Design and Performance of a Multiple Compressor Solar Ice-maker

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Abstract: - This paper presents a solar photovoltaic powered ice-maker which operates without the use of batteries and is therefore environmentally friendly and may be used in truly autonomous applications in remote/isolated areas. The successful operation of the refrigeration compressors by the PV panels is ensured by the use of a dedicated controller, which provides easy startup, maximum power tracking and power management for the 4 compressors of the system. The prototype results have shown very good ice-making capability and reliable operation.

Key-Words: Solar, ice-maker, batteryless

1 Introduction

A solar photovoltaic refrigeration system, without battery, has been developed in the Renewable Energy Laboratory at the Technological Educational Institute of Athens. Our approach is to store the energy in ice and therefore to avoid the need for batteries, which are responsible for a significant portion of the capital cost and much of the maintenance cost. Additionally environmental pollution of lead might be expected from batteries, because their life cycle is limited. Deep cycle batteries are usually not produced in developing countries, making funding, purchasing and transporting them to remote sights difficult. In addition, funds may not be available to pay for the batteries when replacement is necessary. Recycling the used batteries is also very difficult and usually is rare.

The new trend in solar operated or assisted thermal systems is to incorporate the use of a direct-current, variable-speed compressor. It has been shown in several research works that there occur reasons why compressors with capacity control offer distinct advantages over compressors with fixed capacity, especially concerning energy management and overall system efficiency [1-6].

The PV panel is connected directly to a capacity-modulated DC compressor via an efficient controller developed in our Laboratory. The advantage of using the developed controller is the improved utilization of the PV electric energy, achieved by modifying the compressor startup characteristics and exploiting the maximum power of the PV. In addition, the capacity modulation enables continuous efficient operation and also avoids the energy and mechanical costs of repeated start – stop cycles. The compressor is connected with a coolant circuit which is in thermal contact with the evaporator in the ice storage tank interior.

The ice storage tank consists of an inoxydable insulated water tank with a submerged evaporator. The advantage of having an ice storage tank is the small required stores, 10-20% of the size compared to a chilled water store, and 30-50% compared to stores with eutectic salts.

The developed unit can be used as a freezer and/or a refrigerator, and is suitable for a variety of application such as health, commercial and domestic purposes in areas where utility power is unavailable or utility line extensions would be too expensive. In the case where the unit will be used both for refrigerator and freezer, a secondary air-cooled loop can be added in a second compartment. The ability to store ice, instead of electrical energy in batteries, makes the proposed system a multifunction, sustainable and reliable cooling source both day and night without environmental risk.

A conventional domestic refrigerator, with the same volume of refrigeration compartment, compared with the proposed system, takes 2 -3 times more power and consequently, requires more solar panels and moreover a large inverter and batteries.

Compared to kerosene or bottled gas fuelled refrigerators, the proposed system have the following advantages:

- Elimination of fuel supply problems
- Elimination of fuel quality problems
- Greater refrigerator reliability
- Better refrigerator performance
- Elimination of kerosene fuel costs
- Elimination of kerosene transport costs
- Lower refrigerator maintenance costs.
- Reduced needs for backup refrigerators where there are fuel supply or repair problems

The aim of this paper is to present the performance evaluation of a certain batteryless ice-making system that is efficient, reliable in operation and may be used in truly autonomous applications in isolated areas without environmental risk.

Early results from a prototype showed a great improvement in the startup characteristics of the compressor, which effectively allow the compressor to remain operational even during days with low solar irradiation [7-8].

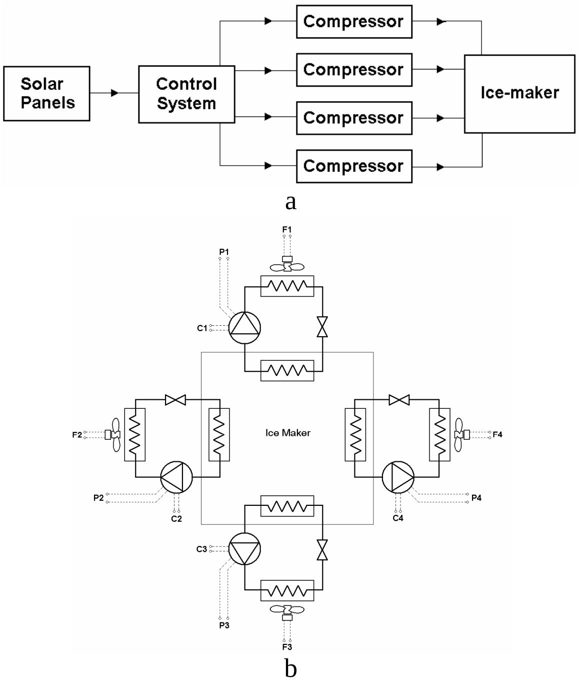

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Fig. 1 The ice-maker configuration. a. Block diagram, b. The cooling circuits.

2 System configuration

The ice making system consists of an insulated ice storage tank filled with water, four small-capacity hermetic compressors equipped with their submerged vertical plate – surface evaporators on which ice is formed, the corresponding air cooled condensers, and photovoltaic array.

The ice storage tank is an inoxydable tank, has a volume of 175 l and is insulated with polystyrene of 10 cm thickness. Four hermetic type reciprocating, direct current compressors are used which are connected to a photovoltaic array of 440 W_p, through a controller. The evaporator is an aluminum roll-bond and consists of two plates which have been bonded together over almost their entire surface. The area which is not bonded forms the evaporator channel. It is commercially available, and can readily be defrosted manually. A plate finned tube condenser has been used, and a small capacity fan forces air between the fins and over the tubes.

Figure 1 shows the configuration of the system. Four independent cooling compressors are fed through a power controller by a common PV array. The compressors’ cooling circuits act on a common water tank. The power ports (P1-P4), the speed ports (C1-C4) of the compressors and the power ports (F1-F4) of the fans are all connected to the system controller.

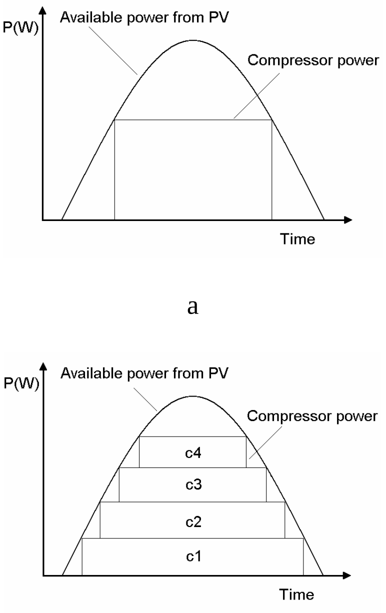

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Fig. 2 a. Operation with single compressor, b. Operation with multiple compressors.

There is a number of reasons why multiple compressor systems may present advantages over single compressor systems. One advantage is that a much wider control range can be achieved. Even with fixed speed/power compressors, the utilization of energy from a variable power source, like PVs, is increased dramatically when using many small compressors instead of one large compressor (Fig.2). The same applies to systems with variable speed compressors. For example, a single variable speed compressor can operate at a minimum power of 50% of its rated power. A system of four small, similar compressors, each rated at ¼ of the single compressor power, will have a total minimum power of operation of 12.5% of the total rated power, since it is possible to operate only one compressor at 50% of its rated power. Another advantage is that the static friction of small compressors is lower than that of large compressors and, as a result, a multiple compressor system has lower startup power requirements. This is of great importance to solar systems, where there is a need for maximum exploitation of the available solar energy. Finally, a multiple compressor system exhibits a much higher degree of fault tolerance than a single compressor one since it will sustain the presence of a number of compressor faults before it becomes inoperative.

2.3 Compressor Controller

The compressor controller has already been presented in [7]. Its main advantages over the compressor manufacturer internal control unit are the startup power reduction and the stable maximum power tracking algorithm. Moreover, the controller structure has been extended to accommodate the use of multiple compressors, [8], employing a control strategy that enhances the process of the successive compressor startups and maximizes the utilization of the PV panels available energy.

3 Results and Discussion

The complete ice-maker was tested on days with different values of total solar energy in order to evaluate the amount of produced ice.

3.1 Instrumentation

In order to evaluate the performance of ice making system, a PC- based automatic data acquisition unit has been used. The unit monitors total solar irradiance on the tilted PV modules' surface, array voltage and current, ambient temperature, cell temperature, low and high pressure across the compressor, inlet and outlet of the refrigerant at the compressor, and temperature at different points in the water tank. The unit scanned all channels in ten seconds intervals, averaged them over 1 min periods and stored them in a hard disk for further processing. The solar irradiance was measured using a first class pyranometer. Current, voltage and pressure were measured by relevant transducers, and finally all temperatures were measured with platinum resistance detectors.

The system operated daily and the ice produced was weighed at the end of the day. At the beginning of each day, before the start of the test, the system was preconditioned so as to have the system always starting with the same condition. The condition was that there was no ice formed on the cooling plates and that the water was at 0°C. This condition was dictated by the practical use of the ice-maker in which the system would start operating every day having kept a fair amount of ice from the previous day. That amount of ice would keep the water temperature at around 0°C at all times. The ice is removed from the plates at the beginning of the day in order to measure the right amount of ice produced in a day only.

Figure 3 shows the operation of the ice-maker during the 7th of March of 2007. It is evident that the compressor power curve closely follows the solar irradiance curve, suggesting the accurate operation of the maximum power algorithm. The system manages to recover very shortly after each sudden reduction of the solar irradiance, and that is achieved due to the controller's startup enhancement operation.

Several of the above measurements were taken throughout many months and the collected data was used to evaluate the ice-making capability of the system.

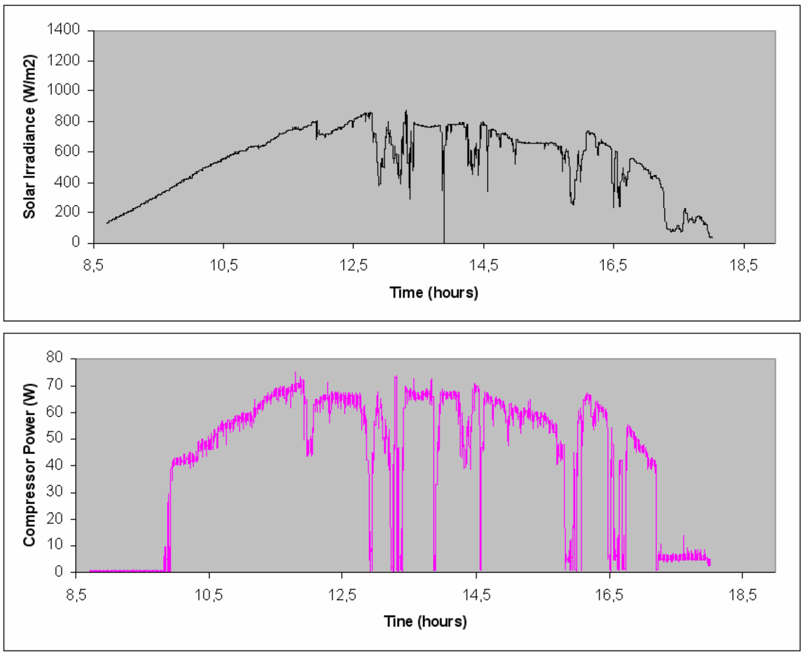

Fig. 3 Operation of the ice-maker for the duration of a day.

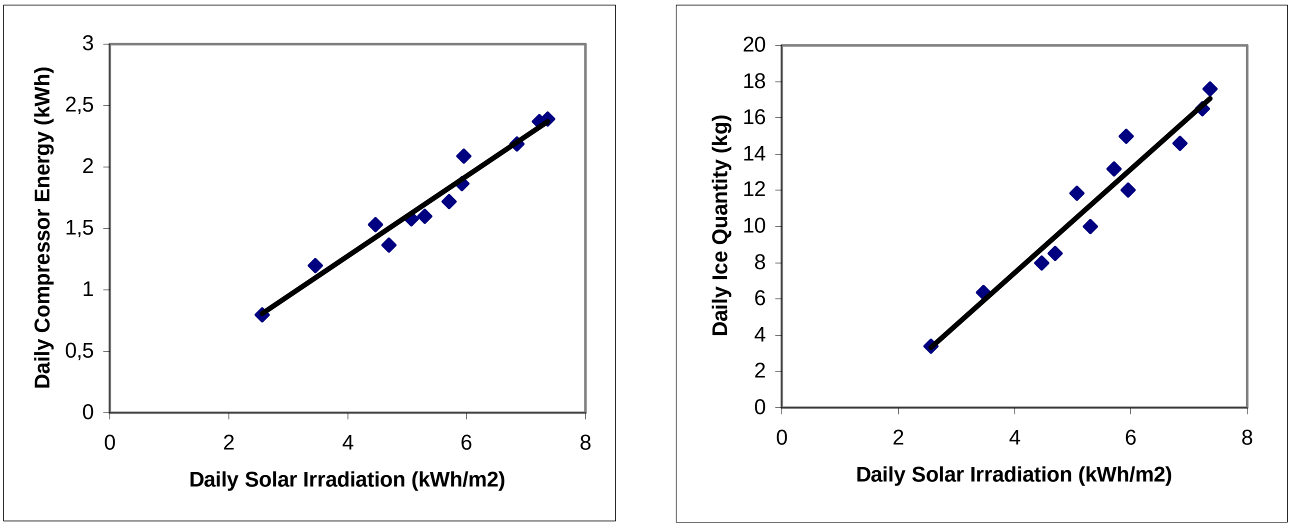

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Fig. 4 The performance curves of the ice-maker. a. Energy exploitation, b. Ice formation.

Figure 4 shows the performance curves of the ice-maker as regards the daily solar irradiation on the tilted surface of the PV array. The compressor energy exploitation curve can be approximated by a linear function with a proportionality constant of around 0.303 kWh(compressor)/kWh/m^2, which, taking into account the PV area of 3.3 m^2, suggests a combined PV panel – compressor efficiency of around 9.2%. This value is quite close to the PV panel nominal efficiency, revealing the accurate maximum power tracking of the controller.

The ice quantity curve shows that the system is capable of producing around 4.5 kg of ice at only 3 kWh/m^2 and up to 17 kg at about 7.3 kWh/m^2, all units per day. One may notice large deviations in the values in this graph. These deviations are largely due to the impact of the solar irradiance profile on the system performance. Two days with the same total solar irradiation but different solar irradiance profile may lead to the production of different quantities of ice. This effect can be attributed to the COefficient of Performance of the compressors in combination with the compressors' speed at different solar irradiance levels. Also, the ambient temperature can affect the performance of the PV array and the condensers and the thermal losses of the ice storage tank, therefore affecting the daily ice production.

4 Conclusions

A batteryless, solar-powered ice-maker has been presented that is truly autonomous and environmentally friendly. The ice energy storage renders the systems maintenance-free and low cost and makes it ideal for application in remote/isolated areas with energy supply limitations. The system controller offers a reliable operation with near-perfect solar energy utilization, providing easy compressor startups, accurate maximum power tracking and power management. The prototype results have shown that the system energy exploitation is very high and that the system can produce a relatively large quantity of ice, even on days with low total solar energy. These results verify the success of the proposed ice-maker configuration in providing a reliable continuous cooling source at low cost for a wide range of solar irradiance levels.

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