and 1.08×10^7 kJ in GC mode. The soil storage energy in FC mode is 76.3% of that in GC mode. During the transition seasons, the GC mode stores more heat than the FC mode.

Comparison of mixed mode and GC mode of summer seasons

Throughout the summer seasons (from June to August), the cooling load is much greater than the cooling capability of the FC mode, so it is important to start-up a mixed mode. In mixed-mode, FC operates until the greenhouse temperature exceeds 29 °C, at which point GC mode begins to replace FC mode. In mixed-mode, shading and natural ventilation also work together.

Comparison of typical day

July 9 is selected as typical day of summer seasons according to ENERGYPLUS. Figure 12 gives the simulation results of electricity consumption and soil thermal storage for the typical day.

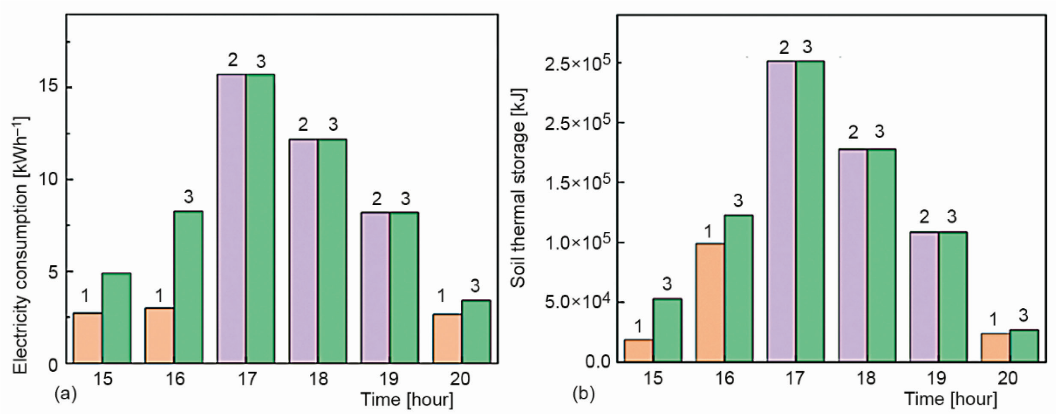

Figure 12. Comparison of simulation results on July 9; (a) electricity consumption in FC mode and GC mode and (b) soil thermal storage in FC mode and GC mode; *1 – FC mode (mixed mode), 2 – GC mode (mixed mode), 3 – GC mode*

Figure 12(a) shows that from 17:00 to 19:00 the mixed mode consumes the same electricity as the GC mode, due to the fact that the GC mode is operating at this time in the mixed mode. From 15:00 to 20:00, mixed mode consumes total 44.56 kWh (FC mode 8.4 kWh, GC mode 36.16 kWh), GC mode consumes 52.73 kWh. At other times on July 9, the cooling load can be removed by natural ventilation and shading.

As shown in fig. 12(b), the mixed-mode soil thermal storage is the same as the GC mode from 17:00 to 19:00. From 14:00 to 21:00, soil thermal storage is 4.46×10^6 kJ in mixed mode (FC mode 0.84×10^6 kJ, GC mode 3.62×10^6 kJ) and 5.27×10^6 kJ in GC mode.

The EER comparison of mixed mode and GC mode is shown in fig. 13.

It can be seen from fig. 13 that between 15:00 and 16:00, the mixed mode actually operates in FC mode, so the EER values are 6.4 and 8.6 respectively. From 17:00 to 19:00, the mixed mode operates in GC mode, EER values are 5.5, 4.4, 3.7, respectively. The mixed mode operates in FC mode, with EER value is 5.7 at 20:00.

From 15:00 to 16:00, the EER values running in GC mode are 3.6 and 5.1 respectively. The EER value is 3.3 at 20:00.

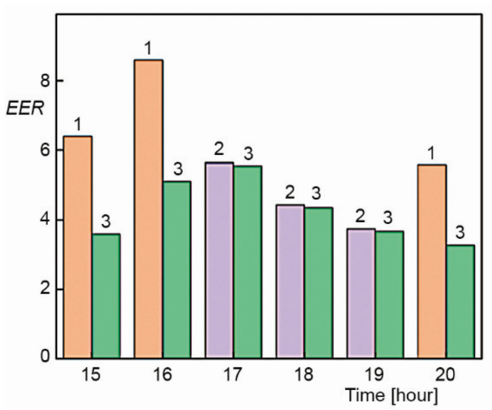

Figure 13. Comparison of hourly EER on July 9; *1 – FC mode (mixed mode), 2 – GC mode (mixed mode), 3 – GC mode*

Comparison of summer seasons

According to our simulation, summer seasons are June, July and August. Figure 14 shows a comparison of electricity consumption and soil thermal storage.

As can be seen from fig. 14(a) that only 11.4% (131.8 kWh) of the 1160 kWh of electricity consumed in June is used in the FC mode of operation. As of July, the power consumption is 1800 kWh, of which only 13.4% (241.9 kWh) is consumed by the FC mode of operation. 1370 kWh of energy use overall in August, only 5.5% is in FC mode, which utilizes 75.2 kWh. The total power consumption of the mixed and GC summer modes are 4330 kWh and 4523 kWh, respectively. The power consumption of the mixed mode is 4.3% less than the GC mode.

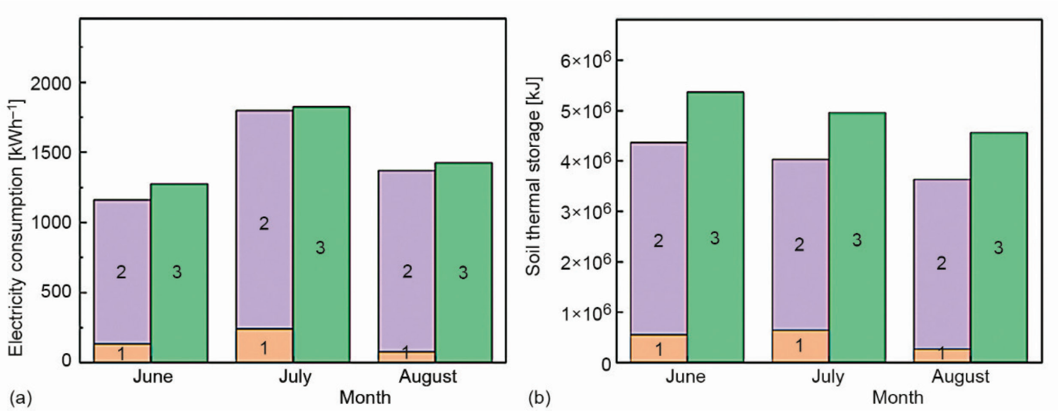

Figure 14. The electricity consumption in summer; (a) the portion of electricity consumption in mixed mode and (b) electricity consumption comparison between mixed mode and GC mode*1 – FC mode (mixed mode), 2 – GC mode (mixed mode), 3 – GC mode*

As shown in fig. 14(b), the total amount of heat storage in the soil in the summer mixed mode is 1.20×10^7 kJ (${1.46 \times 10^6}$ kJ in FC mode) and in the GC mode it is 1.49×10^7 kJ. The soil thermal storage in the mixed mode is 19.5% lower than that in the GC mode. This demonstrates that GC mode is able to transfer more heat than the mixed mode throughout the summer cooling period.

Conclusions

A numerical ground source heat pump system with borehole free cooling model is developed to reduce the energy consumption of greenhouse operations. The FC mode and the mixed mode are compared with GC mode. The following conclusions may be drawn from the previous analysis:

- In transition seasons (May and September), the FC mode consumes 33.6% of the electricity in the GC mode. In transit seasons, because the heat pump is not working, FC mode is significantly energy-efficient compare to GC mode.
- The electricity consumption of the mixed mode (FC and GC) is 4.3% lower than that of the GC mode during summer seasons (June, July and August). In summer, the cooling load is too high, which makes FC mode inadequate. The mixed mode which includes FC mode and GC mode is still energy efficient compared to GC mode.
- During the cooling period, soil absorbs slightly more heat in the GC than in the FC mode (transition seasons) together with the mixed mode (summer seasons). In order to store more heat underground, FC mode can run more time instead of natural ventilation and shading, depending on greenhouse heating conditions. This is helpful to realize underground thermal balance. We will discuss it in the follow-up study.

Acknowledgment

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Nomenclature

C_p – specific heat of circulating fluid, [kJ/kg·°C]
EER – energy efficiency ratio, [–]
E_f – electricity consumption of pump 1, [kWh]
E_{fc} – electricity consumption of FC mode, [kWh]
E_{gc} – electricity consumption of GC mode, [kWh]
E_{hp} – electricity consumption of pump 2, [kWh]
E_{p1} – electricity consumption of pump 1, [kWh]
E_{p2} – electricity consumption of pump 2, [kWh]
G – flow rate of circulating fluid, [kg/s]
Q_s – soil thermal storage, [kJ]
$T_{ghe,in}$ – fluid temperature entering the GHE, [°C]
$T_{ghe,out}$ – fluid temperature leaving the GHE, [°C]

Greek symbol

τ – running time, [s]

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