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# Simulation Analysis and Experiment on Energy Transfer Characteristics of Photovoltaic Energy-Driven Ice Storage Air Conditioning System

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In order to satisfy the refrigeration requirements in modern society from the energy-saving perspective, this paper studies the ice storage air conditioning system driven by solar photovoltaic system. To this end, the methods such as analysis, comparison, and experimentation were adopted. The results show: the maximum of photovoltaic array photoelectric conversion efficiency was 17.58%, the maximum COP of refrigerating unit was 0.51, and the ice making capacity for 8 hours in the daytime 16.98kg, to ensure the cold supply inside the 10m2 room for 4 hours at night. Then the research results were further analysed. Finally, it is concluded that the ice-making process in the ice-flake sliding form causes a larger energy waste, therefore, the immersion-type static ice system by changing the disc evaporator into coiled tubular evaporator could increase the COP power by 40%.

## 1. Introduction

As the quality of life improves in modern society, the social crowd has the new requirements for refrigeration in many aspects. However, there exist many deficiencies with the traditional refrigeration methods, e.g. high energy consumption and pollution, so the demands of social crowd cannot be satisfied finally. In order to solve these problems, some scholars have proposed the idea of ice storage air conditioning system driven by photovoltaic energy system, and then conducted the related studies by analysing its feasibility. The current studies mainly include the energy transfer characteristics of photovoltaic energy-driven ice storage air conditioning system.

By taking the distributed photovoltaic energy-driven ice storage air conditioning system as object of study, this paper makes the simulated calculation for its energy transfer characteristics and exergy flow in the ice storage system, in order to optimize the component parameters, promote system performance, and finally achieve the stable and high-efficient energy supply of the distributed photovoltaic energy system.

## 2. Literature review

Solar cooling has higher compatibility between solar radiation resources and demand for cooling. Applying solar-powered refrigeration has become one of the hotspots and focuses of solar energy research. The operation and stability of the solar thermal refrigeration system need to be further improved, and the conversion efficiency needs to be improved. Compared with the use of photovoltaic modules to directly convert solar energy into high-grade electrical energy to drive compressors with efficient and stable refrigeration. Compared with photovoltaic modules, solar energy is directly converted into high grade electricity to drive the compressor, and its refrigeration effect is more efficient and stable. Especially with the rapid development of distributed photovoltaic technology, the research and application of household-use independent photovoltaic-driven refrigeration equipment has developed rapidly. The cold storage air conditioner adopts the electric refrigerator to refrigerate in the low power consumption night of with low power load, utilizes the latent heat of phase change of ice and the sensible heat of certain temperature difference, and stores the cold amount in a certain way. In the daytime when the power load is high, that is, the peak period of electricity consumption, the stored cooling capacity is

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released to meet the needs of the building air conditioning or production process. In this way, most of the power consumption of the refrigeration system takes place during the low-hour period of night time electricity consumption. In the peak hours of the daytime, only auxiliary equipment with low energy consumption is in operation, which can play a role in balancing the load of the power grid.

There are many foreign studies on photovoltaic-driven ice-making systems, and Tanaka et al. (2016) designed a multi-function photovoltaic refrigerator. The operating conditions of the system were experimentally studied. When the average indoor and outdoor temperatures were 26.3°C and 24.9°C respectively, the minimum temperature of the refrigerator was -10.6°C, and the photovoltaic refrigerator system was stable in different regions. Koohi-Kamali et al. (2014) conducted an experimental study of a photovoltaic DC refrigerator system, and the results showed that the conversion efficiency of photovoltaic modules has a great influence on the system efficiency. Shafiullah et al. (2014) performed dynamic simulations and experimental studies on the performance of photovoltaic refrigerator systems. Studies have shown that the system efficiency increases as the evaporator evaporator temperature decreases. Mohammadnejad et al. (2016) optimized the working model of photovoltaic-driven ice machine compressors, the efficiency of photovoltaic-driven compressors was approximately 9.2%, and solar modules can still operate at the maximum power point when solar irradiance was as low as 150 W/m$^2$. Xu et al. (2016) pointed out that Dian Yanjun of Shanghai Jiaotong University in China conducted detailed theoretical analysis and experimental research on the performance of photovoltaic-driven semiconductor refrigerators as early as 2001. In recent years, Huang et al. (2016) conducted in-depth research and analysis on energy management and system matching of solar photovoltaic DC refrigerator systems. Liu et al. (2014) studied the operating conditions and stability of solar PV refrigeration systems and compared solar adsorption refrigerators with conventional household refrigerators in terms of economy, reliability, and price.

Over the past decade, with the emergence of a worldwide energy crisis, cold storage air conditioners have developed rapidly in developed countries such as Japan and the United States. It is widely used in district cooling and central air-conditioning, becoming a practical energy-saving technology that promotes the coordinated development of energy, economy, and the environment. Hao et al. pointed out that the United States began to use cold storage air-conditioning systems as early as 1930, and the energy crisis made the United States pay more attention to cold storage air-conditioning technology and applied it extensively. By the end of 2014, there were about 11,000 cold storage air-conditioning systems in the United States for different buildings, including office buildings, shopping centers, hospitals, schools, and factory process equipment and assembly centers. Japan is a country with very poor natural resources. Successive governments have attached great importance to energy issues (Hao, et al., 2015). In the early 1980s, Japan began its research on the application of cold storage technology. Starting in April 1984, various power companies formally implemented the night electricity tariff concession system. By 2010, there were approximately 5,474 storage air conditioning systems in operation in Japan, including 3,246 water storage systems and 1,228 ice storage systems. In 2014, there were a total of 12,566 air conditioning systems in Japan, including 4,294 water storage systems and 5,317 ice storage systems. In 2016, more than 5,000 ice storage air conditioners were built and put into operation. It is estimated that by the year 2020, Japan can move 11,420 MW through a cold storage air-conditioning system. In addition to the United States and Japan, in the developed countries such as the United Kingdom, France, Germany, Canada, and Australia, cold storage air-conditioning technology has also been promoted and applied one after another. Due to the energy crisis, in many parts of the world, cold storage air conditioning technology has received more and more attention, and the scale has become larger and larger, and a regional cold storage and cooling system has been formed. It is worth mentioning that South Korea has already enacted legislation in 1999, and public buildings larger than 3,000 square meters must use cold storage air-conditioning systems or absorption refrigeration systems.

China's cold storage air conditioning technology is developed in the 1980s, in which Taiwan's cold storage air conditioning technology is applied earlier. Although cold storage and air conditioning started relatively late, the use of cold storage air conditioning (including ice storage and water storage) has been increasing year by year throughout the country and has achieved initial results. Some aspects have accumulated a lot of their own unique experience. Since the first model project established by the Ministry of Electricity in China, the National Electric Power Dispatch Control Center (7,120Rth total storage capacity), Beijing successively has more than a dozen ice-storage air-conditioning projects such as China Central Television, China National Radio, and Beijing International Trade Center. The Shanghai Science and Technology Museum, a key project in Shanghai, has also adopted an ice storage project with a total area of 100,000 square meters and a total storage capacity of 32,488 kWh (9,240 Rth). Due to the application of a low-temperature air supply system, the system initially invested less than conventional air conditioning systems. Wuhan International Convention and Exhibition Center (10,656Rth of total storage capacity), Hangzhou Yintai Plaza (2,970Rth of total storage capacity) and Xi'an Xianyang International Airport Terminal Building (13,680Rth of total storage capacity) have all adopted the US B.A.C ice coil-type cold storage system. Shenzhen Electronic Technology Building uses the French CIAT ice ball ice storage system. There are also many cold storage projects in Sichuan, Chongqing and Fujian. According

to incomplete statistics, there are currently more than 300 cold storage air conditioning projects that have been put into operation throughout the country.
In summary, the theoretical analysis and experimental research on photovoltaic refrigerators and the research on the concept of ice storage air conditioning systems driven by photovoltaic energy systems have been studied in depth. However, research on the use of distributed photovoltaic energy to drive ice storage air conditioning systems is rare. Therefore, based on the above research, distributed photovoltaic energy-driven ice-storage air-conditioning systems are used as research objects. The energy transfer characteristics and energy flow of the ice storage system are simulated to optimize the parameters of the components and to promote the operation of the system PE. To achieve a stable and efficient power supply of distributed photovoltaic power generation systems.

## 3. Methodology

### 3.1 Controller energy and exergy theoretical model

Energy-balance equation is given in Formula (1): $Q_{c.in} = Q_{c.out-I} + Q_{c.Ioss}$, where $Q_{c.in}$ is the input controller energy per unit of time, $Q_{c.out-I}$ is energy of controller input inverter per unit of time, and $Q_{c.Ioss}$ is controller consumption energy per unit of time. The controller only plays a role in adjusting the current flow, so the energy loss means operation consumption by taking 4% of $Q_{c.in}$ as $Q_{c.ioss}$.
The loss of exergy is calculated in formula (2) as

$$\Delta E_c = Q_{c.Ioss}\left(1-\frac{T_a}{T_c}\right)$$

The exergy balance-equation is given in formula (3) as: $E_{x.in-C} = E_{c.out-C-I} + \Delta E_c$. In formula (2) and (3), exergy loss of controller, $T_C$: the temperature in the controlled area, the actual measured value: 303.15K, $E_{x.in-C}$: the exergy of input controller, and Ex.out-C-I: the exergy of controller input inverter.

### 3.2 Ice-storage system energy and exergy theoretical model

With the stable output energy by the distributed photovoltaic energy system used to drive the ice storage of ice machine, the fan coil was applied to blow out the stored cooling capacity for cooling; then the energy and exergy in the thermodynamics cycle refrigerating process of ice machine was analysed. The energy-balance equation of compressor is given in Formula (4) as $Q_{cp.in} = W_p + Q_{cp.Ioss}$, where $Q_{cp.in}$: input energy of compressor per unit time $Q_{cp.out}$: output energy of compressor per unit time, $W_p$: input power of compressor, and $Q_{cp.Ioss}$: loss energy of compressor per unit time.

### 3.3 Analysis parameter

The analysis parameters are given in Table 1.

*Table 1: Parameters of main parts of ice storage system driven by distributed solar photovoltaic system*

| system | parts | Model | main parameter |
|---|---|---|---|
| Distributed photovoltaic energy system | Photovoltaic module | Crystal energy /JN-245 | Open circuit voltage: 43.5 V; 12-48V 60Acharge; Peak power current: 7.10A. |
| | Controller | PHOCOS/PL60 | |
| | inverter | Kuwait/solar 48V | |
| | Battery | Shengyang/SP12-65 | |
| Ice storage and cooling system | Refrigerant | R134a | Molecular formula$CH_2FCF_3$; boiling point-26.1°C |
| | Ice maker | Shircore/IM50 | |
| | Cold storage tank | Self-control | |

*Table 2: Experimental results of ice storage system driven by distributed solar photovoltaic system*

| parameter | numerical value |
|---|---|
| $T_{out}$ | 22 |
| v(m-s$^1$) | 0.78~2.52 |
| Voc/v | 89.35 |
| /sc/A/ | 8.18 |
| $V_{cd}$/A | 51.6-55.5 |

The energy system consisting of 2 polycrystalline silicon photovoltaic modules in series with 245Wp peak power and 3.2m2 total area, 4 batteries in series, one controller, and one inverter, is applied to drive the refrigerating of ice machine. Table 2 shows the energy supply experimental results of distributed photovoltaic energy system in the typical fine day.
Then, based on the theoretical model, the energy transfer characteristics and exergy calculation results for the distributed photovoltaic energy driven ice storage system were obtained (Table 3 and 4).

*Table 3: Results of energy transferring characteristics of ice storage system driven by distributed solar photovoltaic system*

| Parameter name | numerical value | project | numerical value | classification | numerical value |
|---|---|---|---|---|---|
| Solar power accepted by a voltcomponent | 2595 | Loss power | 2250 | External radiation | 890 |
| Controller input power | 345 | Loss power | 13.8 | Controller output power | 331.2 |
| Battery output power | 111.16 | Loss power | 1.64 | Actual output power | 109.52 |

*Table 4: Exergy of ice storage system driven by distributed solar photovoltaic system*

| Parameter name | numerical value | project | numerical value | classification | numerical value |
|---|---|---|---|---|---|
| The input energy of PV modules | 931.16 | Energy loss | 383.25 | External radiation energy loss | 68.85 |
| The controller input of energy | 547.91 | Energy loss | 0.23 | The controller output energy | 547.68 |
| Battery output energy | 109.52 | The discharge process of energy loss | 0.08 | Battery output energy | 109.44 |

## 4. Results and analysis

Figure 1 and 2 depicts the distributed photovoltaic energy-driven ice storage system structure. The experiment was made to verify the theoretical model. In the experiment, the following parameters have been calculated, including the ice-making cycle of this system 10min, ice production capacity 0.35kg, ice production rate 2.08kg/h, water latent heat of solidification 335kJ/kg, 1kJ/h, cooling supply rate 0.278W, and the cooling power of ice block 193.5W. The cubic ice storage tank is 20cm×20cm×20cm with 0.008m3 capacity at full load ice 6.8kg; it can make cooling continuously for 2h at the cooling efficiency 88.67%. Then it can be concluded that the cooling power of photovoltaic energy-driven ice storage air conditioning system is 171.58W; in Table 3, the theoretical value of cooling power is 176.51W, 4.93W more than actually measured data in the experiment at the tolerance rate 2.79%, indicating that the theoretical calculation results coincide well with the experimental data, therefore, the established model can better reflect the energy transfer characteristics and energy loss of all parts in the operation process of photovoltaic energy driven ice storage air conditioning system.


*Figure 1: Structure of ice storage and cooling system driven by photovoltaic energy*

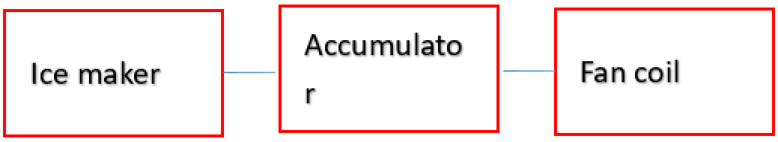


*Figure 2: Structure hardware of an ice storage and cooling system driven by photovoltaic energy*

Afterwards, it was found in Table 3 that the photovoltaic module had the maximum energy consumption, with 86.72% solar energy dispersed and lost in the environment during the system operation, so it is the main target in photovoltaic product research and utilization to improve the conversion efficiency of photovoltaic module. In the photovoltaic energy system, the energy consumption power of controller, battery and inverter were 13.8, 1.64 and 60.72 respectively, occupying 4%, 1.48%, and 13.78% of its respective input/output power. The inverter had more energy loss in the process of transforming the DC power into AC power, but in future it can be optimized by replacing the AC compressor with DC one, so as to reduce the loss and save the system costs. Besides, the ice machine in the single-stage vapor compressed refrigeration thermodynamic cycle, includes four major parts: compressor, condenser, throttle valve and evaporator; in the thermodynamic cycle of ice making, the loss power of compressor was 85.70W, the heat dissipation power of condenser was 2,640W, loss power of throttle valve was 0W, and the endothermic power of evaporator was 1,950W. Hence, it is found that the energy consumption is mainly centred in the two processes: transfer the solar energy into electric energy by photovoltaic modules, and ice-making of evaporator, so it is necessary to optimize the ice-storage process and improve the photoelectric converting efficiency of photovoltaic modules.

In the photovoltaic optothermal comprehensive utilization system, the exergy should be used to evaluate its energy characteristics based on the difference between electric energy and thermal energy. The theoretical calculation was made for the exergy and exergy loss in the operation process of distributed photovoltaic energy-driven ice storage air conditioning system as shown in Table 4. In the photovoltaic energy system, the acquired energy on the photovoltaic module surface was mostly dissipated into air, but the electric power transformed from the 13.28% solar energy could generate the exergy up to 547.91W, while the exergy loss by 86.72% dissipated energy of photovoltaic module was 383.25W; in terms of exergy loss, the loss by radiant heat, heat convection, photovoltaic, or others was 68.85W, 79.61W, 209.16W, and 25.61W respectively, where the photovoltaic modules generated the maximum loss of exergy, taking up 54.57% of total exergy loss, heat radiation 17.96%, and the heat convection 20.77%. besides, the exergy loss of controller, battery, and inverter in the energy system was 0.23W, 0.08W, and 3.82W respectively, occupying about 0.04%, 0.07%, and 0.58% of its respective input/output exergy. Due to the existence of heat absorption and exothermal process in the thermodynamic cycle of air conditioning system, the energy loss cannot be used to judge the performance of all components. The compressor, condenser, throttle valve and evaporator of air conditioning system have the exergy loss: 84.84, 30.86, 23.88 and 23.68W respectively, where the compressor had the maximum exergy loss, taking up 51.97% of total exergy loss, as the maximum-exergy loss component in the ice machine. Therefore, the operating mode of compressor should be optimized to reduce the exergy loss and booster the refrigerating property. For the evaporator, it absorbed heat in the water and external air circulation, with the input exergy 490.1W, where its 73.24% was transferred into useful exergy to making ice block, and the remaining 131.17W exergy was lost in the water and external air circulation, with the exergy loss of circulated water by evaporator 118.69W, about 90.49% of total exergy loss, and that of external air 12.48W.

Finally, it is calculated that the input exergy of total system was 931.16W, the output exergy of external cooling was 358.61W, and use rate of exergy in the system was 38.5%. In the photovoltaic energy-driven ice storage air conditioning system, the exergy loss mainly focuses on three parts: photovoltaic modules, compressor, and circulated water in the ice making process, with sum of exergy loss making up 74.26% of total loss. In view of the internal exergy loss of photovoltaic modules decided by its physical property parameters, the system optimization is mainly concentrated in the operating mode of compressor, and refrigerating model of evaporator. The return on investment of distributed photovoltaic energy driven ice storage air conditioning system has been calculated to show that the payback period of system within the 15-year life cycle is about 12 years, which is rather long, because the batter is used in the system to ensure the stable output of photovoltaic energy system; after the energy coupling between all components and the optimization of photovoltaic energy system control strategy, the battery-free distributed photovoltaic energy system can be applied, and then the payback period of the system can be reduced to 8 years with a certain economic efficiency.

## 5. Conclusion

By simulated analysis and experiments for the energy characteristics of distributed photovoltaic energy driven ice storage air conditioning system, the experiment data is well identical to the theoretical calculation results, so the established model can better reflect the photoelectric energy transfer characteristics, the energy characteristics and exergy loss of all components in the operation process of photovoltaic energy driven ice storage air conditioning system.

It is concluded that 86.72% acquired solar energy by the photovoltaic modules dissipates in the environment, and the remaining 13.28% is transferred into electric energy; then the exergy value of photovoltaic modules by transferring the 13.28% solar energy into electric energy is 547.91W, occupying 58.83% of system exergy loss. In the photovoltaic energy system, the energy consumption power of controller, battery and inverter were 13.8,

1.64 and 60.72W respectively; the exergy loss of controller, battery, and inverter were 0.23W, 0.08W, and 3.82W respectively, occupying about 0.04%, 0.07%, and 0.58% of its respective input/output exergy.
For the ice storage system based on photovoltaic system, its energy transfer characteristics changing with the original energy inputs should be studied in theory by considering the comprehensive indexes in different regions. But due to the limited conditions, only the optical energy in single region has been analysed, producing the analytic results relatively less objective and applicable. Hence, in future, the study should be made in a more in-depth and all-side way.

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## References

Hao L., Liu Y., Gao W., Han Z., Xue Q., Zeng H., 2015, Electrical and photovoltaic characteristics of mos2/si p-n junctions, Journal of Applied Physics, 117(11), 568-571, DOI: 10.1063/1.4915951

Huang B.J., Hou T.F., Hsu P.C., Lin T.H., Chen Y.T., Chen C.W., 2016, Design of direct solar pv driven air conditioner, Renewable Energy, 88(88), 95-101, DOI: 10.1016/j.renene.2015.11.026

Koohi-Kamali S., Rahim N.A., Mokhlis H., 2014, Smart power management algorithm in microgrid consisting of photovoltaic, diesel, and battery storage plants considering variations in sunlight, temperature, and load, Energy Conversion & Management, 84, 562-582, DOI: 10.1016/j.enconman.2014.04.072

Liu Z., Zhang Q., Dong C., Lin Z., Wang Z., 2014, Efficient and security transmission of wind, photovoltaic and thermal power of large-scale energy resource bases through uhvdc projects, Proceedings of the Csee, 34(16), 2513-2522, DOI: 10.1109/pesmg.2014.6672733

Mohammadnejad S., Khalafi A., Ahmadi S.M., 2016, Mathematical analysis of total-cross-tied photovoltaic array under partial shading condition and its comparison with other configurations, Solar Energy, 133, 501-511, DOI: 10.1016/j.solener.2016.03.058

Shafiullah G. M., Oo A.M.T., Ali A.B.M.S., Wolfs P., Stojcevski A., 2014, Experimental and simulation study of the impact of increased photovoltaic integration with the grid, Journal of Renewable & Sustainable Energy, 6(3), 033144, DOI: 10.1063/1.4885105

Tanaka Y., Hoerlein M.P., Schiller G., 2016, Numerical simulation of steam electrolysis with a solid oxide cell for proper evaluation of cell performances, International Journal of Hydrogen Energy, 41(2), 752-763, DOI: 10.1016/j.ijhydene.2015.11.048

Xu Y., Li M., Hassanien R.H.E., 2016, Energy conversion and transmission characteristics analysis of ice storage air conditioning system driven by distributed photovoltaic energy system, International Journal of Photoenergy, 2016(4), 1-17, DOI: 10.1155/2016/4749278