Research on the Optimization of Solar Energy Utilization Based on Sky Radiant Cooling

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Abstract. Addressing global climate change and achieving carbon neutrality as soon as possible is a common aspiration for all of humanity. In this context, the development of refrigeration technology is undergoing a significant transformation. This paper proposes a composite system that integrates sky radiation cooling technology with solar thermal power collectors. Through the analysis of experimental data, it is indicated that the sky radiative cooling technology can significantly enhance the overall energy efficiency of the solar thermoelectric system. With this combination, not only the power generation efficiency of the solar thermal collector and generator is improved, but also the deficiency that the solar thermal collector and generator can only operate during the day and be idle at night is effectively compensated for, thereby reinforcing the sustainability of energy utilization. The analysis shows that sky radiation cooling technology has a significant effect on optimizing the utilization of solar thermal electricity.

Keywords: Sky Radiation Cooling, Solar Thermal Electricity, Integrated Utilization, Energy Conservation and Emission Reduction.

1. Introduction

The main fossil fuels currently used mainly have three major problems: environmental pollution, non-renewable, and uneven regional distribution [1-2], which has prompted us to focus on renewable energy. Solar power generation is a technology that uses solar energy to generate electricity. The current application theory is relatively mature [3], and it has the advantages of environmental protection and durability. It is of great significance to reduce greenhouse gas emissions and protect the environment. With the advancement of technology and the decline of cost, solar power generation has been widely used and promoted worldwide, but there is still room for improvement in power generation efficiency.

The power generation efficiency of solar power generation equipment is affected by temperature. Cooling the equipment and increasing the temperature difference can improve the power generation efficiency [4-6]. If we start from the cooling of the equipment, in order to fundamentally improve the solar power generation, refrigeration needs to be as low as possible. In order to improve the photothermal conversion efficiency of solar thermoelectric generator, a theoretical model based on solar heat pipe vacuum collector is proposed based on the energy conservation of thermoelectric unit in Reference [7], which reduces the heat loss of equipment and improves the utilization efficiency of solar energy. However, there is still a certain gap between the thermal performance and the mature solar collector. Reference [8], a mathematical model of sky radiation refrigeration was established to study the influence of sky radiation refrigeration performance, and the spatial and temporal variation rules of radiation refrigeration resources were obtained. However, only the refrigeration effect of some experimental materials was explored, and the influence factors of many non-radiation items were not explored in depth. Reference [9], aiming at the significant influence of outdoor meteorological environment on the integrated panel building, based on EnergyPlus energy consumption simulation analysis software, the mathematical and physical model of the integrated panel building is established, and the application potential of the sky radiation refrigeration technology of the integrated panel building in different regions is obtained, but the differences of different landforms of the panel building are not further explored. Aiming at the problem of improving the comprehensive utilization of solar photoelectric conversion by sky radiation refrigeration, Reference [10] proposed a new idea of comprehensive utilization of sky radiation refrigeration and solar photoelectric conversion (RSC-PV), and built a simulation experiment to obtain the conclusion that the passive cooling of photovoltaic cells can be effectively realized, but the direct relationship between solar collector utilization and sky radiation refrigeration was not studied.

Based on the above research, this paper proposes a composite system that combines radiant cooling technology with solar collector generators. In this paper, the thermoelectric conversion of the solar collector power generation model is studied. Based on the three energy conversion effects of the thermoelectric effect, the thermoelectric conversion efficiency of the solar collector can be improved by cooling the equipment. Combined with the similarities and limitations of existing radiant cooling equipment and solar collectors, the sky radiant cooling technology and solar collector generator are selected for research. Then, based on the principle of sky radiant cooling and solar collector, this paper selects the appropriate spectral coating and designs the basic model of the system. Finally, TRNSYS and MATLAB are used to carry out the joint simulation analysis of solar energy and sky radiation to verify the rationality of the composite system.

2. Solar collector power generation model

2.1. Thermoelectric conversion

Solar thermal utilization is the oldest way of solar energy utilization. The thermoelectric phenomenon is a direct coupling of electricity and heat inside the material. When sunlight irradiates on certain materials, these materials therefore increase their own temperature. The generation of temperature difference causes the material to produce electron migration, forming a voltage difference, thereby generating current. The process of converting the generated heat energy into electrical energy is called thermoelectric phenomenon. The thermal utilization of solar energy is mainly divided into three parts : low temperature thermal utilization of solar energy less than 100℃, the main applications include solar heating, flat solar hot water / hot air collection, etc.; 100℃-250℃ of solar energy medium temperature heat utilization, the main use includes solar adsorption refrigeration, solar desalination, etc.; the high-temperature thermal utilization of solar energy above 250℃ is mainly used for solar high-concentration photothermal power generation, solar thermochemistry and so on.

In general, the thermoelectric phenomenon needs to meet the three energy conversion effects of the thermoelectric effect, namely, the Seebeck effect, the Peltier effect and the Thomson effect.

In 1821, German physicist Thomas John Seebeck found that when the two ends of two different metals were connected to two nodes at different temperatures to form a loop, the compass placed nearby would deflect. Future generations of physicists have found that the magnetic field is caused by the current generated in the circuit, and this phenomenon is named the Seebeck effect. When the current in the material is zero and there is a temperature gradient, the generated potential ΔV will be proportional to the temperature difference. The proportional constant of the temperature difference and the potential difference is called the Seebeck coefficient [11].

$$\alpha = -\frac{\Delta V}{\Delta T} \tag{1}$$

In 1834, the French scientist Peltier discovered that when the current passes through a closed circuit composed of two different metals, the junction absorbs or releases heat according to the direction of the current. Π_A and Π_B are the Peltier coefficients of materials A and B, respectively [8]. The heat generated by this process is defined as :

$$Q = (\Pi_A - \Pi_B)I \tag{2}$$

In 1854, the British physicist William Thomson defined the relationship between different thermoelectric coefficients:

$$\Pi = TS \tag{3}$$

This allows the Seebeck coefficient and the Peltier coefficient to be linked and can be further organized as:

$$Q = T(\alpha_A - \alpha_B)I \tag{4}$$

In the course of his research, he also found that the current through the thermoelectric material with a temperature gradient will cause the material to continuously produce the Peltier effect, which is called the Thomson effect [12].

The Seebeck effect, the Peltier effect and the Thomson effect are called the first, second and third effects of thermoelectricity respectively, which are the basis for studying the thermoelectric effect and improving the thermoelectric power generation rate.

2.2. Analysis of thermoelectric power generation model

Compared with solar photoelectric utilization, the efficiency of photothermal utilization is higher. Compared with the combined use of solar photothermal photoelectricity, the cost of photothermal utilization is lower and the technology is more perfect.

The efficiency of solar thermal utilization is high, but only low-grade thermal energy can be obtained. Relying on solar collectors, solar collectors can now be coupled with thermoelectric generators to convert low-grade thermal energy into high-grade electrical energy through the Seebeck effect of the solid material of the solar collector. Therefore, the solar collector has become the most critical component in the solar collector system, and its performance directly determines the heat collection efficiency and power generation efficiency of the collector system [13].

From Equation (1), it can be seen that increasing the heat collection capacity of the solar collector can increase the temperature difference. In the traditional solar collector system, due to the influence of natural conditions, the solar collector has little use value in hot seasons and regions. Excessive temperature will lead to increased heat loss and reduce the overall energy efficiency of the system, and it cannot work at night [14]. The flat plate solar collector and the radiant cooling device have similar structures and uses, and their functions and working hours are complementary. By combining the radiant cooling technology, the temperature of the collector can be effectively reduced at night, so that the system can obtain a greater temperature gradient during the day, resulting in a large potential difference, and improving the comprehensive utilization efficiency of energy [15-17].

The traditional radiant cooling device often only has a single cooling function, and the power is low and the cost is high, which makes it difficult to popularize and apply [18]. It has certain limitations in compounding with solar collectors. Sky radiation refrigeration is a kind of passive refrigeration technology through radiation heat transfer with outer space. It is applied to solar collectors. By changing the spectral selection characteristics of the solar collector core and cover plate, the composite equipment can have the characteristics of day heating and night cooling, and improve the power generation efficiency of the solar collector.

According to the principle of sky radiation refrigeration, the cooling coating material can only absorb radiation in the mid-infrared band, especially in the ' atmospheric window ' band with high emissivity, in order to achieve its own passive cooling and cooling effect. Traditional radiative cooling has a very low absorptivity in the solar radiation band, while the solar selective absorption coating has a very low emissivity in the ' atmospheric window ' band, which makes it difficult to carry out radiative cooling at night. In order to realize the function of collecting heat during the day and cooling at night, the cooling coating material must meet the conditions of high solar radiation absorption rate and high emissivity of the ' atmospheric window ' band at the same time [19]. The structure of the composite model is shown in Figure 1.

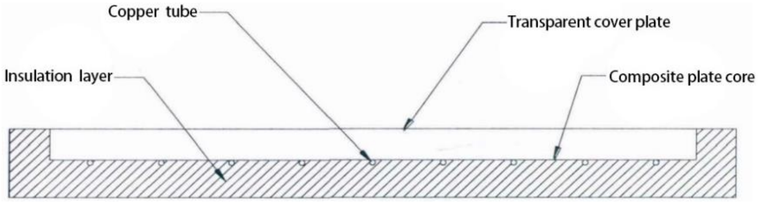

Figure 1. Composite model structure

Based on the above description, the composite model structure design is shown in Figure 1. The composite model mainly includes: transparent cover plate, solar collector-sky radiant cooling composite plate core, copper tube, header, insulation layer and frame, etc. Compared with the traditional solar collector, the main difference of the composite model is that the transparent cover plate with different materials and the plate core material with different coatings are selected.

3. The Combined System of Solar Thermal Collection and Radiation Cooling

3.1. Integrated Utilization of Solar Thermal Collection and Radiation Cooling

The combined system of solar thermal collection and sky radiation cooling fully integrates both technologies, achieving efficient use of energy and enhanced energy efficiency.

Traditional radiative cooling devices, due to their low absorption rates in the solar radiation spectrum, are ineffective at utilizing solar energy for heating during the day. Meanwhile, solar collectors, because of their solar-selective absorption coatings, have low emissivity in the "atmospheric window" wavelength, making them inefficient at radiative cooling during the night. To address this issue, innovatively combining solar thermal collection with radiation cooling has become a novel solution.

In this integrated approach, solar collectors convert solar radiation into thermal energy, used to generate steam or hot water and drive the radiative cooling device. During the day, the system utilizes the solar collectors for solar thermal energy capture, achieving efficient energy collection. At night, even under clear skies, the system can utilize the atmospheric radiative cooling effect for cooling. Thus, the system can operate around the clock without the need for additional energy supply, ensuring stability and reliability in energy provision.

By integrating solar collectors with radiation cooling devices, the system significantly reduces dependence on traditional energy sources, achieving energy savings and environmental protection. Utilization of solar energy as a clean energy source not only reduces fossil fuel consumption but also decreases greenhouse gas emissions. Furthermore, utilizing the atmospheric radiative cooling effect for cooling does not require additional energy, further reducing the system's energy consumption and environmental impact.

Therefore, the combined system of solar thermal collection and sky radiation cooling provides an innovative and environmentally friendly cooling solution, offering new ideas and methods for addressing energy consumption and environmental pollution issues.

3.2. Establishment of Theoretical Models for Solar Thermal Collection and Radiation Cooling Composite Devices

In the combined system of solar thermal collection and sky radiation cooling, establishing theoretical models for the composite devices is crucial for ensuring system design and optimization. Here are the detailed steps and content for establishing these theoretical models:

(1) Solar Collector Theoretical Model:

Geometric Shape and Structural Characteristics: Consider the design of the collector, requiring a model of its geometric shape and structural characteristics. This includes the curvature of the solar reflective surface, the thermal conductivity properties of the materials, and their heat capacity.

Energy Absorption and Conversion: Establish a model of solar radiation absorption and conversion for the solar collector, taking into account the changes in the angle of incidence and intensity of solar radiation. The model needs to include factors such as the reflectivity, absorptivity, and transmissivity of the collector surface.

Heat Transfer and Loss: Consider the process of heat transfer within the solar collector, including the absorption, conduction, and radiation of heat, as well as potential heat loss mechanisms, such as convective and radiative losses.

(2) Sky Radiation Cooling Device Theoretical Model:

Atmospheric Radiation Characteristics: Establish a model of atmospheric radiation characteristics, including the radiation spectrum, temperature distribution, and radiation transmission process. This model should consider the absorptive and scattering properties of the atmosphere, as well as the radiative cooling effect at night.

Cooling Efficiency and Energy Consumption: Establish a model of cooling efficiency and energy consumption for the sky radiation cooling device, based on the radiative cooling effect and the structural characteristics of the device. Consider the working principles of the cooling device, the refrigerant circulation process, and the relationship between cooling effects and energy consumption.

(3) Coupled System Model:

Couple the solar thermal collection and radiation cooling subsystems, establishing an overall theoretical model of the combined system. This model needs to consider how the heat produced by the solar collectors drives the sky radiation cooling device and the temperature regulation effects of the cooling device. Through this model, the energy conversion efficiency and cooling performance of the system under different operating conditions can be evaluated.

(4) Energy Balance Equation:

When establishing theoretical models, consider the system’s energy balance equation to ensure that the energy input and output reach a balanced state. This equation should include the energy input of the collectors and cooling device, the system’s heat losses, and other energy loss factors. Through the energy balance equation, the system’s energy utilization efficiency and stability can be assessed.

Parameter Optimization and Performance Evaluation:

Finally, after completing the theoretical models, parameter optimization and performance evaluation are necessary. This includes optimizing system parameters to maximize the energy conversion efficiency and cooling performance, and evaluating the system’s performance under different operating conditions through simulation and calculation methods.

By implementing these steps, the theoretical models of the solar thermal collection and radiation cooling composite devices can accurately describe the working principles and performance characteristics of the system, providing theoretical guidance and technical support for system design and optimization.

3.3. Theoretical Model of the Combined Heat and Cooling Device

3.3.1 Energy Balance Equation for the Transparent Cover Plate

In the combined system of solar thermal collection and sky radiation cooling, the transparent cover plate serves as a crucial component of the solar collector. We assume that the temperature across the thickness of the transparent cover plate is uniform, and we disregard any heat conduction in the plane direction, considering the temperature of the entire transparent cover plate to be the same. The energy balance equation for the transparent cover plate can be expressed as follows:

$$h_{ac}(T_a - T_c) + h_{sc}(T_s - T_c) + h_{pc}(T_p - T_c) + \alpha G = 0 \tag{5}$$

In this, T_a represents the ambient temperature, T_C is the temperature of the transparent cover plate, T_s denotes the sky temperature, and T_p indicates the temperature of the combined heat and cooling plate core, all in units of K. h_{ac} represents the convective heat transfer coefficient between the cover plate and the environment, h_{sc} is the radiative heat transfer coefficient with the sky, and h_{pc} is the total heat transfer coefficient between the cover plate and the combined heat and cooling plate core (including both radiative and convective heat transfer coefficients), all in units of $W/(m^2 \cdot K)$. α_C is the absorptivity of the cover plate to solar radiation; G is the solar radiation intensity, in units of W/m^2.

3.3.2 Energy Balance Equation for the Combined Heat and Cooling Plate Core

We assume that the temperature in the vertical direction of the combined plate core is uniform, and have established a two-dimensional steady-state heat conduction equation for the combined heat and cooling plate core:

$$k_p d_p \frac{\partial^2 T_p}{\partial x^2} + k_p d_p \frac{\partial^2 T_p}{\partial y^2} + h_{pc}\left(T_c - T_p\right) + u_{ap}\left(T_a - T_p\right) + \left(\tau\alpha\right)_p G - Q_{pt} - Q_{radnet} = 0 \tag{6}$$

In this, k_p represents the thermal conductivity of the combined heat and cooling plate core, in units of W/(m^2·K); d_p is the thickness of the combined heat and cooling plate core, in meters; u_{ap} denotes the total heat exchange coefficient between the combined heat and cooling plate core and the surrounding environment, in units of W/(m^2·K); $(\tau\alpha)p$ is the effective absorption rate of solar radiation projected onto the light-receiving surface of the combined device by the combined heat and cooling plate core; Q_{pt} indicates the heat flux density from the combined heat and cooling plate core to the copper tubes, in units of W/m^2; Q_{radnet} describes the net radiative heat exchange between the combined heat and cooling plate core and the sky, in units of W/m^2.

3.3.3 Energy balance equation of the copper tube

The energy balance equation of the copper tube is as follows:

$$\pi \frac{D_0 + D_i}{2} \frac{D_0 - D_i}{2} k_t \frac{\partial^2 T_t}{\partial y^2} + \pi D_i h_{ft}\left(T_f - T_t\right) + \frac{T_p - T_t}{R_{pt} \cdot dy} = 0 \tag{7}$$

Where, D_0 and D_i respectively are the outer and inner diameters of the copper tube, in meters; k_t is the thermal conductivity of the copper tube, $W/(m\square K)$; T_f and T_t are respectively the temperatures of the copper tube and the internal heat exchange medium, in K; h_{ft} is the convective heat transfer coefficient between the copper tube and the internal heat exchange medium, $W/(m^2 \cdot K)$.

3.3.4 Energy Balance Equation of the Heat Exchange Medium Inside the Copper Tube

The energy balance equation for the internal medium is as follows:

$$m_f c_f \frac{\partial T_f}{\partial y} = A_t k_f \frac{\partial^2 T_f}{\partial y^2} + P_t h_f t(T_t - T_f) \tag{8}$$

Where, $\dot{m}_f$ denotes the flow rate of the heat exchange medium, in kg/s; c_f represents the specific heat capacity of the heat exchange medium, in $J/(kg\square K)$; A_t is the cross-sectional area of the copper tube channel, in m^2; k_f indicates the thermal conductivity of the heat exchange medium, in $W/(m\square K)$; P_t is the perimeter of the inner surface of the copper tube, in m.3.Joint simulation analysis of solar energy and sky radiation.

4. Solar and sky radiation co-simulation analysis

4.1. Basic principle of comprehensive utilization

Passive Sky Radiation Cooling (PSRC) is an innovative passive cooling method utilizing a radiator. When the sky's temperature is lower than the radiator's, the radiator emits heat as infrared radiation, achieving free cooling without extra energy. This system views the sky as an ultra-low temperature cold source, discharging heat efficiently without flexible components. The grating structure, a periodic micro-structure, excites various radiation effects, absorbs solar radiation, achieves high absorption peaks, and maintains a low absorption rate. It's wavelength-selective and ideal for sky radiation cooling. To enhance PSRC performance, this study combines an optimal grating structure, such as Figure 2 with it to create a novel combined refrigeration system. By simulating the structure's cooling power in buildings, we aim to investigate indoor temperature changes, system efficiency, and operational factors, laying a theoretical foundation for cooling technology optimization [20].

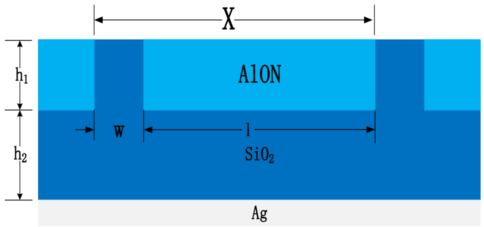

Figure 2. Grating structure

4.2. Experimental model and control strategy analysis

4.2.1 Joint simulation of TRNSYS and MATLAB

TRNSYS is an important dynamic simulation software for building energy consumption simulation and ventilation and air conditioning control. It adopts modular structure and has more than 200 commonly used modules. TRNSYS can co-simulate with other software such as Energy Plus and MATLAB, and realize data sharing through COM interface. Users can take advantage of TRNSYS 's global meteorological data- base, which covers more than 1,000 regions of meteorological information for accurate simulation. In this chapter, we will take Nanchang area as an example for simulation calculation. The data interaction between TRNSYS and MATLAB mainly depends on the Type155 component, which supports iterative mode (strong coupling) and non-iterative mode (relaxation coupling). In the simulation calculation of this chapter, we use the strong coupling mode to operate [21].

4.2.2 Overview of simulated environment

In TRNSYS software, we use Type56 components and TRN Build visual interface to build building simulation model, input including building maintenance structure, air conditioning equipment, indoor heat load and the use of detailed parameters such as schedule. Taking Nanchang City as the simulation site, an office with a length of 10 meters, a width of 5 meters and a height of 3.5 meters is studied, focusing on simulating summer refrigeration. Water is selected as the refrigerant, and the fan coil is the terminal equipment of indoor air conditioning, and the ventilation is set once an hour. The specific parameters are shown in Table 1 and Table 2.

Table 1. Enclosure structure parameter table

Envelope parameters	External wall	Floor	Roof	Window
Heat transfer coefficient ($W/m^2 \cdot K$)	0.8	0.5	0.6	3.2

Table 2. Indoor personnel, mechanical equipment load and operation schedule

Number of indoor personnel	Equipment power density	Light load density	Number of air changes	Running time
6	$11W/m^2$	$18W/m^2$	1/h	8:00-18:00

Figure 3 is the monthly average temperature of Nanchang City. The analysis found that July was the highest temperature period of the year. Therefore, the simulation selected a week in mid-July to explore the indoor temperature dynamics. According to the indoor heat source (such as personnel, lighting, equipment and maintenance structure), the hourly cooling load is calculated, as shown in Figure 4.

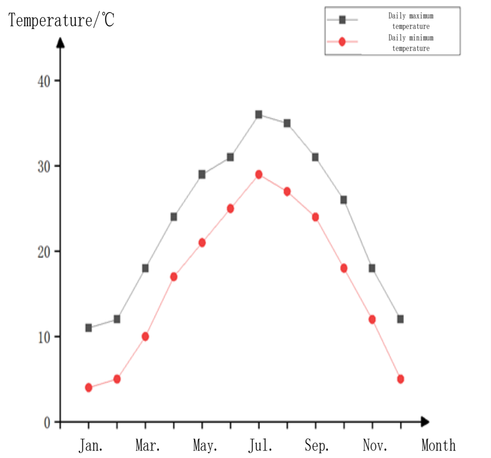

Figure 3. The monthly average temperature of Nanchang City

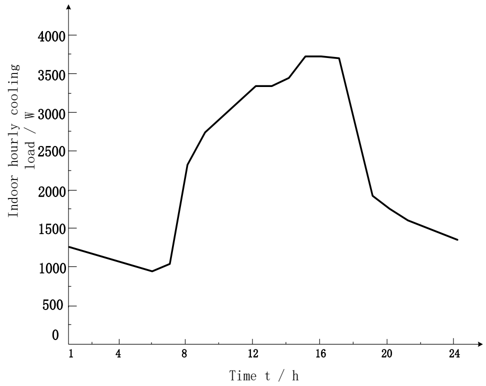

Figure 4. Indoor hourly cooling load curve Diagram of a year in Nanchang

4.2.3 Simulation environment overview system design

The system consists of a radiator, a cold storage device, a control module and an end device. The results are shown in Figure 5.

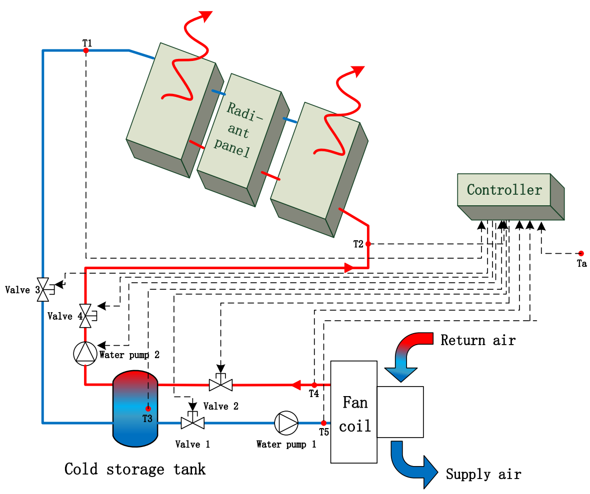

Figure 5. Joint system schematic diagram

Radiator uses advanced materials for stable 24-hour cooling fluid supply. It employs water as the cooling medium with fan coil indoors. The intelligent control system comprises thermocouple, control valve, and pump switch, supporting three modes. In building integration, radiators are mounted on flat or low-pitched roofs for optimal sky view.

4.2.4 Joint system control scheme

The combined control scheme covers three modes: when there is no indoor cooling load, the system saves the cold energy to the cold storage tank. When the water temperature of the cold storage tank is too high, the radiator is started to be connected in series with the cold storage tank for refrigeration. The temperature of the cold storage tank is too low, and the radiator stops storing cold and turns to separate refrigeration.

Table 3. Joint system control

Operational mode	Whether there is load indoors	Overview of the system	System control scheme
1	NO	The cold energy is stored to the cold storage tank.	The pump 1 is closed, the pump 2 is opened, the valve 1-2 is closed, and the 3-4 is opened.
2	YES	The temperature of the cold storage tank is too high, and the combined refrigeration mode of the radiator cold storage tank is converted.	Pump 1 opens, pump 2 closes, valve 1-2 opens, 3-4 closes.
3	YES	When the temperature of the cold storage tank is too low, the radiator stops storing cold and turns into a separate refrigeration mode of the cold storage tank.	Pump 1-2, valve 1-4 all open.

4.2.5 Joint system parameter calculation

Before the implementation of the system simulation, the specific values of the following parameters must be determined: the area of the system radiation plate, the size of the cold storage tank, the air flow of the fan coil and the water supply of the pump. These parameters need to be accurately calculated according to the hourly cooling load in the building.

According to the indoor hourly cooling load curve shown in Figure 4, we know that the maximum indoor cooling load is 3704W. In order to meet the maximum cooling demand during the day, we combine the cooling power (72.42W) of the radiator during the day with the maximum indoor cooling load, and calculate that the area of the radiant panel should be 51.14m^2. Considering the actual situation, the radiation plate area we selected in this paper is 50m^2.

Volume calculation of cold storage tank:

$$V_t = \frac{\sum_{i=1}^{24} \max\left[(q_i - \overline{q_t}),0\right] \bullet 3600}{\rho_{wt} c_{wt} \Delta\overline{T}} \tag{9}$$

q_i is the hourly cooling load value inside the building. $\overline{q_t}$ represents the average daily cooling power of the radiator. $\rho_{wt}, c_{wt} and \Delta\overline{T}$ represent the density of water, the specific heat capacity of water and the daily average temperature difference of the cold storage tank, respectively. Take $\Delta\overline{T} = 4℃$.

According to the hourly cooling load curve and the average cooling capacity of the radiator in Figure 4, the volume of the cold storage tank is calculated to be 7.62m^3. The ideal volume of the cold storage tank with a diameter of 2m and a height of 2.5m is 7.85m^3.

The calculation method of water supply of pump 1-2 is as follows:

$$P = \frac{Q_{MAX}}{c_{\mathrm{wt}} \Delta T_{wt}} \tag{10}$$

The specific heat capacity of water is 4.19 kJ/kg·K, and the temperature difference ΔT_{wt} between supply and return water is set to 5°C. Based on these parameters, we calculated that the water supply is 0.64m^3/h. Therefore, the pump model is determined to be Wilo-NL32/200-0.75/4, and its power is 0.75kW.

The calculation method of fan coil air supply volume is as follows:

$$R = \frac{Q_{MAX}}{c_{\mathrm{air}} \Delta T_{air}} \tag{11}$$

The specific heat capacity c_{air} of the air is 1.005kJ/kg·K, and the air supply temperature difference ΔT_{air} is set to 8°C.

After calculation, the water supply is determined to be 1284m^3/h, the pump model is YGFC-14CC2ZXFXCLD, and the input power is 0.209W. It is assumed that the rated power of the two control pump switches is 60W. The initial conditions are set, the simulation cycle is constructed, and the building refrigeration simulation is carried out to evaluate the operating energy consumption and COP.

4.3. Joint system simulation and result analysis

Selected July's highest temp week in Nanchang for simulation. Cold storage tank capacity: 7.85m^3, radiator surface area: 50m^2. Figure 6 shows system operation & indoor temp changes from July 17-23. Max solar radiation: 502-998W/m^2, max ambient temp: 30.6-37°C. Figure 7 show that during the working period, the average indoor temperature rises and is not cooled at night. However, the average indoor temperature is still lower than that of outdoor, 17.94-22.4°C throughout the day, 10.44-18.33°C lower. It proves that the system refrigeration effect is excellent. The daytime temperature of the cold storage tank rises with a threshold of 10°C, exceeding but not switching to mode 2. It shows that the outdoor wind speed is too high, the convective heat transfer is severe, and the cycle cannot start. At night, the main mode 1 runs, and mode 0 is used in some periods, and the sky radiator suspends cooling. Due to the excessive wind speed, the outdoor air and the radiant plate convection heat transfer, the radiator cooling capacity is less than 0, the system suspends the water pump 2 for cooling.

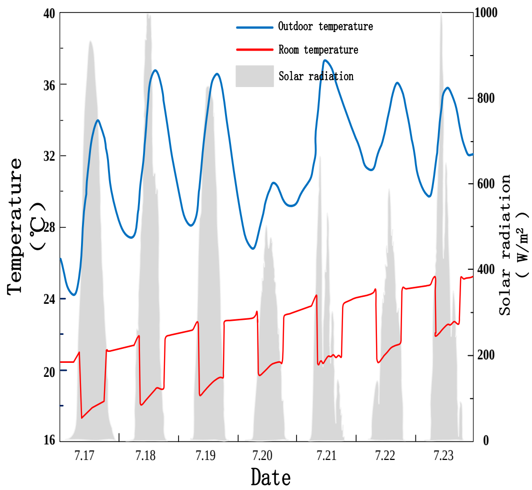

Figure 6. Solar radiation and indoor and outdoor temperature change curve

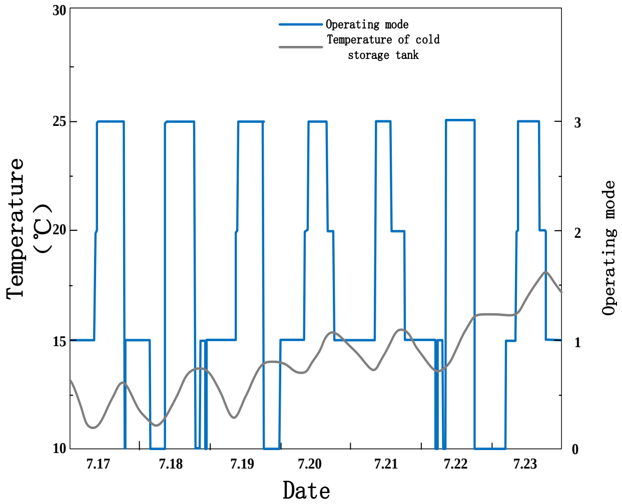

Figure 7. System operation mode and cold storage tank temperature

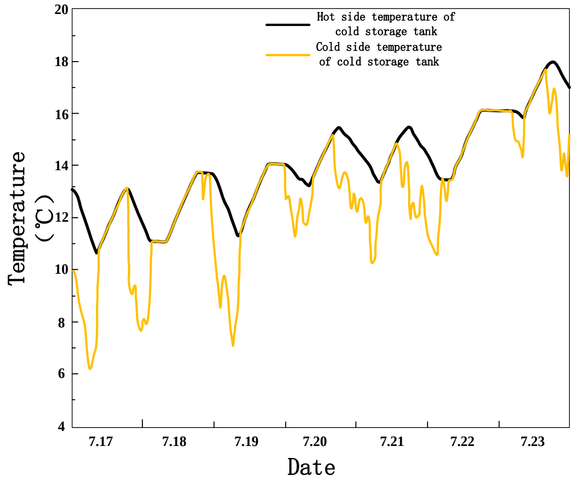

Figure 8. The temperature change diagram inside

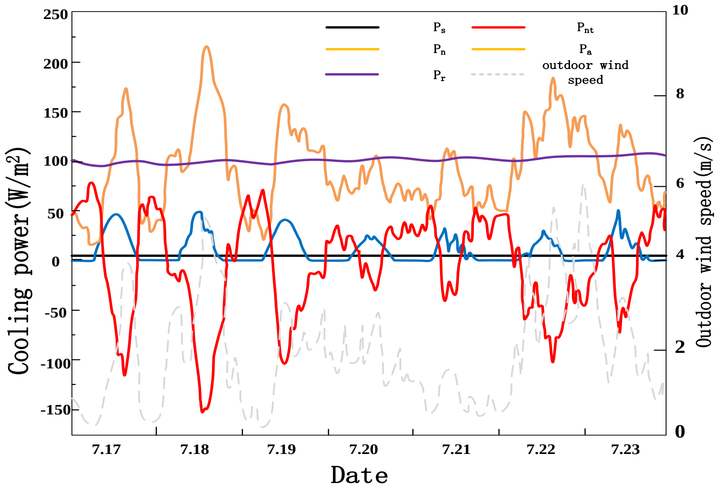

Figure 9. The radiation power and outdoor wind speed curve

In-depth analysis of the energy efficiency of the combined refrigeration system, Figure 10 shows that the hourly cooling capacity and power consumption are stable from May to September. Figure 11 show the change of COP, with an average of 1.75 and a maximum of 1.88 in July. Since the main energy consumption comes from the water pump and the fan, in order to obtain the maximum cooling of the room, the simulation has no temperature threshold, resulting in continuous operation of the water pump and the fan during the day, and the actual power consumption is high, affecting the COP value.

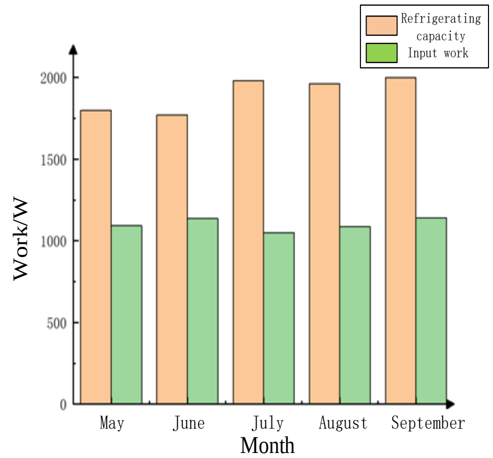

Figure 10. Cooling power and input power

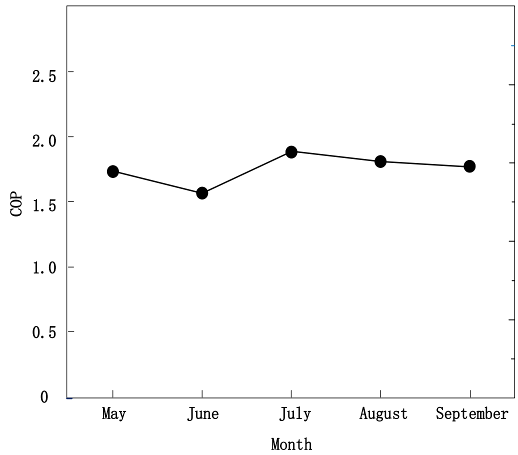

Figure 11. System energy efficiency ratio

Outdoor wind speed does have a significant negative effect on the capacity of the refrigeration system, which is reflected in the monthly decline in cooling capacity and the reduction of energy efficiency ratio. As shown in Figure 10, the temperature of the cold storage tank is significantly lower than the ambient temperature, which just meets the building 's demand for refrigeration. However, when the cooling demand increases, we need to take some measures to reduce the energy loss caused by wind speed.

In this case, an effective strategy is to install a windshield around the radiator. Such a device can effectively block the strong wind and reduce the impact of wind speed on the refrigeration system. In summer, strong winds may cause refrigeration systems to frequently operate under suboptimal conditions, which not only affects the cooling effect, but also may increase unnecessary power consumption.

The installation of the windshield device can significantly reduce the loss of cooling capacity caused by wind speed. This is because when the wind speed decreases, the heat exchange between the cold storage tank and the surrounding environment will slow down, thereby maintaining a lower temperature and improving the cooling effect. In addition, the windshield device can also prevent the refrigeration system from operating in unnecessary situations, thereby saving electricity.

5. Conclusion

This study utilizes an optimal grating selective structure as a radiator to simulate the performance of a joint system in practical applications, focusing on indoor temperature, system operation performance, and system energy efficiency variation in the hottest month of Nanchang. Results indicate that during daily working hours, the average indoor temperature remains 10.44-18.33℃ lower than the outdoor temperature. Convective heat transfer dominates the radiation cooling process when outdoor wind speed is high. Therefore, in areas with excessive summer wind speed, adding a windshield device around the radiator is recommended to enhance net cooling capacity.

The system's energy efficiency ratio (COP) varies with time, being higher in the morning and evening due to lower outdoor temperatures and better radiation cooling effect, and lower at noon due to higher outdoor temperatures weakening the cooling effect. To improve system performance at noon, considering shading devices to reduce outdoor radiation intensity can enhance indoor radiation cooling. Connecting the radiator to a cold storage tank can also be used for room cooling. This simulation research provides a theoretical basis for promoting passive sky radiation refrigeration systems in practical applications.

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