Experimental investigation of static ice refrigeration air conditioning system driven by distributed photovoltaic energy system

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Abstract. The static ice refrigeration air conditioning system (SIRACS) driven by distributed photovoltaic energy system (DPES) was proposed and the test experiment have been investigated in this paper. Results revealed that system energy utilization efficiency is low because energy losses were high in ice making process of ice slide maker. So the immersed evaporator and co-integrated exchanger were suggested in system structure optimization analysis and the system COP was improved nearly 40%. At the same time, we have researched that ice thickness and ice super-cooled temperature changed along with time and the relationship between system COP and ice thickness was obtained.

1. Introduction

With the dramatic climate changes, the cooling demand has been increased and led to a rapid growth of energy consumption, which causes traditional fossil fuel energy shortage and great damage to climate and environment with the emissions of CO$_2$ and harmful particles by extensive use of traditional fossil energy. Furthermore, using the electric air conditioning increases the electrical pressure in the peak time and increases the tense situation between power supply and demands. Therefore, refrigeration driven by solar energy becomes one of the promising approaches to reduce or partially replace the conventional refrigeration systems. There are two main working modes of solar...
refrigeration namely solar thermal refrigeration and solar photovoltaic refrigeration [1, 2].

Solar photovoltaic (PV) refrigeration has more advantages on refrigerating effect, stable operation and energy utilization rate compared to solar thermal refrigeration. Aktacir [3] designed a multifunctional PV refrigerator and found that when indoor and outdoor average temperatures were 26.3 °C and 24.9 °C, the minimum temperature of the refrigerator reached -10.6 °C, but the system COP should be improved. To improve system efficiency, Bilgili [4] studied the performance of PV refrigerator. It was reported that the coefficient of the performance variation of the cooling system decreases with the decreasing of evaporating temperature. So a reasonable cooling temperature can manually defined is beneficial to the refrigeration efficiency. Ekren et al. [5] studied the photovoltaic DC refrigerator system and found that PV module conversion efficiency has a greater impact on the system exergy efficiency, so the increasing photo-electric conversion efficiency of PV module day by day is good for PV refrigeration. And the researched results also showed that the energy matching and coupling between photovoltaic arrays and refrigeration systems is a key point in PV refrigeration research. So in order to improve the energy matching and coupling characteristics, Kaplanis & Papanastasiou [6] improved the performance of a traditional refrigerator which driven by PV. The energy conversion, management and operation performance for PV refrigerator system powered on three conditions such as, photovoltaic components, battery and outage showed that the system COP gradually decreases from morning till night and the energy coupling between PV modules and refrigerator was very good when DC variable frequency compressor was adopted. And Mba et al. [7] used MATLAB software to simulate PV refrigeration system operating process and analysis system operating characteristics in different conditions. The energy conversion, management and operation performance for PV refrigerator system powered on three conditions such as, photovoltaic components, battery and outage showed that the system COP gradually decreases from morning till night [8]. Axaopoulos & Theodoridis [9] designed a PV Ice-maker without battery and studied its performance when the compressor operating efficiency was 9.2%, they found that this prototype have a good ice-making capability and reliable operation as well as a great improvement in the startup characteristics of the compressors, which remain working even during days with low solar irradiation of 150W/m².

Recently, the PV refrigeration system has been improved and developed in the aspects of product structure, operating efficiency and refrigeration performance. According to comprehensive analysis, PV refrigeration system research is currently mainly concentrated on ice generator driven by PV. Batteries are essential component to store energy and to solve the intermittent of solar energy in PV refrigeration system. Thus, static ice refrigeration conditioning system (SIRACS) driven by distributed photovoltaic energy system (DPES) was established based on our previous research results [10]. At first, experimental work has been done to analyze the energy coupling and transferring characteristics in light-electricity-cold conversion process. And then, the system structure optimization analysis was also investigated and optimized another SIRACS was put forward and experimental research has been done. The higher energy utilization efficiency and better financial rewards were achieved.

2. Materials and methods
2.1 Configuration of SIRACS driven by DPES

Static ice refrigeration conditioning system (SIRACS) driven by distributed photovoltaic energy system (DPES) is mainly configured by DPES, ice generator, static ice storage system and air conditioning system. The system structure and work diagram are shown in Figure 1.

**Figure 1.** Structure and work diagram of SIRACS driven by DPES

In daytime, DPES receives solar energy and turns it into direct-current (DC) electric power which can be converted to alternating current (AC) electric power by inverter to drive AC compressor, water pump, ethylene glycol pump and fan coil. To maintain the stability of electric energy supply, batteries are adopted and connected with controller to maintain the energy conversion and supply in the best way. Ice generator and storage system is made up with AC compressor, condenser, expansion valve, disc evaporator and static ice storage tank. Circulating water can be frozen in the disc evaporator and then the ice fallen into static ice storage tank. Thereby, the ice generator works as vapor compression refrigeration. In AC compressor, refrigerant R134a is compressed into high temperature and high pressure gas, filtered in gas-liquid separator and to release heat in condenser. Refrigerant is condensed to mild temperature and high pressure gas. When the gas inflows into throttle valve, it can be throttled to low temperature and low pressure liquid then feeds into plat evaporator. And then, refrigerant flows into the other gas-liquid separator to be sucked into the compressor. Thereby, the refrigeration cycle will be completed. Air conditioning system is mainly made up of coiled pipe cold exchanger fixed in static ice storage tank, Ethylene glycol pump, solenoid valve, proportional control valve and fan coil. Ethylene glycol is an adopted cold exchanging medium. According to the working principle diagram, a 0.2 kW SIRACS driven by DPES was established as shown in figure 2 and the main component parameters are shown in Table 1.

**Table 1.** Main component parameters of SIRACS driven by DPES

| Component                 | Model  | Parameters |
|---------------------------|--------|------------|
| Air conditioning system   |        |            |
| Ice making and storage system |      |            |
| Distributed PV energy system |   |            |

2016 International Conference on New Energy and Future Energy System (NEFES 2016) IOP Publishing
IOP Conf. Series: Earth and Environmental Science 40 (2016) 012027 doi:10.1088/1755-1315/40/1/012027
DPES were made up of two 245 W polycrystalline silicon PV in series. Four batteries in series were used to store electric power and the controller and inverter were adopted in DPES. SIRACS were made up with ice generator, static ice storage tank and fan coil.

Refrigerant (R134a) temperatures and pressure were measured by T-type thermocouples and pressure transducers, respectively. Voltages and currents of PV modules were measured by a digital multi-meter. The wind speed was measured by the wind speed transducer. Solar irradiation was measured by Pyranometer. Compressor input power was measured by a wattmeter. Electromagnetic flow meter was used to measure refrigerant flow and Ethylene glycol flow. The parameters of all instruments were shown in Table 2.

**Table 2. Parameters of instruments**

| Component | Description |
|-----------|-------------|
| PV module | JN-245, $P_{m}=245$ W, $V_{m}=34.5$ V, $I_{m}=7.10$ A, $V_{OC}=43.5$ V, $I_{SC}=8.18$ A |
| Controller | PL60, 12-48 V 60 A charge, 30 A load |
| Inverter | 3 kW, DC input voltage: 48 V, Output voltage: 220 V |
| Batteries | Solar 48 V, SP12-65, Battery capacity: 12 V 65 Ah, four batteries in series |
| Refrigerant | R134a, Boiling point: -26.1 °C, Critical temperature: 101.1 °C. Ice production: 2.08 kg/h, P: 380 W, Capacity: 0.008 m³ |
| Ice generator | IM50 |
| Static ice storage tank | / |
| Cold exchanging medium | Ethylene glycol, Melting point: -12.6 °C, Viscosity: 25.66 mPa·s |
| Pump | RS15-6, Power: 46-93 W, Life: 6 m, Maximum flow rate: 3.4 m³/h |
| Fan coil | /, Speed: 2800 r/min, number of fins: 95, Size: 23 cm*8 cm*20 cm, Coil numbers: 26, Coil inner diameter: 6 mm |

**Figure 2.** Pictures of 0.2 kW SIRACS driven by DPES
Table 2. Measuring instrument parameters

| Instrument                     | Parameters and accuracy                                      |
|-------------------------------|-------------------------------------------------------------|
| Digital multi-meter           | FLUKE F-179, DC voltage measurement accuracy: ±0.9%+2, DC current value measurement accuracy: ±1%+3. |
| Thermocouples                 | Type: T, range: -200 to 350 °C, accuracy: ±0.4% of full scale |
| Wind speed transducer         | EC-9S, range: 0-70 m/s, accuracy: ±0.3 m/s, resolution ratio: 0.1 m/s |
| Electromagnetic flow meter    | SIEMENS FUP 1010, range: -12 m/s~12 m/s, accuracy: <0.3 m/s (1 ft/s), ±0.5% ~ ±2.0%, |
| Electronic balance            | AHW-3, range: 0-3 kg, accuracy: ±0.05 g                   |
| Pressure transducer           | Range: 0-0.6 MPa low side and 0-1.8 MPa high side; accuracy: ±0.25% of full scale at 25 °C |
| Pyranometer                   | Kipp & zonen CMP6, Range: 0-2000 W/m², accuracy: ±5%         |
| Wattmeter                     | DELIXI DDS607, Type: 220 V 20 A 50 Hz 3200 imp/kW, accuracy: 0.01 kW·h |
| Data acquisition              | Agilent34972A data acquisition unit                         |

2.2 Theoretical models of SIRACS driven by DPES

Solar energy absorbed by PV modules can be estimated as:

\[ Q_{PV} = \alpha \tau G S_P \]  

(1)

\( \alpha \) is solar cells absorption coefficient and \( \tau \) is PV module cover glass transmittance. \( G \) is the solar irradiance, W·m\(^{-2}\). \( S_P \) is the total areas of PV modules, m\(^2\).

The photo-electric transformation instantaneous efficiency of PV modules is given by:

\[ \eta_{PV} = \frac{I_P V_P}{Q_{PV}} \]  

(2)

\( I_P \) and \( V_P \) are respectively the PV modules output current and voltage values can be tested with Fluke digital multi-meter, A and V.

Batteries were used in order to provide the stability for system operation. The transient energy balance equation of batteries is expressed as:

\[ Q_b = \pi (I_p V_p) - I_b V_b \]  

(3)

\( Q_b \) is batteries storage electricity per time, W. \( I_b \) and \( V_b \) are respectively the batteries output current and voltage values, A and V. \( \pi \) is defined as switching constant in this equation. When DPES is connected with load, \( \pi \) equates 1 and \( \pi \) equates 0 when load is disconnected.

In ice making process, the energy balance equation is given by:

\[ W_p = \dot{m}_r C_r (T_{con,in} - T_{con,out}) + \dot{m}_b Q_{loss} \]  

(4)

\( W_p \) is ice generator compressor operation power, W. \( \dot{m}_r \) is refrigerant mass flow tested by electromagnetic flow meter, kg·s\(^{-1}\). \( C_r \) is average specific heat capacity of refrigerant flowing in the
condenser, J·kg\(^{-1}\)·K\(^{-1}\). \(T_{\text{con.in}}\) is refrigerant temperature at condenser inlet, K. \(T_{\text{con.out}}\) is refrigerant temperature at condenser outlet, K. \(m_i\) is the ice production per time, kg·s\(^{-1}\). \(h\) is ice latent heat, J·kg\(^{-1}\). \(Q_{\text{loss}}\) is energy loss per time in static ice making process, W.

And the instantaneous COP of static ice generator is shown as:

\[
COP = \frac{n_i h}{W_p}
\]  

(5)

Ice produced by static ice generator are stored in the tank when the fan and ethylene glycol pump are turn on, the cold stored by ice can be exchanged and transferred to cooling indoor air. The instantaneous efficiency of static ice storage air conditioner can be expressed by:

\[
\eta_a = \frac{C_a n_d \Delta T_a}{n_d h}
\]  

(6)

\(C_a\) is specific heat capacity of air indoor, kJ·kg\(^{-1}\)·K\(^{-1}\). \(n_d\) is air mass flow produced by fan, kg·s\(^{-1}\). \(\Delta T_a\) is the temperature change of air through fan coil, K.

And system instantaneous energy efficiency is written:

\[
\eta = \eta_{\text{PV}} \cdot \text{COP}_{\text{PV}}
\]  

(7)

3. Results and discussion

0.2kW SIRACS driven by DPES was tested on October 22 Kunming. Firstly, global solar radiation and ambient temperature were tested, as shown in Figure 3.

![Figure 3](image-url)  

**Figure 3.** Variations of global solar radiation and ambient temperature on 22th NOV, 2015 in Kunming

![Figure 4](image-url)  

**Figure 4.** Variations of wind speed and PV modules temperature on 22th NOV, 2015 in Kunming

PV modules temperature is a decisive component of output performance, which can be affected by wind speed changing at any time. Thus, wind speed and PV modules temperature can only be obtained by experimental measurement, as shown in Fig. 4. When SIRACS was driven by DPES, the output current and voltage of PV modules are tested and the change curves are shown in Fig. 5. Batteries were adopted to ensure power output stability and store excess power generated by PV modules. And so the output current and voltage of batteries changed with that of PV modules and the output characteristics of batteries were given by Figure 6.
It was observed that in figure 5 the maximum current value was 8.6 A at 12:35 and output voltage changes were 50.8 V-54.2 V and the maximum voltage appears at 12:36. Research results for batteries charging and batteries discharging are shown in figure 6. In batteries discharging, statics ice generator can be driven for 10 hours by batteries only which were in full power state and disconnected with PV modules until the batteries electricity decreased and cannot drive the statics ice maker. The voltage declined from 54.88 V to 44.6 V step by step and output current maintain about 7 A with a small fluctuations between 5.4 A and 7.4 A. In charging process for batteries, batteries disconnect with ice generator and connected with PV modules. Batteries current changed with solar irradiance and voltage increased gradually until batteries were in floating state.

The static ice generator operation cycle time was 10 min and the ice production was about 0.35 kg every cycle. Ice making efficiency was 2.08 kg/h. The temperatures of ice generator with every component in thermodynamic cycle have experimental tested, as shown in figure 7.

According to the above experimental results and calculation formulas, the maximum value of PV
modules photoelectric conversion efficiency can be calculated. At the same time, batteries storing or releasing electricity, the minimum energy loss and COP maximum value of static ice generator and the maximum energy utilization efficiency of air conditioner made up with fan coil also were calculated and shown in Table 3.

**Table 3.** Experimental and computational results of SIRAS driven by DPES

| PV modules | Batteries | Static ice maker | Air conditioner |
|------------|-----------|------------------|-----------------|
| α          | 0.92      | Ib = -7.1~7.3 Wb | Wp = 380 Tcon,out = 296.0~303.6 Ca = 1 |
| τ          | 0.90      | Ip = 0.1~8.6 Vp | 44.6~56.5 $\delta_i$ = 0.0127 $\alpha_i$ = 2.08 $\alpha_i$ = 0.12 |
| G          | 282-985   | Tcon,in = 297.7~307.5 h | 335 $\Delta T_a$ = 0~1.5 |
| Vp         | 50.8~54.2 | $C_r$ = 650 |
| $\eta_{PV,max}$ | 17.58% | $Q_b$ = -380~401 $Q_{loss,min}$ = 128.66 COP$_{max}$ = 0.51 $\eta_{a,max}$ = 93.00% |
| $\eta_{max}$ | 8.34% | |

It was observed that in Table 3 the maximum value of system energy utilization efficiency was only 8.34%. The low photoelectric conversion efficiency of PV modules is one of the reasons leading the low system efficiency and static ice generator with a 0.51COP low refrigeration coefficient caused lost of energy loss. Because in ice making process, ice pasted well together with five solid walls of grid plate evaporator and cannot be separated off by ice gravity. Thus, compressor must be shut down and a special solenoid valve as shown in Figure 13 must be opened which used for adjust refrigerant flow and introduced the high temperature and high pressure refrigerant steam expelled from compressor into evaporator. And then, the evaporator plays the role of condenser to release heat to ice through solid walls and ice interfaces begin melting. Ice was divorced from evaporator and fall into tank. Meanwhile, evaporator inlet temperature and outlet temperature increased sharply until the solenoid valve was closed and compressor was turned on and a new ice making process begins. The refrigerant flowed out evaporator into throttle valve and become low temperature and low pressure liquid. And then, the refrigerant flow into condenser to absorb heat from outside and condenser inlet and outlet temperature decline sharply when low temperature refrigerant flows into it. Condenser outlet temperature was higher than condenser inlet because refrigerant absorb heat form outside through condenser, as shown in Figure 12. Refrigerant next flow into compressor and compressor inlet temperature increase a lot compared to ice making process, which can be changed with inlet and outlet temperature variation of evaporator and condenser. Compressor stops running in ice melting abscission process and the refrigerant gas cannot be compressed in compressor. Therefore, the compressor outlet temperature drops sharply when the solenoid valve opens and it returns smoothly when ice making process opened. Ice melting abscission process was extremely unfavorable to SIRAS for a number of reasons as the following:

- Ice generator operation period extended for 200s; furthermore, the ice melting abscission time was one third time of an ice making cycle.
Service life of compressor will be shortened by frequent start and stop compressor, which has a great impact on ice making process and was extremely unfavorable for energy supply process of DPES. Electricity consumption of solenoid valve was $3.0 \times 10^{-4}$ kW h in ice melting abscission process and the total electricity consumption was 0.024 kW h from 7:30 to 19:00. Therefore, in order to improve the performance of SIRAS driven by DPES, some optimization and improvement measurements were proposed as follows:

- Photoelectric conversion efficiency of PV modules must be improved. But there are some difficult to greatly improve the efficiency limited the current technology level and material processing technology. It is very expensive to optimize the efficiency.
- In another way, the COP of static ice generator can be improved easily through structural improvement and performance optimization. Firstly, Evaporator immersion static refrigeration mode was adopted to replace ice harvester refrigeration mode. The optimized coil evaporator was immersed into water to absorb heat and produce ice and then all the energy could be utilized, as shown in figure 9.

![Figure 9. Profile of evaporators and cold exchanger immersed in the static ice storage tank](image)

And then, The coiled pipe cold exchanger was co-integrated with coil evaporator. In refrigeration process, coiled pipe cold exchanger has the priority to get cold transferred from the coil evaporator next to the cold exchanger to supply cold for user. Surplus cold is used to make ice to store cold. Consequently, SIRACS not only has the out-of-the-box function of ordinary air conditioning, but also effectively improve the appearing phenomenon of over cooling and remedy the disadvantage of cold supply after ice making process in traditional submerged ice making system. The top view of co-integration evaporators and cold exchanger immersed in the static ice storage tank is shown in figure 10.
Another evaporator immersion static ice generator was constructed according to the optimization design, shown as figure 11.

In figure 11, the evaporator was co-integrated with cold exchanger with fins, which were immersed in the water stored with tank. The evaporator was connected with a 735 W refrigerator. Experimental test work has been done and the results are shown in Table 4.

| Compressor power /W | Runtime /s | The weight of water /kg | Initial water temperature /K | Final water temperature /K | The quantity of ice /kg | COP |
|---------------------|------------|-------------------------|------------------------------|---------------------------|------------------------|-----|
| 735                 | 7200       | 31                      | 290.15                       | 275.15                    | 5.4                    | 0.71|

Experimental results showed that the COP of evaporator immersion static ice generator improved nearly 40% than that of ice slide static ice maker. But it is very obviously observed in experiment that the ice thickness increasing rate gradually decreased. For low heat conductivity, when ice thickness increased the cold in evaporator could not be delivered to the ice surface in time. So the cold could not be fully absorbed by water, which will cause that too much liquid refrigerant flowed into the gas-liquid separator and gas refrigerant was not enough sucked by compressor leading to compressor...
shutdown for too low air pressure. So the experimental research on ice thickness and ice super-cooled temperature must be carried out for system performance optimization and ensuring compressor operating safely and stably. The results were shown in figure 12. At the same time, the relationship between system COP constantly changing and ice thickness was studied with experiment also and the result was shown in figure 13.

![Figure 12. Variation curves of ice thickness and subcooled temperature](image)

![Figure 13. Relationship between COP and ice thickness](image)

In figure 12, it was observed that the ice thickness on the evaporator gradually increased along with increasing time but the growth rate gradually reduced. At the same the ice subcooled temperature gradually declined and the decline rate was gradually increased. So to ensure the optimum coupling between ice thickness and ice temperature, the best working time range was given, which was 20min~32.5min when ice making process was begun. Both of ice thickness and ice temperature were in best value. Among them, the best ice thickness range was 16.5mm~18.8mm and the best ice super-cooled temperature was 272.76K~272.87K. From Figure 13, the system COP decreased along with ice thickness increasing and the COP decreased rapidly when ice thickness was more than 14mm. the COP range is 1.75~1.21 corresponding with the best ice thickness given by Fig. 12. All of the research Results can provide reference and technical support for immersion static ice generator working efficiently and the application and popularization of SIRAC driven by DPES.

4. Conclusion
In this paper, a 0.2kW SIRACS driven by DPES was constructed. The system characteristic parameters were tested and the energy conversion efficiency of each component was calculated according to the experimental data. And the optimal design scheme was proposed based on the analysis of each component energy loss. So another evaporator immersion static ice generator test platform was built after optimization and relevant experimental research work has been carried out. All of the research results are shown as:

- The maximum value of system energy utilization efficiency was only 8.34%. The main reasons is the COP of ice generator was only 0.51. Because the ice slide work model of ice generator include ice making process and ice melting abscission process, which not only leads to much of energy has been lost but also the ice generator operation period extended for 200s and ice melting abscission time was one third time of an ice making cycle.
Optimal design scheme about ice making model was proposed. Evaporator immersion static refrigeration mode was adopted to replace ice harvester refrigeration mode and the coil cold exchanger was co-integrated with coil evaporator.

Experimental test work on evaporator immersion static ice generator has been carried out. The COP of evaporator immersion static ice generator was 0.71 improved nearly 40% than that of ice slide static ice generator. The best ice thickness range was 16.5mm~18.8mm with the system COP changed among 1.75~1.21. The best ice super-cooled temperature was 272.87K~272.76K.

5. Acknowledgement
The authors gratefully acknowledge the financial support provided by National International Scientific and Technological Cooperation Program (2011DFA62380). The authors are also grateful to Renewable Energy Research and Innovation Development Center in Southwest China (05300205020516009), Research and Innovation Team of Renewable Energy in Yunnan Province and Yunnan Provincial Renewable Energy Engineer Key Laboratory and Yunnan Provincial Department of Education Science Research Fund Project (2015J035).

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