Research on simulation of energy consumption of ground water-source heat pump air conditioning system in plant factory

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Abstract. The study of low-cost energy supply methods for large plant factories in China is of great significance to promote the healthy and steady development of large greenhouses. Aiming at the problems of high cost, poor stability, chaotic production management, and no indicator of long-term operation energy consumption in the operation of large plant factories, this paper analyzes long-term operation data by studying the heating situation of Chongming plant factory to improve plant factory regulation methods for the purpose of energy saving and cost reduction. A plant factory model was constructed using TRNSYS to simulate typical annual energy supply throughout the year to obtain cooling and heating energy consumption. The simulation results show that the annual peak heat load of the plant factory is 1502.6 kW and the peak cooling load is 913.8 kW. The annual energy consumption of the whole plant factory is 3799.12 GJ for cooling and 4468.34 GJ for heating, and the annual energy consumption of the whole plant factory is 8267.46 GJ. A8 and its three surrounding greenhouses A6, A7, and A10 can be used as a single zone for energy supply. This zone takes advantage of the structural characteristics of the building to reduce energy consumption. The simulation shows that the ground source heat pump system is sufficient to supply the energy consumption of these four greenhouses and even to achieve the optimal temperature conditions for growing vegetables inside them.

1. Introduction
With the development of the economy and the improvement of energy use, heat pump systems are widely used in buildings[1,2], greenhouse[3,4], biogas digesters[5,6]. Most importantly, the actual energy supply engineering energy utilization effect is worthy of attention. There are two schemes to discuss: engineering test and software simulation. Engineering test will be time-consuming, while software simulation can save a great deal of costs, as well as carry out the design and verification of various control schemes. Therefore, the simulation of the ground source heat pump was studied [7,8]. Hobbie[9] et al. presented a model of an indirect forced circulation solar water heating systems for domestic hot water requirements and used TRNSYS simulation program to determine the optimum values. The results of this study indicate that the system could provide 80% and 30% of the hot water demands in summer and winter. YAU [10] et al. designed a complete empirical transient systems simulation program model to estimate the entire typical meteorological year energy consumption of an operating theatre located in Kuala Lumpur, Malaysia.
The above researches are mostly concentrated in the field of construction. So far, however, there has been little discussion about the simulation of energy consumption of water storage underground water source heat pump air conditioning system in a plant factory. This study aims to bridge the gaps by establishing a model of heat pumps based on using TRNSYS to obtain energy consumption of refrigeration and heating in the large plant factory on Chongming Island.

2. System principle
National Engineering Research Center of Protected Agriculture has plant factories with an area of 21000m$^2$, divided into three zones A, B, and C. The seven plant factories in Zone A adopt a water storage underground water source heat pump air conditioning system with an area of 5880m$^2$. The plant factory was 35m long, 6.5m at the gutter, and 7.5m high at the ridge and consisted of 6 spans each 4m wide.

As shown in Figure 1, the water storage underground water source heat pump air conditioning system of the plant factory consists of a heat pump unit, air handling unit, plant factory side circulating water pump, hot water storage tank, cold water storage tank, and its pipeline accessories.

![Figure 1. Ground water-source heat pump air conditioning system](image)

1. Hot water well 2. Cold water well 3. Cryogenic plate heat exchanger 4. Cold water storage tank 5. Heat pump unit 6. Plant factory 7. Hot water storage tank 8. High-temperature plate heat exchangers 9. Boiler B1: Submersible pump B2: Side circulating water pump B3: Cooling pump B4: Side circulating water pump of plant factory(summer) B5: Plant factory side circulating water pump B6: Heat pump load side circulation pump B7: Side circulating water pump(winter) of plant factory B8: Heat pump B9: Side circulating water pump(summer) B10: Heat pump boiler V1-V24: Electromagnetic valve

The energy supply system of the plant factory has the following four operating modes: (1) In winter, when the heat supply of the heat pump unit is greater than the heat load of the plant factory, the energy supply system starts heating while storing heat. In summer, when the cooling capacity of the heat pump is greater than the cooling capacity of the plant factory, the energy supply system starts storing cold while cooling. (2) In winter, when the heat supplied by the heat pump unit and the hot water storage tank is less than the heat load of the plant factory, the heat pump unit and the hot water storage
tank begin heating. In summer, when the cooling capacity of the heat pump unit and the cold water storage tank are less than the cold load of the plant factory, the heat pump unit and the cold water storage tank start cooling. (3) In winter, when the price of electricity is at its peak and the heat from the hot water storage tank meets the requirements of the heat load of the plant factory, the cooling water wells stop storing cold.

3. Simulation of ground water-source heat pump air conditioning system in plant factory using TRNSYS

TRNSYS Simulation of ground water-source heat pump air conditioning system in a plant factory is built based on Figure 1. TRNSYS simulation of the system should include meteorological parameters, vacuum tube solar collector, heat pump unit, hot water storage tank, digester, buried pipe, pump, operation controller, calculation result printing, etc. The corresponding modules in TRNSYS are shown in Table 1.

| Name of component                  | Module of TRNSYS          | Note                                      |
|-----------------------------------|---------------------------|-------------------------------------------|
| Meteorological parameters         | Type 109-TMY2             | TMY2-type weather parameters in Shanghai  |
| Multi-regional greenhouses        | Type 56                   | Entering a range of building parameters   |
| Calculator                        | Unit 0                    | Implementation of simple calculation functions |
| Switch Control                    | Type 2d                   | Setting the time switch                   |
| Printer                           | Type 65c/d                | Output Results                            |
| Outdoor temperature               | Type 69b                  | Calculation of temperature by outdoor meteorological parameters |
| Psychrometric chart               | Type 33e                  | Calculation of humidity and dry bulb temperature |

Regulate the optimal temperature to adapt to the growth of different plants in each plant factory. Strawberries are grown in Zone A2, the most suitable temperature for strawberries is 18-25°C, and the heating target in winter is set to 25°C during the day and 18°C at night, and the cooling target in summer is 27°C during the day and 20°C at night. Cucumbers are planted in areas A4 and A6. The most suitable growth temperature for cucumbers is 20-30°C. The heating target in winter is 30°C during the day and 20°C at night; the cooling target in summer is 32°C during the day and 22°C at night. The most suitable temperature for growing colored pepper in the A8 area is 17-27°C. The heating target in winter is set at 27°C during the day and 17°C at night; the cooling target in summer is 29°C during the day and 19°C at night. Planting large tomatoes in the A9 area, the most suitable temperature is the same as that of cluster tomatoes. The heating target in winter is set at 28°C during the day and 18°C at night; the cooling target in summer is 30°C during the day and 20°C at night. Set 7:30-17:30 in winter as daytime, other times as evening, summer 6:30-19:00 as daytime, and other times as evening. In TRNSYS’s Type 65, set the heating temperature, heating schedule, cooling temperature, and cooling schedule suitable for different plant factories, and select the typical meteorological year data as the outdoor weather parameters. Due to the actual greenhouse energy supply project, there will be a transition season with daytime cooling and nighttime heating conditions. In order to prevent errors in the control logic, when simulating the year-round heat load, the air conditioner cooling energy supply is turned off by default; when simulating the cold load, the air conditioner heating function is turned off by default. Although the setting of such energy supply mode will have some errors with the actual situation, the winter and summer seasons will not be confused, and the data required for the hourly heat load is the peak cooling and heating load, and the peak will not appear in the transitional season, and the error is only caused by the lower cooling and heating load in the transitional season, which will not have a great influence on the result. Input the required parameters of each module to simulate the annual cooling and heating load of seven plant factories, and add the results to get the annual cooling and heating load, as shown in Fig2,3. The typical annual
cooling and heating energy consumption and total energy consumption results of the seven plant factories are shown in Table 2.

Looking at Figure 2 and 3, it is apparent that the peak heat load is 1502.6kW and the peak cooling load is 913.8kW. The gap at the bottom left of the hourly heat load curve indicates that the seven plant factories need almost all-day heating in January and February, while the gap in the middle of the hourly cooling load curve indicates that the seven plant factories need all-day cooling in July and August.

| Plant factory | A2  | A4  | A6  | A7  | A8  | A9  | A10 | Total  |
|---------------|-----|-----|-----|-----|-----|-----|-----|--------|
| the peak cooling loads (kW) | 304.0 | 113.4 | 113.5 | 235.1 | 86.4 | 159.6 | 185.0 | 913.8 |

**Figure 2.** Hourly heat load of seven plant factories throughout the year.

**Figure 3.** Hourly cooling load of seven plant factories throughout the year.

**Table 2.** Cooling and heating energy consumption and total energy consumption results for seven greenhouses.
From the table 2 above, we can see that the cooling and heating energy consumption of a plant factory shows a similar trend: the higher the cooling energy consumption, the higher the heating energy consumption; the larger the contact area with the outside world, the higher the cooling/heating energy consumption. Plant factory A2 has the highest annual total energy consumption, while plant factory A8 has the lowest; plant factory A4 and A6 have similar annual total energy consumption, while plant factory A7, A9 and A10 have similar annual total energy consumption; the reason for the low heating energy consumption in plant factory A8 is that the three surrounding plant factories provide heat, which is equivalent to surrounding plant factory A8 and has a significant thermal insulation effect; The reason why the cooling energy consumption of plant factory A8 is not the lowest is that the main source of heat in the summer plant factory comes from sunlight, and the surrounding plant factory affects its heat dissipation. However, the annual cooling energy consumption of plant factory A8 itself is still very low.

Therefore, the best strategy for the operation of a plant factory can be derived from it. The plant factories should take advantage of the thermal insulation effect brought about by their different building structures to achieve energy savings. If only the three rooms around A8 and A8 are heated, that is, the four plant factories A8, A6, A7, and A10 are provided. Since the three plant factories A6, A7, and A10 surround A8, the left wall of A6 is not in contact with outdoor air, but A4 plant factories. A7 and A10 are also in contact with A9, so the four plant factories for heating only are the minimum annual energy consumption that can be achieved when heating the same area of the plant factory. According to the simulation results, the sum of the maximum heating load of the four plant factories for heating is 799.7kW, and the sum of the maximum cooling load is 620kW, which is exactly the same as the maximum heating/cooling power of the heat pump. Theoretically, the ground-source heat pump energy supply system can supply the energy consumption of these four plant factories, and even reach the optimal temperature conditions for growing vegetables inside. Therefore, choosing the energy supply interval according to the plant factory building structure can bring about the energy-saving effect.

4. Conclusion
Simulation of annual energy consumption of seven plant factories to control the optimal climate for suitable plant growth was carried out. The simulation results show that the total annual heating energy consumption to reach the optimum temperature is 4468.34 GJ and the total annual cooling energy consumption is 3799.12 GJ. A8 and its three surrounding plant factories A6, A7, and A10 can be used as a separate zone to supply energy. This zone takes advantage of its unique architecture to reduce energy consumption, and the existing ground source heat pump system is theoretically sufficient to supply these four plant factories with energy and even to achieve the optimum temperature conditions for growing vegetables inside.

Acknowledgments
This work was financially supported by National High Technology Research and Development Program (863 Program).

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