Electronic Supplementary Material

Precise quantification of microclimate heterogeneity and canopy group effects in actively heated solar greenhouses

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Table S1 The details and characteristics of sensors used for monitoring data in greenhouse.

Sensor	Solar radiation	Temperature &Humidity	LiDAR	Outdoor microclimate
Photograph				
Measured variable	Photosynthetically active radiation.	Temperature Humidity	The canopy structure of cucumber plants.	Temperature Humidity Wind velocity Solar radiation
Accuracy	≤±5%	±0.4℃ ±2%	±1 mm	±0.4℃ ±2% ≤±5% ±0.2 m/s
Response time	0.1s	≤8s	2MPts/s	≤25s
Measurement range	0~2000 W/m^2	-40℃ to 120℃ 0 % RH~100% RH	0.5~100 m	-40℃~120℃ 0 % RH~100% RH 0~70 m/s 0~2000 W/m^2
Operating temperature	-25℃~60℃	-40℃ to 80℃	-10 ℃ to 55 ℃	-25℃ to 60℃
Manufacturer	Shandong Jianda Renke Electronic Technology Co., Ltd., China.	Shandong Jianda Renke Electronic Technology Co., Ltd., China.	FARO Focus, LakeMary, Florida, USA	Shandong Jianda Renke Electronic Technology Co., Ltd., China.

Table S2 Statistical analysis results of the model accuracy

Temperature	PRMSD (%)	NMSE (%)	MAE	MRE (%)
Air	3.25	2.33	0.48	2.93
Water	4.10	0.25	1.62	3.64

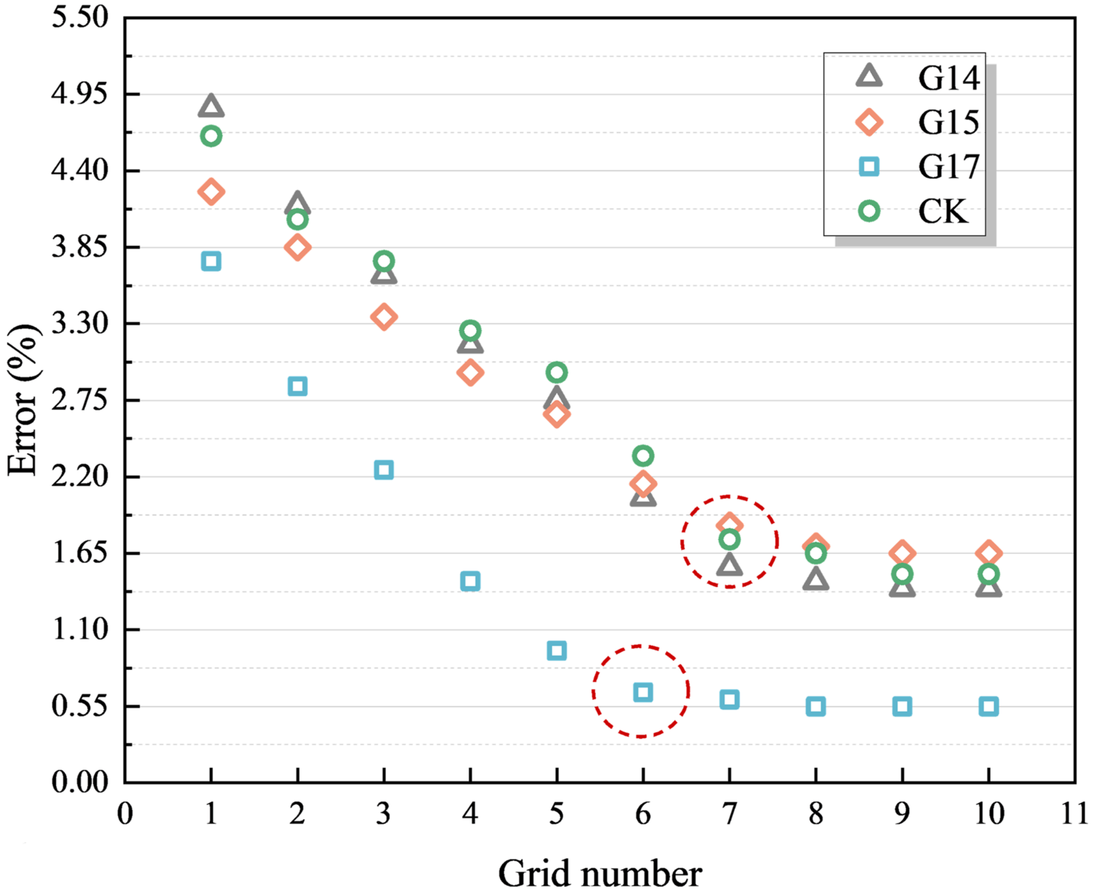

Fig. S1 Grid independence verification: air temperature error for ten grids comparing to the Richardson extrapolation results.

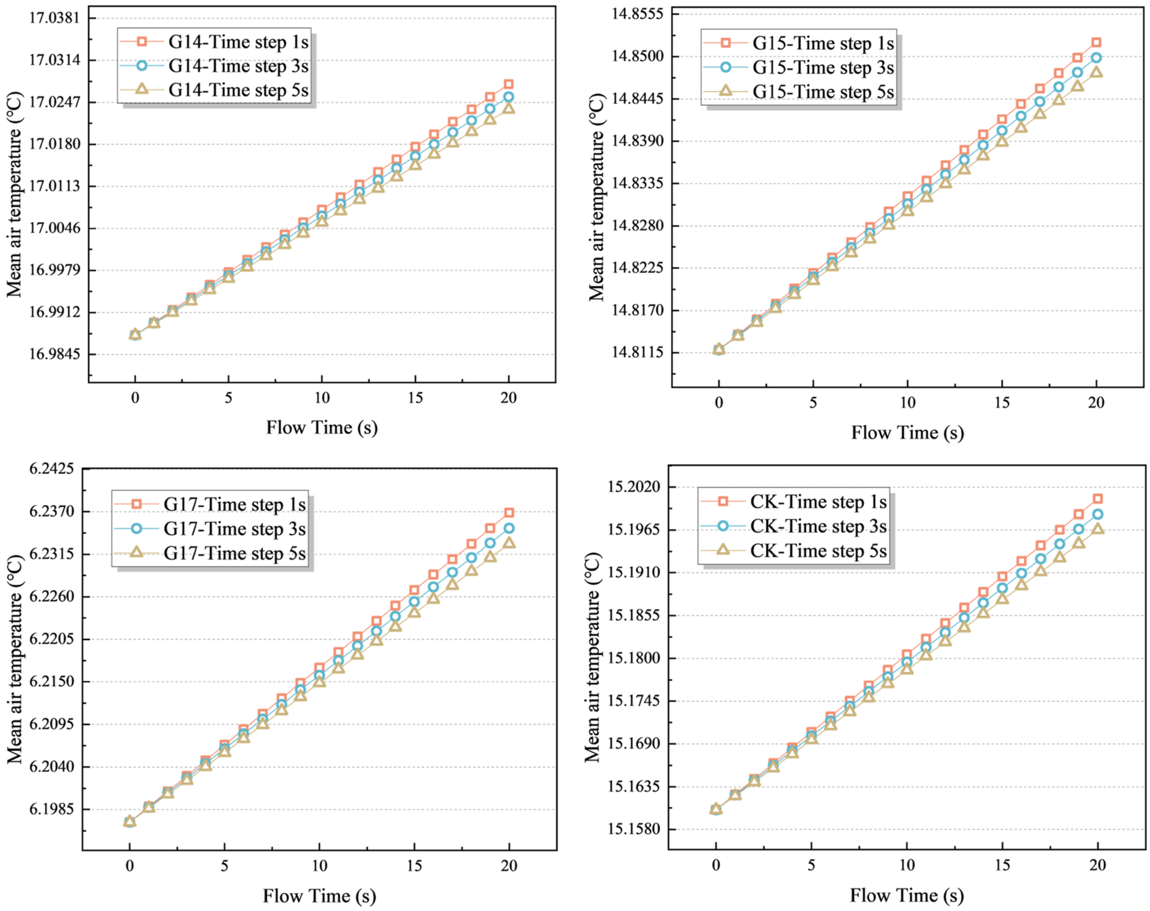

Fig. S2 Grid independence verification: air temperature error for ten grids comparing to the Richardson extrapolation results.

Microclimate sensors in the CSG canopy were categorized into upper, middle, and lower layers vertically. As shown in Fig. S3, during sunny day, the upper canopy exhibited significantly higher average temperature compared to the middle and lower parts, with differences of 0.9 °C and 1.8 °C, respectively. The overall temperature in the western section of the greenhouse was higher than those in the eastern and middle sections, with daily average temperatures of 21.1 °C, 20.2 °C, and 20.4 °C, respectively. In contrast to the temperature trends, humidity at the top of the canopy was notably lower than those in the middle and lower parts, with relative humidity decreasing from top to bottom, recorded at 70.1 %, 76.0 %, and 78.0 %, respectively.

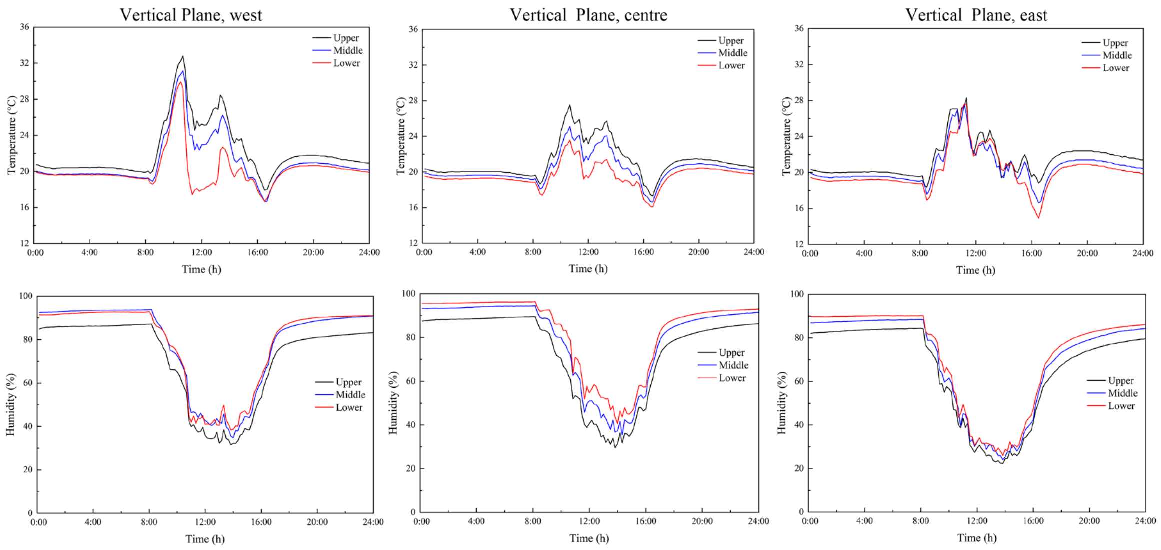

Fig. S3 Vertical heterogeneity parameters (air temperature and relative humidity) measured at each measurement station with the height of 0.5m, 1.0 m and 1.5 m (December 1st, 2023).

As shown in Fig. S4, temperature near the greenhouse wall, particularly in the northern part, were significantly higher than in the central and southern parts, with the southern part recording the lowest temperature. The temperature difference between the northern and southern parts was 0.7 °C in the CSG western, 0.7 °C in the central part, and 0.6 °C on the eastern side. In terms of humidity, the areas near the wall (northern part) exhibited lower humidity compared to the central and southern parts. Specifically, the humidity variation trends were more similar between the central and southern parts in the western side of the greenhouse. The eastern part of the greenhouse generally exhibited lower relative humidity.

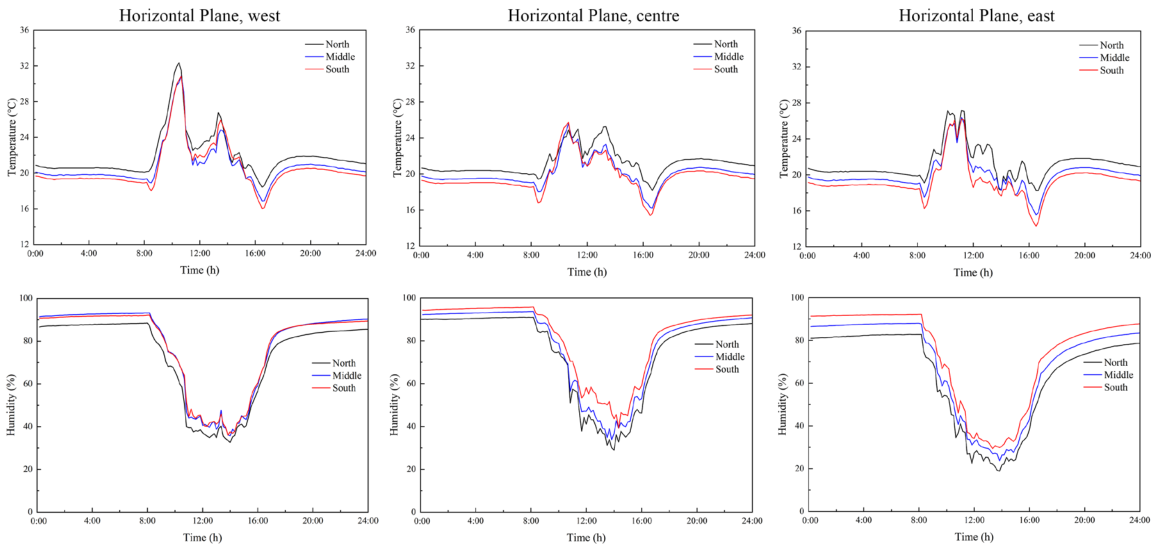

Fig. S4 Horizontal heterogeneity parameters (air temperature and relative humidity) measured at each measurement station with the height of 0.5 m, 1.0 m and 1.5 m (December 1st, 2023).

Figure S5 illustrated the vertical temperature trends on cloudy day. It was evident that after closing the quilt, the average temperature trends at different canopy heights during the day were similar. Temperature decreased uniformly from top to bottom, with an average vertical temperature difference of 0.5 °C in the western part, while the difference was only 0.1 °C in the central and eastern parts. The relative humidity at the top of the canopy was significantly lower compared to the middle and bottom sections, with no significant difference between the middle and bottom parts.

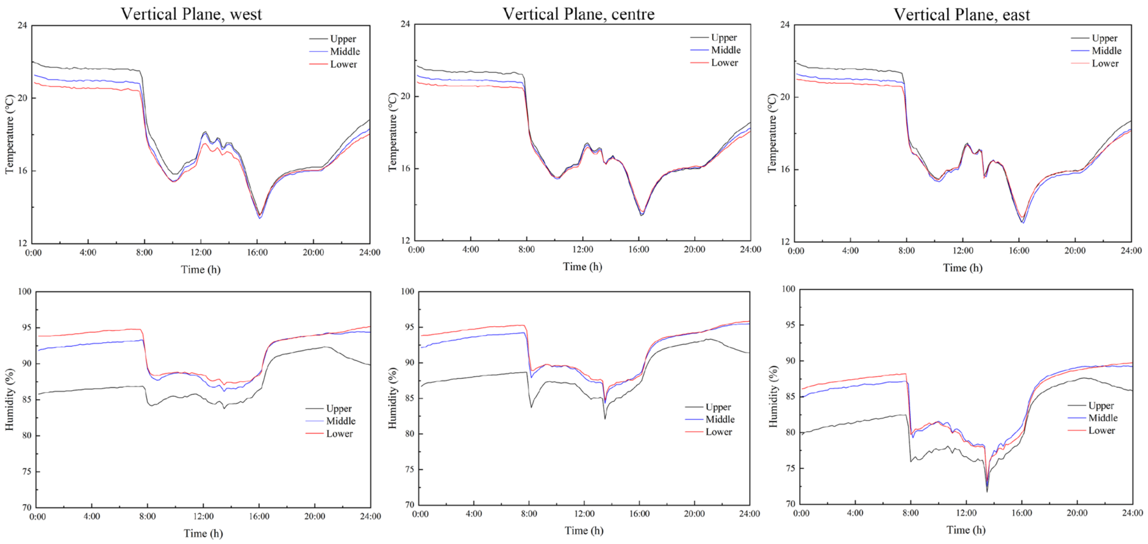

Fig. S5 Vertical heterogeneity parameters (air temperature and relative humidity) measured at each measurement station with the height of 0.5 m, 1.0 m and 1.5 m (December 10th, 2023).

Unlike the vertical temperature variations, the horizontal north-south temperature trends on cloudy day during the daytime showed distinct patterns, with the northern part being warmer than the central part, and the southern part being lowest, with average temperatures reaching 18.5 °C, 17.7 °C, and 17.3 °C, respectively. The relative humidity in the southern part of the greenhouse was the lowest. Compared to the central and western parts, the differences in relative humidity were more significant in the eastern parts along the north-south direction, with daily average relative humidity values of 79.2 %, 84.0 %, and 87.7 %.

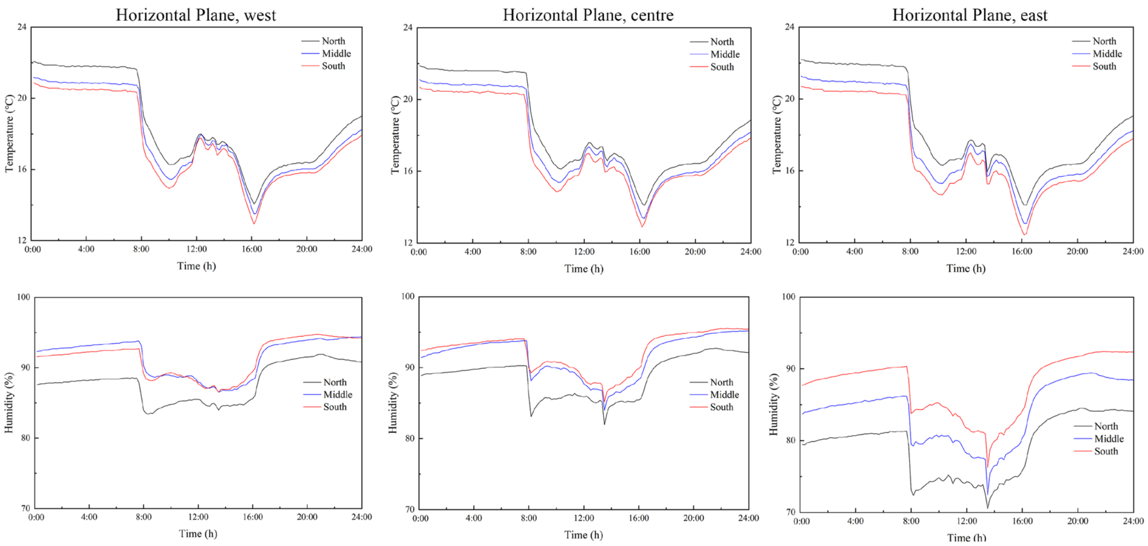

Fig. S6 Horizontal heterogeneity parameters (air temperature and relative humidity) measured at each measurement station with the height of 0.5 m, 1.0 m and 1.5 m (December 10th, 2023).

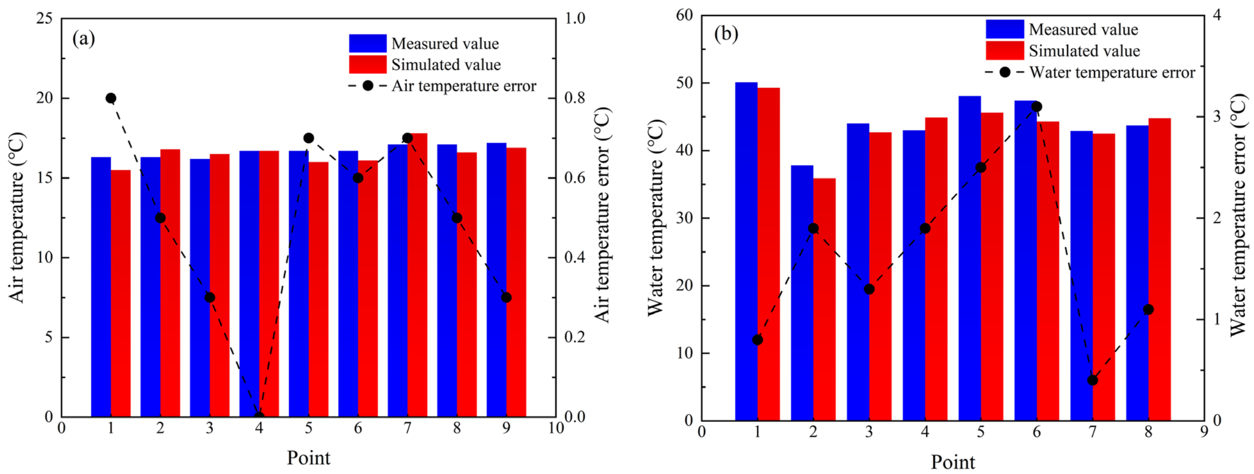

Fig. S7 Verification of simulation model accuracy based on different measuring points of greenhouse No. 14. (a) verification of air temperature, (b) Verification for water temperature of heating device media.

Calculation flow

(1) Solar radiation energy

Based on the GroIMP platform combined with outdoor solar radiation intensity, a 3D greenhouse model, and optical properties of greenhouse materials, the quantitative analysis of solar radiation entering the greenhouse lighting roof was achieved. Through the calculations, the total solar radiation captured by the greenhouse front roof over a day amounted to 2025 kW.

$$Q_R = \sum_{t=9}^{t=16} Q_L \tag{1}$$

(2) Heat loss of solar greenhouse

Dissipation of heat transfer (Q_1):

The variables in the thermal analysis of CSG building envelopes are defined as follows: A_j represents the total area of the envelope components (lighting roof, wall, side walls, roof), k denotes the thermal transmittance coefficient in unit of W m^{-2}·K^{-1}, t_{in} signifies the indoor temperature (°C), t_{out} indicates the outdoor temperature (°C). μ_i represents the thickness of the i-th layer of building material (m), γ_i stands for the thermal conductivity of the i-th layer of building material in W m^{-1}·K^{-1}.

$$Q_1 = \sum_{i=1}^{n} A_j k_j (t_{in} - t_{out}) \tag{2}$$

$$k = 1/\sum_{i=1}^{n} \frac{\mu_i}{\gamma_i} \tag{3}$$

Osmotic heat loss (Q_2):

W is the wind speed, V stands for the volume of greenhouse (1876 m^3), and N is the number of air changes per hour.

$$Q_2 = 0.5W \cdot V \cdot N \cdot (t_{in} - t_{out}) \quad (4)$$

Soil heat loss (Q_3):

$$Q_3 = \sum kA_s(t_{in} - t_{out}) \quad (5)$$

During winter in Beijing, the greenhouse quilt was in open from 9:00 a.m. to 4:00 p.m., providing closed for 16 hours out of the 24-hour day. Based on analysis of experimental meteorological data, daytime indoor temperature was maintained at 17 °C with an outdoor temperature of -3 °C, while nighttime temperatures were set to 12 °C indoors and -12 °C outdoors. The greenhouse experienced natural ventilation averaging 3.4 air changes per hour during the day, and nighttime infiltration brings this rate to 1.2 air changes per hour. The thermal transmittance coefficient of the single-layer polyethylene film is 6.8 W $m^{-2}\cdot K^{-1}$, with a thickness of 0.03 m and a thermal conductivity of 0.04 W $m^{-1}\cdot K^{-1}$. Consequently, the overall thermal conductivity of the lighting roof, including the quilt cover, is 1.115 W $m^{-2}\cdot K^{-1}$. The wall thickness is 0.37 m with a thermal conductivity of 2.2 W $m^{-1}\cdot K^{-1}$, and the outer layer is covered with a 3 cm thick polystyrene board with a thermal conductivity of 0.03 W $m^{-1}\cdot K^{-1}$, resulting in a wall thermal conductivity of 0.69 W $m^{-2}\cdot K^{-1}$. The thermal conductivity of the roof is 1.03 W $m^{-2}\cdot K^{-1}$. The detailed calculation process is as follow:

Daytime:

$$Q1 = (6.8 * 681.55 + 0.69 * (224 + 46.9) + 1.03 * (118.93)) * (20) = 98.88\ \text{kW} \quad (6)$$

$$Q2 = 0.5 * 1 * 1876 * 3.4 * 20 = 63.78\ \text{kW} \quad (7)$$

$$Q3 = 0.24 * 640 * (20) = 3.07\ \text{kW} \quad (8)$$

$$Qd = Q1 + Q2 + Q3 = 98.88 + 63.78 + 3.07 = 165.73\ \text{kW} \quad (9)$$

Nighttime:

$$Q1 = (1.15 * 681.55 + 0.69 * (224 + 46.9) + 1.03 * (118.93)) * (24) = 26.24\ \text{kW} \quad (10)$$

$$Q2 = 0.5 * 1 * 1876 * 1.2 * 24 = 27.01\ \text{kW} \quad (11)$$

$$Q3 = 0.24 * 640 * (12 - (-12)) = 3.69\ \text{kW} \quad (12)$$

$$Qn = 26.24 + 27.01 + 3.69 = 56.94\ \text{kW} \quad (13)$$

(3) Calculation of energy balance

Based on the calculations of the solar radiation intercepted by the greenhouse and the heat loss during the day and night, it is determined that the active heat storage system needs to supplement 211.88 kW to maintain the ideal growing environment.

$$QL = Qd + Qn = 1325.84 + 911.04 = 2236.88\ \text{kW} \quad (14)$$

$$QR = 2025\ \text{kW} \quad (15)$$

$$Q = QL - QR = 2236.88 - 2025 = 211.88\ \text{kW} \quad (16)$$

(4) Calculation of heat radiator

When calculating the greenhouse heating load, the nighttime heat loss is used as the basis for radiator calculations.

The heat provided per unit time, Q_C, is 56.94 kW. G15 has 24 column-type radiators, with each column providing a heat output of 0.154 kW, $\beta 1 = 1$, $\beta 2 = 1$, $\beta 3 = 1$.

Column radiator:

$$N = (Q_C/q_h) \cdot \beta_1 \cdot \beta_2 \cdot \beta_3 \tag{17}$$

$$F = (56.94/0.154) * 1 = 369.74 \tag{18}$$

For the sake of insurance, increase the insurance factor by 20 %:

$$Ft = 369.74 * 120\,\% = 443.69 \tag{19}$$

Light tube radiator:

$$Ap = 56940/[13.9 * (49 - 38.5)\,] = 390.13 \text{ m} \tag{20}$$

The heat dissipation coefficient of the light tube radiator is 13.9 W m^{-2} $°C^{-1}$.

(5) Calculation of power consumption

The power consumption for the heating systems in G14 and G15 operating for one day (11 hours) is calculated as follows:

$$Ec14 = (21 + 2.2) * 11 = 255.2 \text{ kWh} \tag{21}$$

$$Ec15 = (21 + 0.18) * 12 = 254.2 \text{ kWh} \tag{22}$$

$$Qr14 = 6.3 * 4.2 * (49 - 38.5)/3600 * 11 = 0.85 \text{ GJ} \tag{23}$$

$$Qr15 = 6.9 * 4.2 * (45 - 38)/3600 * 12 = 0.68 \text{ GJ} \tag{24}$$

where, the water flow rate is 6.3 m^3 h^{-1}, and the specific heat capacity is 4.2 kJ kg^{-1} $°C^{-1}$. The conversion factor 1 GJ = 277.8 kWh. The COP of the two greenhouses can be calculated as follow:

$$COP\_E14 = 0.85 * 277.8/255.2 = 0.93 \tag{25}$$

$$COP\_E15 = 0.68 * 277.8/254.2 = 0.74 \tag{26}$$

The agricultural electricity rate in the Beijing area is 0.5955 yuan per kWh. The daily cost for actively heating the two greenhouses is calculated as follows:

$$Rc14 = 255.2 * 0.5955 = 151.97 \tag{27}$$

$$Rc15 = 254.2 * 0.5955 = 151.38 \tag{28}$$