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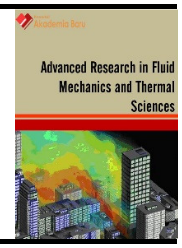

Performance evaluation of a small-scale solar driven refrigeration system

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ABSTRACT

The conventional refrigeration systems use fossil fuels for their energy inputs. Due to the growing environmental degradation and fossil fuel depletion issues, energy supply from alternative sources is gaining huge attention. Solar driven refrigeration system, which uses solar energy as its energy input, not only addresses these challenges and but also enhances sustainable development. In this work, we have developed a small-scale solar driven refrigeration system by combining several components such as a solar panel, a charge controller, a compressor, an inverter, an evaporator-tank, a condenser and a few connection wiring. We have operated the system for several days to check its functionality and performance. During operation, we have measured solar panel's current and voltage with a 5-minute interval to calculate power that has been supplied as an input to the compressor. The evaporator coils pass through the water tank to cool down water to a desired temperature (i.e. 4 ºC). The temperature of the evaporator and condenser was also recorded for calculating the cooling effect created by the refrigerant R-134a. We have calculated coefficient of performance (COP) of the system for both actual cooling load of water and cooling effect created by the refrigerant. The refrigeration system successfully operates with an actual COP of 0.95. Despite the COP is low, the solar driven refrigeration system, which does not require any fuel, is a promising option in regard to both environment and economic aspects.

1. Introduction

Refrigeration system is used in moving heat from one location to other location in a controlled condition. It also can be termed as a cooling process, which is used in removing unwanted heat from certain object, substance, or space and transfers it to other object, substance, or space [1]. Refrigeration is used to maintain optimum transit environment of the product and to prolong their shelf life [2]. Removal of heat can be accomplished by several ways such as using of ice, snow and chilled-water, phase changing substances, power-driven cooling etc. [3]. The conventional refrigeration processes generally use fossil fuel sources for their power inputs. Due to the growing

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concern of environmental degradation and fossil fuel depletion issues, power supply from alternative energy sources are gaining enormous attentions [4–7]. Renewable source, particularly solar, has appeared as a potential candidate to supplement conventional fossil sources and counteract the above challenges [8]. A major advantage of solar energy over other renewable sources is that solar energy is abundant in most of the countries [9,10]. Price of fossil fuel sources also fluctuates over time, whereas solar energy does not incur any fuel cost thus has no point of fluctuation [11]. Using of solar energy will reduce the amount of fossil fuel related emissions and will enhance the persuasion of green technologies. Advantageous climate condition makes solar energy as the best renewable energy source in Malaysia as the weather is almost sunny throughout the year [12]. Refrigeration system, powered by solar electricity, can benefit the country in many aspects.

There are several types of refrigeration systems popularly used for cooling purposes. One of the most common refrigeration systems is vapor-compression refrigeration system, which has been in use to preserve food, provide air-conditioning, and in a variety of industrial processes [10]. The vapor-compression system uses compressor, which requires electric power to run it. Solar photovoltaic (PV) panel can produce electricity from solar source and serves electric power to run the compressor. Torres *et al*. [13] performed a simulation study on photovoltaic cooling system in a Cuban hotel and observed that the system runs smoothly with a COP range of 0.4–0.6. Kalbande and Deshmukh [8] performed an experimental study to examine the performance of a solar photovoltaic based vapour compression refrigeration system. The authors successfully accomplished a cooling temperature between 2–8 ºC for the purpose of vaccination preservation. Alshqirate *et al*. [9] also performed an experimental study on a 160 Watts domestic refrigerator by supplying power from a photovoltaic generator in Jordan. They found that the refrigerator works smoothly and continually by using a PV generator module of 140 W peak. Despite a few studies have attempted experimental investigation on solar refrigeration systems, neither of them has explicitly developed a solar driven refrigeration system and examined the performance. In this work, we design and build a small-scale solar driven vapour compression refrigeration system and perform evaluation of its technical performance in Malaysian conditions. As a refrigerant (working medium), we have used Refrigeration-134a, which is environmental friendly and does not have ODP (ozone layer depletion potential) [4]. We use water in a tank as a cooling load through which evaporator coil passes. We determine coefficient of performance (COP) of the refrigerator system and measure power input by the PV, cooling effect delivered to the water and cooling effect created by the refrigerant.

2. Overview of Solar Driven Refrigerant System

Refrigeration systems can be different types depending on working principle, temperature range, energy input, refrigerant types etc. [1]. The major refrigeration systems are vapour compression system, vapour absorption system, gas refrigeration system, thermo-electric refrigeration system, thermo-acoustic refrigeration system etc. In this work, we perform experimental study on a solar PV driven vapour compression refrigeration system. The following sections briefly describe solar PV driven vapour compression refrigeration system.

2.1 Vapor-compression Refrigeration System

Vapor-compression cooling system is the most commonly used system for refrigeration and air-conditioning applications. This system consists of four major components, which are compressor, condenser, expansion device, and evaporator. A low pressure, low temperature liquid is converted to vapor in the evaporator, thus absorbing heat from the refrigerated space or substance and lower the temperature of the space or substance [4]. The fluid is driven around the cycle by the compressor, which compresses the low temperature, low pressure vapor leaving the evaporator to high pressure, high temperature vapor. That vapor is condensed to liquid in the condenser, thus giving off heat to the surrounding environment [14]. Finally, the high pressure, high temperature liquid leaving the condenser is cooled and reduced in pressure by passing it through an expansion device [15].

2.2 Solar Driven Refrigeration

Solar driven refrigeration system uses the sun's energy either directly as thermal energy (heat) or through the use of photovoltaic panels or transparent photovoltaic glass. Standard photovoltaic solar panels are the most efficient application for electricity generation. However, photovoltaic glass allows generation from surfaces like building windows that were freely available [16]. Concentrated solar power uses multiple lenses or reflectors to collect more of the sun's thermal energy. The solar panel directly converts solar radiation into direct current (DC) electricity. The generated DC electricity flows out of the solar panel and passes through an inverter. The inverter converts that DC power into alternating (AC) power and drive the compressor motor. There are some other components that are usually used when we build up a solar driven system such as charge controller and backup battery [10]. One kWh of solar electricity offsets about 0.75 to 1 kg of CO_2 comparing to 1 kWh of electricity from coal.

3. Methodology

3.1 Experimental Setup

Solar refrigeration system was developed by combining several components, which are a solar panel, a compressor, an inverter, an evaporator tank, a charge controller and a battery bank. The components are connected to each other by a DC wiring systems and made a complete circuitry of the system (Figure 1). The solar panel is placed on an adjustable fixture to ensure the proper alignment of the panel to make sure it will collect the highest amount of sunlight and continuously provide electricity for the system (Figure 2). The battery acts as a backup for the solar panel to make up power when the PV power goes below the threshold limit of the compressor to run due to cloud or shading. A charge controller was connected between PV panel, and inverter and battery to protect the devices from over charging. In our experiment, we take the measurements in a way that the initial and final storage in the battery were kept same. It means that the refrigeration system received net zero power from the battery throughout the experiment. Thus, the using of battery does not affect the net power output from the solar panel and net power input to the compressor for the achieved cooling load.

Charge controller is use to limit the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and may protect against overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk. From this charge controller we can take measurement of voltage and current supply by using multi-meter and clamp-on meter. Inverter is used to change direct current (DC) to alternating current (AC) as the compressor operates on alternating current. The detail specification of solar panel is provided in Table 1.

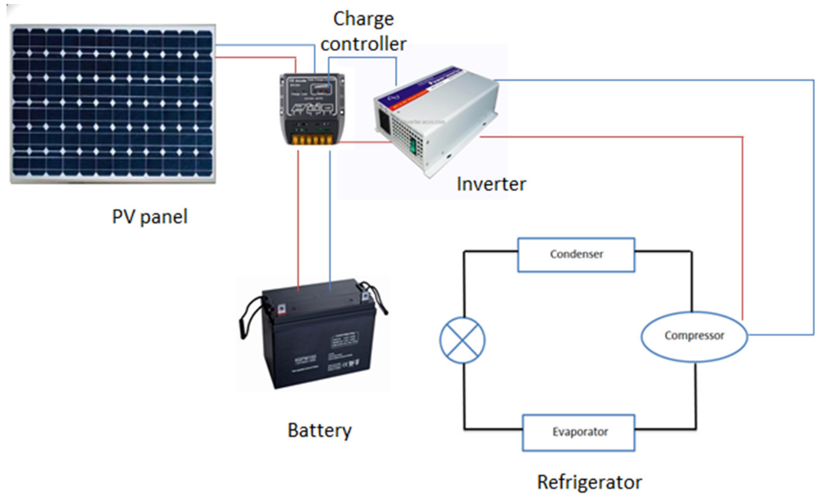

Fig. 1. System layout of Solar driven refrigeration system

Table 1
Solar panel specifications

Items	Descriptions
Part Number	TSN-250PC05
Maximum power	250W
Maximum power voltage	30.3V
Maximum power current	8.27A
Type of voltage supply	DC Voltage
Panel size	1.219m x 0.914m

(a)

(b)

Fig. 2. (a) Solar refrigeration system set-up, (b) Evaporator tank

3.2 Evaluation of Performance

Several measurements and calculations were performed to evaluate the performance of the system. We had determined the energy output by the PV system, PV efficiency, cooling load of the system and coefficient of performance (COP). In our experiment, we had not applied data logging application. In this case, the PV outputs such a voltage and current must be measured over a finite period of time. In a standard experiment, this time period should be in the order of 5 to 10 minutes.

3.2.1 PV energy

The total energy generated by the PV panel can be calculated by Eq. (1).
Energy output by PV system EPV (Wh)

$$E_{PV} = \frac{\int_{t=0}^{T} VIdt}{3600} \tag{1}$$

where, *dt* (s) is the time period, over which the performance can be averaged. V (V) is the instantaneous voltage at time *t*, *I* (A) is the instantaneous current at time t. The experiment stated at t=0 and ended at t=T (s).

The power input to the compressor, $W_{net,in}$ (W) can be determined by Eq. (2) as below.

$$\dot{W}_{net,in} = \frac{E_{PV}}{\Delta t} \tag{2}$$

where, Δt (h) is the total time period over which the experiment is done and E_{PV} (Wh) is the total energy generated by the PV panel.

The PV electricity can also be determined by Eq. (3)

$$E = A \cdot r \cdot H \cdot PR \tag{3}$$

where, *E* (Wh) is the energy generated by the PV panel, *A* is the effective solar panel area (m^2), *r* (%) is the solar panel efficiency, *H* (Wh/m2/day) is the annual averaged daily solar irradiation on tilted panels (shadings not included), PR is the performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75).

3.2.2 Cooling load

Cooling load is an amount of heat energy that would need to be removed from water (cooling substance) to cool water to the desired temperature. The cooling load delivered to water Qw (Wh) can be determined by the Eq. (4) below.

$$Q_w = \frac{m_w c_p (T_{initial} - T_{final})}{3600} \tag{4}$$

where, Q_w (Wh) is the cooling load delivered to water, mw (kg) is the mass of water in the container, C_p (J/kg.K) is the specific heat of water, ($T_{initial}$ -T_{final}) is the initial and final temperature difference of water.

The cooling effect created by the refrigerant can also be determined by the equation below.

$$\dot{Q}_L = \dot{m}_L (h_1 - h_2) \times 1000 \quad (5)$$

where, $\dot{Q}_L$ (W) is the cooling load of refrigerant, $\dot{m}_L$ (kg/s) is the mass flow rate of refrigerant, and (h_1-h_2) is the enthalpy difference in the evaporator (kJ/kg).

3.2.3 Coefficient of performance (COP)

COP is defined as the ratio of the desired output to the required input. There are equations below that can be used to calculate the COP.

$$COP = \frac{\dot{Q}_w}{\dot{W}_{net,in}} \quad (6)$$

$$COP = \frac{\dot{Q}_L}{\dot{W}_{net,in}} \quad (7)$$

4. Results and Discussions

This section presented the findings on the technical performance of the solar PV refrigeration system. The power generated by PV is very important to determine the cooling load of the water and the coefficient of performance (COP) of the system. In this work, the experiment has been conducted in several days to make sure that the power supply from solar panel to the compressor is consistent. The data were collected during the sunny days. The data were collected for a 5 minute step. Data that has been collected are current, voltage, radiation, temperature, and time.

4.1 Current, Voltage and Power

The Figure 3 shows current output from the PV system from 10:00 am until 5:00 p.m. The lowest current was found as 1.4 A and highest current was found as 4.2 A.

The Figure 4 shows output voltage of the system from 10:00 am until 5:00 pm. The voltage produced by the solar panel ranges between 23 V to 27 V. The maximum voltage of the solar panel according to the specification is 30.3, which is in the good agreement with the experimental results.

The average power input to the compressor was determined by the Eq. (1). The power produce by the system for every 5 minutes is shown Figure 5.

The average power $\dot{W}_{net,in}$ was found as 79.99 W for the whole period of time from Eq. (2).

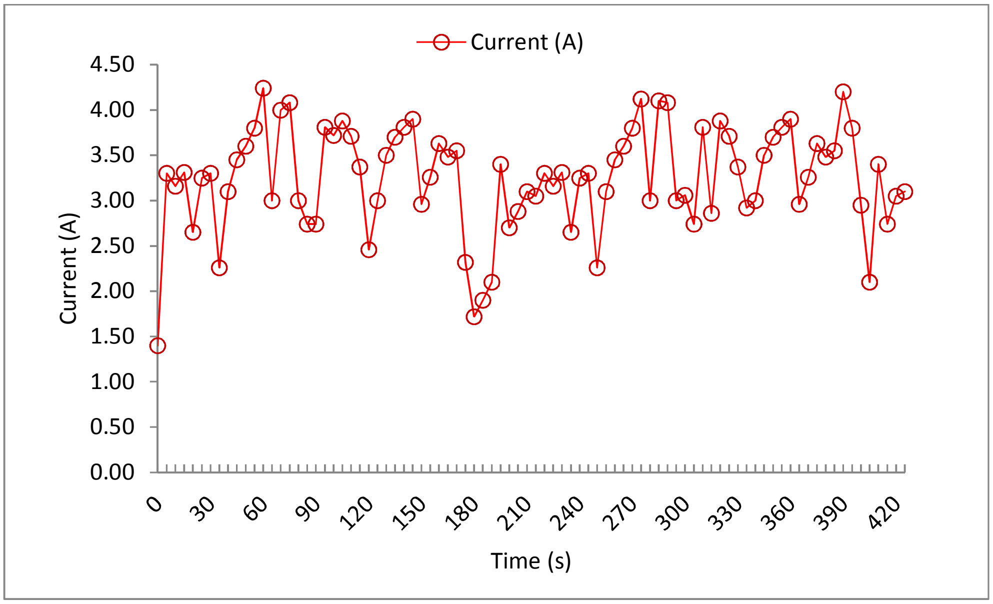

Fig. 3. Current (A) versus time(s)

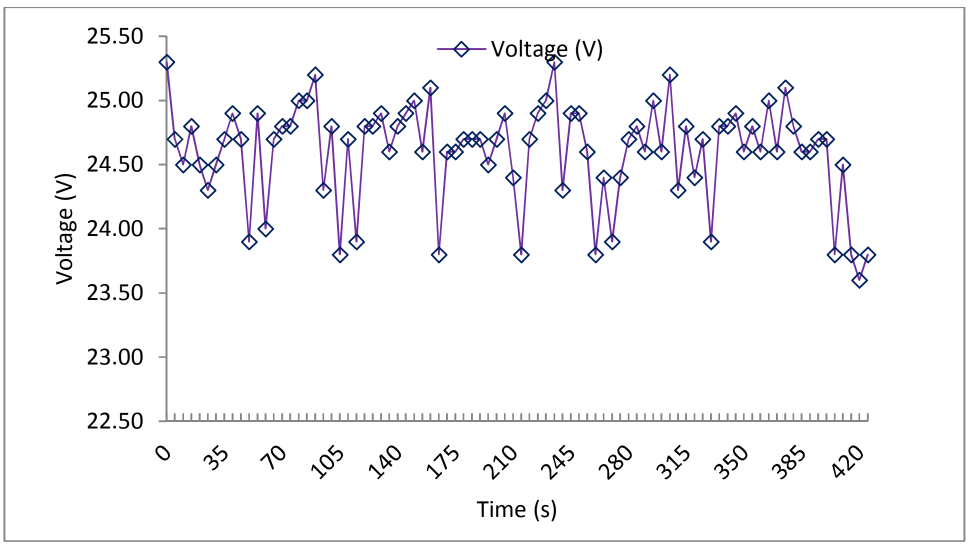

Fig. 4. Voltage (V) versus time (s)

4.2 Cooling Load Delivered to Water

The cooling load delivered to water was calculated by using Eq. (4) with initial and final temperature differences of water. Cooling load is an amount of heat energy that was removed from water to achieve desired water temperature. In this case, the cooling load of water is the amount of energy removed by the water until it reaches 4 degree Celsius temperature. To achieve the water temperature the system takes 1 hour and 55 minutes. This average cooling load delivered to water was calculated from the following parameters (Table 2).

Table 2
Parameters used to determine the cooling load of water

Parameters	Values
Diameter of tank	0.136 m
Height of tank	0.09 m
Density of water	1000 kg/m^3
Specific heat of water (C_p)	4218 J/kg.K
$T_{initial}$	301 K
T_{final}	277 K
Rate of heat removed from water ($\dot{Q}_w$)	76.15 W

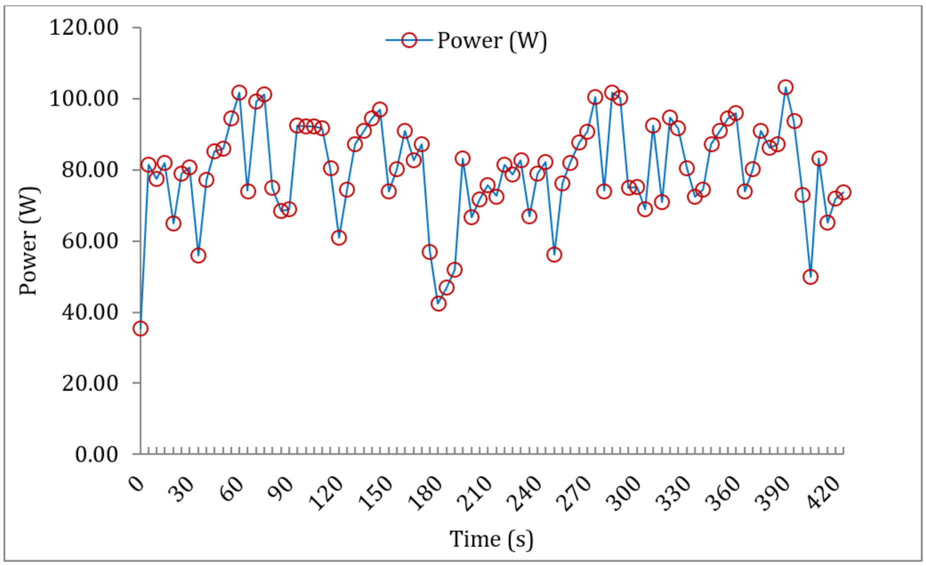

Fig. 5 Power (W) versus time (s)

4.3 Cooling Effect Created by the Refrigerant

We have measured the condenser temperature as 309 K and evaporator temperature as 273 K. For making the measurement, we have considered that the refrigeration cycle works on an ideal cycle with refrigerant is in saturated vapour condition at the exit of the evaporator and saturated liquid condition at the exit of the condenser (Figure 6). We have determined the enthalpy values from R134 a property Table A11 as follows:

h_1 = hg (at temperature 277 K)
h_1 = 250.45 kJ/kg
$h_4 = h_3 = h_f$ (at temperature 309 K)
h_4 = 102.33 kJ/kg
$\dot{Q}_L = 148.22$ W

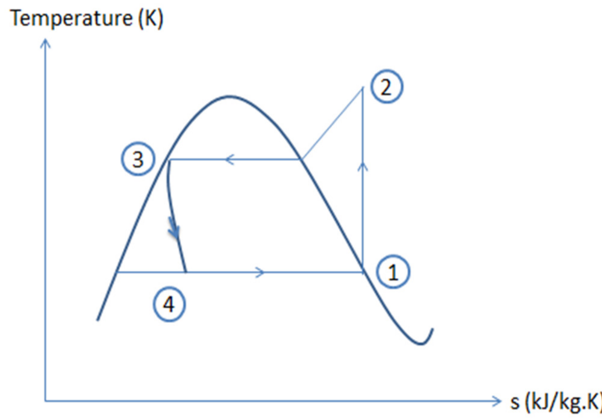

Fig. 6. T-s diagram on ideal refrigeration cycle

We have measured the water temperature for a period of 2 hours with a 5-minue interval to calculate actual cooling load delivered to water (Figure 7).

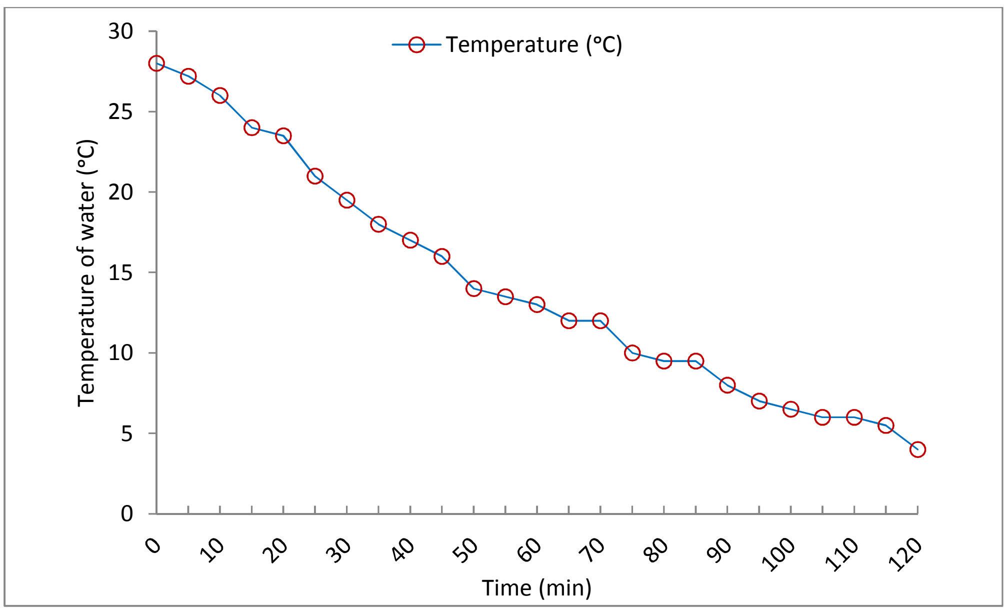

Fig. 7. Water temperature during the experiments for a period of 2 hours

4.4 Coefficient of Performance (COP)

$$COP = \frac{\dot{Q}_w}{\dot{W}_{net,in}}$$

Coefficient of performance (COP) from cooling load delivered to water, COP = 0.95

$$COP = \frac{\dot{Q}_L}{\dot{W}_{net,in}}$$

Coefficient of performance (COP) from refrigerating effect created by refrigerant, COP_R = 1.85. These two COPs show the performance of the solar refrigeration system. The COP is promising since the energy input is free of cost and environmental friendly. The difference between the two COPs is due the heat transfer losses from evaporator pipes to the water tank and temperature lift between evaporator coils and water.

5. Conclusions

The solar panel successfully provided enough power to sustain the power input needed by the compressor during the experiment. The system works well in sunny days and achieved the desired cooling temperature of 4 ℃. Power output by the solar panel and coefficient of performance (COP) of the system has been calculated. We have observed a COP of 0.95 for the actual cooling load and a COP of 1.85 for the cooling effect created by the refrigerant. Although the COPs are low, because it does not require any fuel, the solar driven refrigeration system is a promising option in respect to both environment and economic aspects.

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