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Development and Performance Evaluation of an Energy Efficient Solar-driven Refrigeration System with Thermal Energy Storage

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ABSTRACT

A solar-powered vapour refrigeration system integrating eutectic phase-change material (PVC) as thermal energy storage at evaporator was constructed and tested. Creating a satisfied temperature and potential difference to activate the compressor and run it constantly at 2A, the panels were placed in parallel. The direct current that powers the compressor was initially generated from sunlight and transformed into alternating current utilizing an inverter. The PVC tank was iced by the circulated eco-friendly isobutene (R134a) refrigerant. Using PV system software, an investigation was conducted to examine the differences in the efficiency of a solar photovoltaic panel (PVP) driven refrigeration system. Analysis was done on the voltage, energy, and energetic efficiency changes of PVP. With a maximum solar intensity of 911.90 W/m^2, a cell temperature of 56.11 °C resulted in an 8.26% energy efficiency at 13 hours of the day. The desired temperature of the refrigerated water was maintained during the off-cycle of the compressor, which increased the off-cycle. When compared to without PCM to eutectic PCM used, the system coefficient of performance (COP) improved by 32% operation. These findings contribute to society by saving energy, reducing compressor work, improving the system refrigerating effect and reducing national grid consumption.

1. INTRODUCTION

Like food, water, and shelter, energy is a basic human requirement for everyone on the planet. Every nation depends on it for both economic expansion and technical improvement, and the amount of energy that is readily available indicates the standard of living in that nation (Hassan *et al.,* 2012). It is critical to do research into new and efficient methods of producing energy resources due to the rise in global energy consumption brought on by increases in the world's population, economy, and per capita income. Between 2003 and 2030, the world's energy consumption is predicted to rise by 71% (Sarbu and Adam, 2011). About 80% of humanity's energy reserves are made up of fossil fuels, which are the world's main source of energy. Global energy consumption is always rising, especially for air conditioning and refrigeration systems; hence, it's critical to develop non-renewable alternatives to fossil fuels. Renewable energy resources, such as wind, biomass, solar, geothermal, ocean, and tidal fuel cell energy sources, are being used to mitigate the effects of our over-reliance on fossil fuels. These energy sources are less expensive, more readily available, cleaner, and renewable (Ullah *et al.*, 2013; Colesca and Ciocoiu, 2013; Abu-Hamdeh and Al-Muhtaseb, 2010).

The sun's radiation, which is created by thermonuclear events taking place inside its core, offers a possible substitute. The world's total energy consumption is estimated to be 1.84×10^{13} W, while the total solar radiation transferred to the earth is estimated to be 1.74×10^{17} W (Srinivas and Jayaraj, 2013). These findings practically showed that the sun has an abundant amount of energy, which we can capture with the help of effective technology (Mazhari, 2011).

Cold storage is a common appliance used to chill food, preserve materials, create a comfortable environment for the body, and store perishable food items and medications. It is typically powered by electricity, which is not readily available in certain regions of the world, or low-grade energy derived from fossil fuel resources. At present, there is a lot of interest in solar energy, with refrigeration being an especially appealing use because solar radiation is available at the same time as peak cooling demand. Refrigeration systems driven by thermal, electrical, or solar energy can generate cooling. If used effectively, the abundant solar radiation available could help solve the power issue with refrigeration systems that rely on high-grade energy sources like electricity (Fernandes, 2014).

Many technologies, such as solar electric, thermo-mechanical, sorption, and some recently developed technologies, are available to provide refrigeration from solar energy. In order to meet the cooling needs of residential and commercial buildings, sorption refrigeration was supported by this cutting-edge thermal solar system (Sarbu and Sebarchievici, 2015).

To provide effective operating conditions, a model low-photovoltaic power refrigeration system employing PV modules—two modules with 36 solar cells each—has been experimentally studied and analyzed. The vapor compression refrigeration system demonstrated its suitability for various African climate zones and may be applied to the preservation of perishable food, the enhancement of healthcare facilities, and the amelioration of living conditions in isolated and rural communities devoid of grid electricity (Yilanci *et al.,* 2011).

Conductive substances are used in photovoltaic (PV) technology, which converts solar radiation directly into DC electricity. A DC motor is connected to the compressor of a vapor compression refrigeration system through the use of solar photovoltaic panels to generate DC electrical power. Choosing the right electrical characteristics for the motor operating the compressor and matching the available current and voltage provided by the PV array are the primary factors to take into account when building a PV refrigeration cycle (Pandey *et al.,* 2013; Steffen, 2013).

Lead batteries eventually corrode while being stored and produce pollutants. As a result, the current study uses phase change material to directly assess how well a local refrigerator that runs on solar energy performs when paired with thermal energy storage. The cycle's coefficient of performance is calculated based on the solar collector's efficiency at various times and temperatures, as well as the refrigeration cycle's efficiency.

2. MATERIALS AND METHODS

2.1. Materials and Experimental Procedure

The photovoltaic refrigeration system employs a PV panel, a vapor compressor, thermal storage, and a phase change material. The panels were set up in parallel so that there is adequate potential difference

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to activate the compressor. The panels faced south and were attached to a rooftop at a 35° tilt angle from horizontal. The controller for solar freezers and refrigerators can handle voltage variations between 10 and 45 volts. For a refrigeration system, the array size was determined using the solar irradiance data in order to meet the system's power requirements. For the compressor to start and run continuously at 2A on a 12V module, around 4.5 A of current is needed. The compressor is powered by the AC electrical power that was converted from solar radiation to DC power via an inverter. This system uses a vapor compression refrigeration loop to draw heat from an insulated enclosure while circulating isobutene (R134a) refrigerant, which is not a greenhouse gas. In order to prevent lead battery deterioration for energy storage, the enclosure contains the thermal reservoir and a phase-change substance in the ice chamber. When the enclosure's heat is removed, this material freezes. By creating an "ice pack" via this procedure, the enclosure's temperature may be maintained even when there is no sunshine. Figure 1 displays the schematic diagram for the solar direct-drive refrigerator.

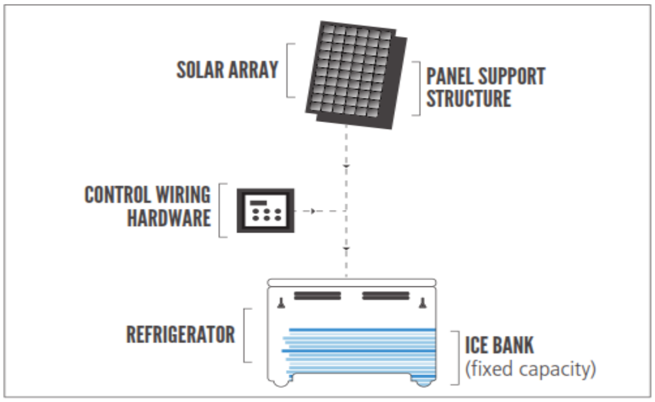

Figure 1: Schematic diagram of Solar direct drive Refrigerator

A solar-driven refrigerator was designed with a temperature range of 0 ^{o}C to +8 ^{o}C that satisfies the current PVP standards for coolers without a battery backup. The cabinets are chest-style with 100 mm of polyurethane insulation. To optimize energy efficiency, a solar refrigerator features a lot of insulation surrounding the storage compartments. With the 18 kg of ice stored in plastic containers removed, the cabinet's net volume is around 55–60 liters. The refrigeration compartment is kept cool throughout the day by forced convection in the evaporator, which is integrated within the ice storage. Natural convection from the ice chamber keeps the cabinet chilly during the night. Four days with no power are spent keeping the refrigeration compartment cool. The energetic and exergetic study of solar photovoltaic (SPV) modules under various climatic circumstances is the basis for evaluating the PV system's efficiency measured from April to June, 2023. Presented in Table 1 are the specifications of the various components of the PV refrigeration system.

Table 1: Specifications of PV refrigeration system components

Parameters	Specification
Storage capacity	50 – 60 liters
Door	Top opening
Type of refrigeration	VCR system
Make	Danfoss
Power consumption	90 W
Refrigerant	R143a
Operating voltage	230V AC
Maximum and minimum internal temperature	0˚C to +8˚C
Insulation	100mm thick
Dimension	37 x 19 x 20cm
Weight	21.2 kg
Number of panels	1
Make	REIL, Jaipur
Max. power output	110 Wt
Size of the array (LxBxT)	1480mm x 540mm x 35mm
Make	Intelligent
Power output	1500WT
Type	Ice
Capacity	18 Litres

2.2. Photovoltaic Efficiency of the Solar Panel

The ratio of electrical power generated to incident radiation is known as the solar panel's efficiency, and it ranges from 10% to 15% when the PV array is operating at maximum power. Equation 1 was used to calculate the photovoltaic efficiency of a solar panel under both no load and full load scenarios (Steffen, 2013; Sudhakar and Tulika, 2013; Martinez and Medina, 2010).

$$\eta_{pv} = \frac{P_{\max}}{SA_{pv}} \tag{1}$$

Where, η_{pv} is efficiency of photovoltaic system, P_{max} is maximum power from photovoltaic system (W), A_{pv} is area of the photovoltaic system (m^2) and S is solar irradiance (W/m^2)

2.3. Photovoltaic Exergy Analysis

Exergy is consumed or destroyed due to the irreversibility present in every real process. The energy output of the photovoltaic system is found by Equation 2 (Steffen, 2013).

$$Ex_o = \left\{ V_m I_m - \left(1 - \frac{T_0}{T_{cell}}\right)\left(h_c A_{pv}\left(T_{cell} - T_0\right)\right) \right\} \tag{2}$$

Where V_m, I_m, h_c, A, T_{cell} and T_o are the maximum voltage, current of the photovoltaic system, convective heat transfer coefficient from the photovoltaic cell to the ambient, area of the photovoltaic surface, cell temperature, and ambient temperature, respectively.

The convective heat transfer coefficient from the photovoltaic cell to the ambient is found by using correlation in Equation 3.

$$h_c = 5.7 + 3.8 \times \upsilon \tag{3}$$

Where, v is wind velocity (m/s)

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The module temperature is used to predict the energy production of the photovoltaic module. This cell temperature (T_c) is a function of ambient temperature (T_a), wind speed and total irradiance. The cell temperature is determined by Equation 4.

$$T_{cell} = 0.943T_a + 0.028\, I_r - 1.528\, \upsilon + 4.3 \tag{4}$$

The exergy input of the photovoltaic system, which is the energy of solar energy, is calculated as contained in 5.

$$Ex_{in} = Ex_{solar} = A_{pv} S \left\{ 1 - \frac{4}{3}\left(\frac{T_0}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4 \right\} \tag{5}$$

Where, T_{SUN} is temperature of the sun taken as 5760 °K

The energy efficiency of the photovoltaic system is the ratio of the total output energy to the total input energy, expressed as shown in Equation 6.

$$\varphi_{pv} = \frac{Ex_o}{Ex_i} \tag{6}$$

2.4. Solar PV System Sizing

The power output from the solar panels and the quantity of ice required to keep the refrigeration chamber at a constant temperature for days without a power source are two crucial factors that determine how well the battery-less PV refrigeration system works. The following formula is used to determine how much power and energy each load that the solar PV system must supply will require: The system is powered by one 110-watt PV module and inverter.

2.5. PV System Performance Evaluation

PVsyst. software is required to import meteor data or parameters from the PV array and present results in graphs and tables as exported for use. Numerous variables are used in the simulation process, and the results file stores the every-month values of these variables. Hourly measurements of solar intensity were made, and at an average solar insulation of 6.5 MJ/m^2, measurements of short circuit current and open circuit voltage were made when the refrigeration system was not in use.

The coefficient of performance for the system, COP was calculated by Equation 7.

$$COP_s = \frac{R_c}{C_w} \tag{7}$$

3. RESULTS AND DISCUSSION

3.1. Performance Evaluation of Photovoltaic System

Based on data from "PVsyst," the solar system's performance was assessed in terms of energy and photovoltaic energy efficiency. Tables 2, 3, and 4 show the hourly fluctuation of conversion efficiency of solar irradiation, voltage, photovoltaic, and exergetic efficiency for each month. Figure 2 shows the power and current against voltage for a single-crystalline photovoltaic module under various operating scenarios. With regard to heat impacts, the Tables 2 to 4 demonstrated that efficiency was comparatively higher in the morning and afternoon than it was at midday. The relationship between the module temperature and conversion efficiency is inverse. The solar system's average photovoltaic efficiency for the month of May, 2023 (Table 3) was 9.93% and that of June, 2023 (Table 4) was 8.5%, respectively. Whereas the system's photovoltaic efficiency for April, 2023 was 8.46%. The solar exergy on a cloudless day and the total irradiance incident on the inclined plane of the photovoltaic modules indicate the exergy efficiency of the photovoltaic system.

Table 2: Solar irradiation, photovoltaic and exergetic efficiency for April, 2023

Time (hr)	Solar irradiation (W/m^2)	Photovoltaic efficiency (%)	Exergy efficiency (%)
9:00	520	10.13	15..24
10:00	687	9.84	12.36
11:00	715	9.77	11.97
12:00	735	10.05	11.84
13:00	789	9.86	11.32
14:00	805	10.22	11.79
15:00	755	11.35	12.06
16:00	492	11.29	15.62
17:00	356	11.64	22.04

With the increased temperature brought on by additional solar radiation, the exercise was at its peak. Slightly lower efficiency is determined by higher PV array temperatures; nonetheless, Srinivas and Jayaraj (2013) found that efficiency is greatest when array temperatures are maintained close to room temperature. An increase in cell temperature to 56.11 °C and a maximum sun intensity of 911.90 W/m2 resulted in an 8.26% energy efficiency at 13 hours. A lower cell temperature (35.9 °C) led to a determination of 19.15% energy efficiency at 17 hours.

Table 3: Solar irradiation, photovoltaic and exergetic efficiency for May, 2023

Time	Solar irradiation	Photovoltaic efficiency	Exergy efficiency
9:00	615	8.97	13.56
10:00	705	9.12	11.73
11:00	803	8.85	10.59
12:00	857	9.09	10.04
13:00	848	9.21	10.11
14:00	769	8.89	10.23
15:00	668	9.36	11.68
16:00	415	10.41	14.87
17:00	395	11.01	19.32

Table 4: Solar irradiation, photovoltaic and exergetic efficiency for June, 2023

Time	Solar irradiation	Photovoltaic efficiency (%)	Exergy efficiency
9:00	613	8.88	495
10:00	712	9.02	412
11:00	819	8.76	376
12:00	906	8.85	354
13:00	894	9.01	349
14:00	860	8.71	376
15:00	680	9.12	405
16:00	510	10.02	515
17:00	405	10.43	700

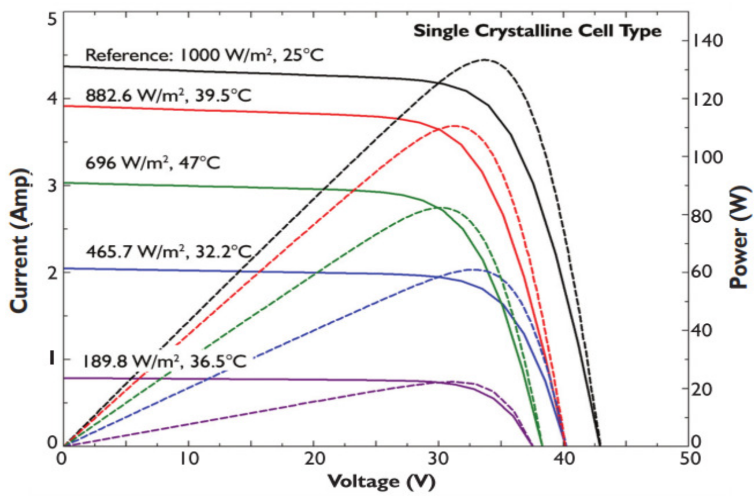

Figure 2: Current (solid lines) and power (dotted lines) against voltage for a single crystalline PV module at different operating conditions

The PV system is unaffected by the average photovoltaic conversion efficiency and energy efficiency, which were found to be closer to 8.5% and 11%, respectively, in both the no-load and full-load scenarios. Exergy was severely destroyed in solar systems because the temperature of the modules was found to be lowering both the photovoltaic and exergy efficiency. The PV array's maximum power ranges between 30 and 35 volts, as indicated by the module depicted in Figure 7. At peak power conditions, the solar array's efficiency generated incident radiation ranging from 8% to 10%.

3.2. System Performance Evaluation

As heat transfer rate in the evaporator increases, there is improving COP of the refrigerator. The desired temperature of the refrigerated product was maintained during the off-cycle of the compressor, which increased the off-cycle. When compared to without PCM to Na_2SO_4 .$10H_2O$ as eutectic PCM used, the compressor work decreased by 30 kJ. The system COP improved by 32% when compared Na_2SO_4 .$10H_2O$ eutectic PCM without PCM operation. The results of the COP contribute to society by saving energy, reducing compressor work and improving the system refrigerating effect.

4. CONCLUSION

The study demonstrates that photovoltaic (PV) refrigeration is both practical and cost-effective. The viability and cost-effectiveness of solar refrigeration systems will be greatly enhanced by future advancements in solar panel efficiency. By switching out the PV refrigeration system's chemical storage for thermal storage—which is less expensive, better for the environment, and more effective—the system's cost is decreased. The PV refrigeration system provides a solution to all of these issues, including the world's growing reliance on fossil fuel supplies, the difficulty of ignoring global warming, and the unavailability of electricity in isolated places.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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