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Design and Analysis of Solar Powered Vapour Compression Refrigeration System

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Abstract

Solar refrigeration system has the potential to improve the quality of life of people who live in area of insufficient electricity. This paper is about the study and analysis of solar powered vapour compression refrigeration system to keep vaccine placed at rural area in the temperature range between 2 to 8 °C without grid. The cooling load to be met by the photovoltaic generator depends on ambient air temperature, the special condition of refrigerator to preserve vaccine at this temperature range and size of the cooling space and matching condition between the photovoltaic module and compressor's power. This paper presents the calculation of the heat gain through the refrigerator wall and heat absorbed by the vaccine bottle based on ambient air temperature of the hottest months (March, April, and May). And then, the performance analysis of refrigeration system is represented by using experimental result data. The photovoltaic generator and vapour compression refrigerator are matched by DC inverter. The relationship of outside temperature of surrounding and power of photovoltaic module are deal by MATLAB software.

Keywords: Solar energy, photovoltaic module, vapour compression, refrigeration system, vaccine

1. Introduction

Energy is a vital input for sustainable development and economic growth of any country. Electrical energy is considered as the most convenient form of energy sources in rural and urban areas. Photovoltaic (PV) systems sometimes called solar cells have found widespread application because they are simple, compact and have high power to weight ratio. The solar photovoltaic system has no moving parts and probably yields the highest overall conversion of the solar energy into electricity. There are several cases, where small or medium size PV powered refrigerators are required. Those have to be optimized in size; both the PV generator and its components, as well as the refrigerator volume, in order to meet efficiently the start-up power and the cooling load, in general. The cooling load to be met by the PV generator depends essentially on: (1) the ambient temperature, (2) the refrigerator's room temperature, determined by the special conditions of the refrigerator has to be operate, i.e., food preservation 10-20 °C, preservation of vaccines 2-8°C, etc, (c) the size of the cooling space, and (d) the matching conditions between the PV generator and the power consuming compressor.

2. Solar Powered Vapour Compression Refrigeration System

So far most of the work on solar cooling has been on absorption machines, possible because only large systems have been built and also because of their reduced maintenance compared with mechanical compression systems. PV cells open the field for small mechanical systems using reciprocating type compressors that are widely developed. The system configuration of a solar powered refrigerator is shown in Fig. 1.

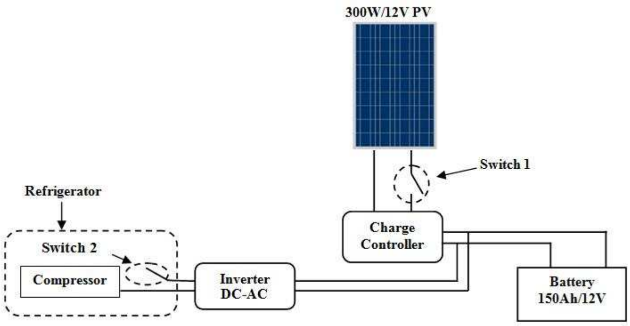

Fig. 1 System Configuration of Solar Refrigerator

2.1. Photovoltaic Conversion

Solar energy can be converted directly into electricity in photovoltaic (PV) panels. Such panels are direct current generators whose output is proportional to solar irradiance. A PV panel is characterized by its peak power (Wp) which is the electric power delivered at 25° C under an irradiance of 1000 W per square meter in clear sky conditions. For small power applications electrochemical storage plays the role of an imperfect impedance adapter by keeping the voltage at a constant value.

Due to the daily variation of solar irradiance and to this non-perfect impedance adaptation, the mean daily power delivered by a PV panel is much lower than its peak power.

Reliability of PV generators has been demonstrated and a life time of at least 15 years can be guaranteed. For small daily energy consumption (10 to 50 kWh) or in locations far from the power grid PV generators are cost effective compared to diesel engine generators; they are more reliable and require no maintenance.

2.2. Vapour Compression Refrigeration System

As mentioned, vapour compression refrigeration systems are the most commonly used among all refrigeration systems. As the name implies, these systems belong to the general class of vapour cycles, wherein the working fluid (refrigerant) undergoes phase change at least during one process. In a vapour compression refrigeration system, refrigeration is obtained as the refrigerant evaporates at low temperatures. The input to the system is in the form of mechanical energy required to run the compressor. Hence these systems are also called as mechanical refrigeration systems. Vapour compression refrigeration systems are available to suit almost all applications with the refrigeration capacities ranging from few Watts to few megawatts. A wide variety of refrigerants can be used in these systems to suit different applications, capacities etc.

3. Design Calculations

A cooling cabinet is a refrigerated space where evaporation of water vapour and refrigeration effect takes place. A well-insulated rectangular type cabinet was chosen to save the cooling coil length and simplify the design. The cabinet is designed for storing 200 bottles of 20 μg vaccine.

3.1. Solar Radiation

Solar radiation is an important variable to consider when estimating the potential photovoltaic electrical output along with temperature, wind, and precipitation. The possible assumptions shown in Table 1 are taken for design calculations.

Table 1. Design Considerations

No.	Items	Conditions
1	Location	Hlaing Thar Yar (Yangon)
2	Latitude, φ	16° 52′ N
3	Longitude, LL	96° 4′ E
4	Longitude of standard time meridian, LSTM	97° 30′ E
5	Elevation, H	6.91 m
6	Solar incident angle, β	60°
7	Tilt angle, θ	10°
8	Solar constant, I_o	1373 W/m^2

There are many solar radiation prediction models have been developed around the world, which are used only commonly measured climate data. Annually result data of beam, diffuse, hemispherical and total solar radiation are calculated and shown in Table 2.

Table 2. Annually Result Data of Solar Radiation at Noon

Month	**Date**	**H_b (W/m^2)**	**H_d (W/m^2)**	**H_h (W/m^2)**	**H_T (W/m^2)**
Jan	17	751.93	107.81	605.58	851.64
Feb	16	775.52	110.51	671.98	880.22
Mar	16	799.85	113.45	759.73	910.77
Apr	15	810.43	114.78	824.72	925.44
May	15	804.72	113.96	834.99	919.72
Jun	11	795.28	112.63	818.84	908.61
Jul	17	791.35	112.08	806.88	903.74
Aug	16	797.89	113.01	812.76	911.17
Sep	15	804.74	113.99	807.68	918.39
Oct	15	798.88	113.31	758.80	909.66
Nov	14	776.79	110.67	675.39	881.77
Dec	10	755.99	108.28	615.54	856.49

3.2. Determination of Solar Arrays

The daily energy output from the PV array, P_{module} can be determined by the daily solar radiation in the plane of the PV array, H_T (W/m^2) as below:

$$P_{module} = H_T A_{pr} \eta_p \qquad (1)$$

Where, A_{pr} = area of the PV module, m^2
η_p = overall efficiency of the PV panel

Table 3 shows the annually result data of PV array output power.

Table 3. Annually Result Data OF Array Output Power

Month	**P_{module} (W/m^2)**
January	203.22
February	211.79
March	219.09
April	220.83
May	221.25
June	218.58
July	219.15
August	220.96
September	222.71
October	218.83
November	210.41
December	204.38

The next step is to determine the hourly solar radiations and hourly module output power for the three hottest months (March, April, May), July, August and the two coldest months (November, December) in Myanmar. These values are shown in Table 4.

Table 4. Result of Hourly Module Output Power, P_{module} (w) for March, April, May, November and December

Month	10:00	11:00	12:00	13:00	14:00	15:00
Mar	221.5	229.9	232.2	228.8	219.2	201.2
Apr	218.7	229.1	232.5	232.0	220.4	201.8
May	211.6	220.2	221.9	218.5	209.5	192.8
July	217.4	225.4	228.1	225.5	217.4	201.9
Aug	218.4	228.8	231.5	231.6	220.1	201.4
Nov	214.6	223.4	224.5	218.4	203.5	174.8
Dec	196.6	207.6	209.9	204.4	189.3	159.9

3.3. Determination of Heat Rate and Compressor Power

The daily heat rate of the evaporator, Q_{evap}, can be determined by the refrigeration load. Then the compressor power, W_{comp} and the compressor motor power are calculated for the three hottest months (March, April, May), July, August and for the two coldest months (November and December) in Myanmar. Next, the previous values are also determined for the maximum temperature of 44°C due to the heat wave of uncharacteristically strong El Nino effect. The results of the hottest day in each month and outside temperature 44°C due to heat wave are shown in Table 5.

Table 5. Results of Q_{evap}, W_{comp}, and Motor Power for March, April, May, July, August, November, December and Heat Wave

Month	Max; T_a(°C)	Q_{evap} (W)	W_{comp} (W)	Motor Power (W)
March	38	353.28	71.41	79.34
April	40	374.89	75.78	84.19
May	39	364.09	73.59	81.77
July	32	288.44	58.30	64.78
August	33	299.25	60.49	67.21
November	35	320.86	64.86	72.06
December	34	310.06	62.67	69.63
Heat Wave	44	419.13	84.72	94.13

3.4. PV Module Sizing

From the calculation results of refrigeration system, the maximum compressor motor power of 94.13 W is required even if the heat wave occur due to climate change. For the operation to this type of refrigerator with 6 hours/day and assuming motor power is 100 W, the daily energy requirement of the motor is obtained 600 Whr/day. Then the required energy output for PV panel is calculated by taking the system efficiencies, such that 95% for battery, 98% for controller, 97.5% for inverter and 95% for cable. Taking peak sun hours as 6 hr/day, the size (rating) of PV panel is 115.963 Wp.

For the high reliability of the system 300 W Mono-crystalline PV module is selected for solar powered vapour compression refrigerator. Then the required battery, controller and inverter sizes are also determined.

A. Battery Sizing: Taking the daily energy requirement as 600 Whr, battery nominal voltage as 12 V, the energy storage requirement for 2 days of 'No Sun' condition as 1200 Whr and the maximum discharge capacity as 70% of the rating, the ampere-hour rating of the battery is obtained as 150 Ah. Thus, one unit of 150 Ah battery is needed for the refrigeration system.

B. Controller Sizing: The controller rating is can be determined by the maximum output current of PV module and obtained as 17.7 A. According to the market availability, H_F - 110 D controller is selected for the cooling system.

C. Inverter Sizing: Inverter rating can be determined by the following equation and is obtained as 127 VA.

$$\text{Inverter rating} = (\text{Load} + (1 + A_f)) / \eta_{inv} \qquad (2)$$

Table 5 shows the parameters for components used in the solar powered vapour compression refrigeration system.

Table 5. Parameters for Components Used in Refrigeration System

No.	Component	Quantity
1	OPAI 300 W Monocrystalline Model Max; power, Wp = 300 W Max; voltage = 22.3 V Max; current = 17.7 A	1
2	Battery Nominal voltage = 12 V Storage capacity = 150 Ah	1
3	Controller Input voltage = 12 V Input current = 10 A	1
4	Inverter Power = 127 VA	1

4. Results and Discussion

4.1. Energy Consumption

The energy is necessary for compression of the refrigerant vapour by increasing its pressure and temperature. The mechanical energy necessary to drive the compressor is finally converted into heat. This heat must be removed by the condenser to condense the refrigerant vapour. The energy consumption of a refrigeration system is determined by the refrigeration capacity and the difference between the condensation and evaporation temperatures.

The amounts of heat absorbed by the evaporator, Q_{evap}, for the three hottest months, the two coldest months and the other two months with their respective monthly maximum temperatures are shown in Fig. 2. It can be seen that the energy used by the evaporator, Q_{evap} values depend upon the ambient temperature, T_a.

The energy consumption by the cooling system (evaporator) is varied from 234.41 W (27°C at December) to 374.89 W (40°C at April). For the heat wave due to El Nino effect, the energy consumption by the evaporator is 419.125 W with ambient temperature of 44°C.

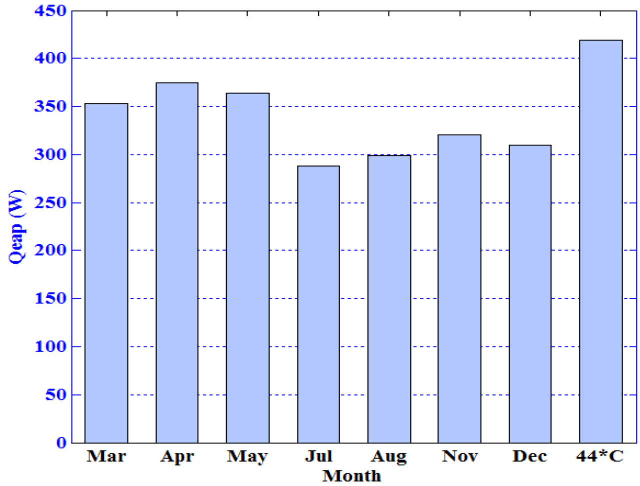

Fig. 2 The values of Q_{evap} for March, April, May, July, August, November, December and Ta=44°C for heat wave with their atmospheric temperature

The compressor power and motor power consumptions for three hottest months, two coldest months and T_a = 44°C for heat wave are shown in Fig. 3. All power consumption values are lower than 100 W. For the high reliability of the system 300 W PV panel can be used for the refrigeration system.

Thus, the compressor power, W_{comp}, is satisfied within the system even in very hot condition due to climate change. If the compressor power is greater than the expected values, the energy can store with an extra battery connected in series with the previous one and can be charged the inverter.

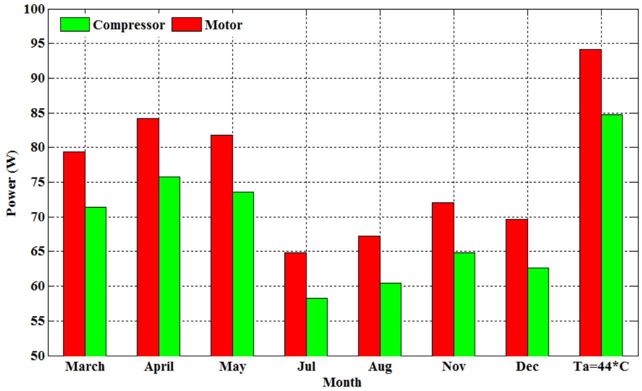

Fig. 3 Motor and compressor power for March, April, May, July, August, November, December and Ta=44°C for heat wave

4.2. Output from the PV array

Fig. 4 shows the hourly energy output from the PV array, P_{module} of March, April, May, July, August, November and December. The values of P_{module} varies from 195.9 W to 232.5 W. P_{module} values of lower Day of Year (n) for hottest three months is not much different from that of higher Day of Year (n) for coldest two months. P_{module} values also satisfy with the selected PV panel.

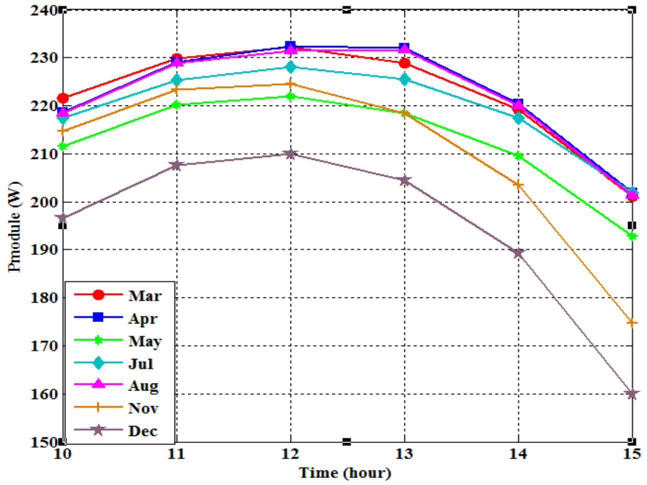

Fig. 4 Hourly P_{module} values for March, April, May, July, August, November and December

5. Conclusions

Solar panel can serve as an alternative source of energy for powering refrigeration system. The performance of solar refrigerator is sufficient for vaccine storage even in a very hot climate with ambient temperature 44°C. Finally, the solar refrigeration system can be used for remote off-grid area and this system is environmental friendly.

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