

Experimental Performance Evaluation of a PV-Powered Refrigeration System

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crossref <http://dx.doi.org/10.5755/j01.eee.114.8.684>

Introduction

As the technology evolves and the price of fossil fuel resources grows rapidly, the increasing focus on renewable energy resources is observed [1]. Recently, energy conservation and reduction of global warming effect become one of the most important subjects in the worldwide. Since the proportion of the refrigeration systems' energy consumption in overall energy consumption is steadily increasing, these systems are under research. Many vehicles used in transportation of goods or recreation such as trucks, caravans, boats, cars, etc. are often equipped with small cooling appliances. Compressor of these kind of applications might be designed to operate low voltage direct current, such as, 12-24 volts. The electrical energy produced by renewable energy systems like photovoltaic panels is in the form of the DC electrical energy [2]. Also, because there are innumerable places in the developing countries where the power supply is still intermittent and irregular, for the storage of vaccines and life saving drugs in such areas, refrigeration systems based on usage of solar energy can be considered to be the optimal solutions. The electricity supplied is mainly from conventional fuel based power plants which are the greatest contributors to global warming [3]. Environment friendly solutions are mandatory for the sustainable world. Therefore, solar PV power system applications are increasing. The photovoltaic power systems are becoming important in the power production market with each succeeding year what can be determined by the skyrocketing development of cumulative installed power of the PV installations in the EU countries and worldwide [4]. Considering the fact that the cooling demand increases with the intensity of solar radiation, solar refrigeration has been considered a logical solution. PV refrigeration systems with batteries have existed for several decades but have only been used in limited applications. A PV powered refrigerator or freezer has a cooling capacity lower than

typical alternative current (AC) unit because of its smaller compressor. Using the energy efficiently in solar or other renewable energy powered systems is more crucial than others since the limited sources and high costs for the storage capacity. The second law of thermodynamics (or exergy analysis) deals with the quality of energy. More specifically, it is concerned with the degradation of energy during a process, the entropy generation/irreversibility, and the lost opportunities to do work; and it offers plenty of space for improvement. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems [5]. In this study, exergy analyses of a household refrigerator, powered by a photovoltaic has been investigated to obtain efficient operation conditions based on experimental data.

Experimental setup

The experimental setup has a household refrigerator with DC operated hermetic compressor and capillary tube as an expansion device. Internal volume of the refrigerator is 50 liters and its cooling capacity is 76 W. The compressor of the refrigerator consumes 50 W in average. Ozone friendly R134a is used as a refrigerant. Several temperatures were monitored at several locations to conduct exergy analysis of the refrigerator. These locations are compressor suction and discharge, condenser inlet and outlet, evaporator inlet and outlet. Also, temperatures on the aluminum evaporator surface, center of inner volume of the refrigerator, wall temperature of the refrigerator at outside, compressor surface temperature, PV surface temperature and environment temperature values are obtained experimentally. All temperatures are measured by insulated copper-constantan (type T) thermocouples in association with a 20 channels multiplexer and HP data logger. Furthermore suction and discharge pressure, voltage and current are measured. Fig. 1 shows experimental setup and its schematic.

A lead acid battery with the capacity of 80 Ah is used for no sun period. It has capacity to run the refrigerator for 15 hours without sun. The charge regulator maintains the power supply within the current and voltage range tolerated by the refrigerator and prevents overcharge of the battery. In this study, an 80 Wp is used. The experimental conditions are: cool-down of the refrigerator from the ambient condition with no storage items and low, nominal, overloaded conditions. Refrigerator inside temperature was set to 1 °C and 15 °C.

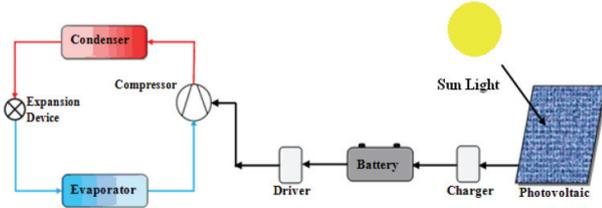


Fig. 1. Experimental set-up of the PV powered refrigerator [6]

Exergy analysis

In an ideal refrigeration cycle, exergy balance of an adiabatic compressor is given as below

$$(\dot{E}x_{in} - \dot{E}x_{out})_{comp} - \dot{W}_{comp} - \sum \dot{\Gamma}_{comp} = 0, \quad (1)$$

where \dot{W}_{comp} is the supplied actual power to the compressor.

For a condenser, exergy balance is formulated as

$$(\dot{E}x_{in} - \dot{E}x_{out})_{cond} - \dot{Q}_{cond} \left(1 - \frac{T_o}{T_{cond}}\right) - \sum \dot{\Gamma}_{cond} = 0. \quad (2)$$

Similarly, exergy balance of an expansion device is defined as

$$(\dot{E}x_{in} - \dot{E}x_{out})_{exp} - \sum \dot{\Gamma}_{exp} = 0. \quad (3)$$

Exergy balance of an evaporator can be written as

$$(\dot{E}x_{in} - \dot{E}x_{out})_{evap} + \dot{Q}_{evap} \left(1 - \frac{T_o}{T_{evap}}\right) - \sum \dot{\Gamma}_{evap} = 0. \quad (4)$$

The performance of a refrigerator is expressed in terms of the energetic coefficient of performance (COP_R), defined as

$$COP_R = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}}, \quad (5)$$

where \dot{Q}_{evap} is the refrigeration capacity. The exergetic coefficient of performance of a refrigeration system is as below

$$COP_{R,ex} = \frac{\dot{Q}_{evap} \left(1 - \frac{T_o}{T_{evap}}\right)}{\dot{W}_{comp}}. \quad (6)$$

The energy of a PV module depends on two major components--electrical and thermal. While electricity is generated by the PV effect, the PV cells are also heated due to the thermal energy present in the solar radiation. The electricity (electrical energy), generated by a photovoltaic system, is also termed "electrical exergy" as it is the available energy that can completely be utilized in useful purpose. Since the thermal energy available on the photovoltaic surface was not utilized for a useful purpose it is considered to be a heat loss to the ambient. Therefore, due to heat loss, it becomes exergy destruction. The exergy output of the photovoltaic system can be calculated as

$$\begin{aligned} \dot{E}x_{out} &= \dot{E}x_{electrical,max} - \sum \dot{\Gamma}_{PVs} = \\ &= V_{oc} I_{sc} - \left[(V_{oc} I_{sc} - V_m I_m) + \dot{Q}_{loss} \cdot \left(1 - \frac{T_o}{T_{cell}}\right) \right], \end{aligned} \quad (7)$$

here, $V_{oc} I_{sc}$, represents the maximum electrical energy which can be produced by photons, and the second part $(V_{oc} I_{sc} - V_m I_m)$, denotes the exergy destruction due to photovoltaic irreversibility. \dot{Q}_{loss} which is the exergy destruction of heat loss, can be expressed as

$$\dot{Q}_{loss} = h_c \cdot A \cdot (T_{cell} - T_o), \quad (8)$$

where h_c , A , T_{cell} and T_o are the convective heat transfer coefficient from the photovoltaic cell to ambient, area of the photovoltaic surface, cell temperature and ambient temperature (dead state temperature), respectively. The convective heat transfer coefficient from the photovoltaic cell to ambient can be calculated by using $h_c = 5.7 + 3.8 \times v$ correlation [7] for natural convection, considering wind velocity (v), density of the air and the surrounding (ambient) conditions.

Considering equations 7 and 8, the exergy output of the photovoltaic system can be defined as

$$\dot{E}x_{out} = V_m I_m - \left(1 - \frac{T_o}{T_{cell}}\right) \cdot [h_c \cdot A \cdot (T_{cell} - T_o)] \quad (9)$$

Exergy input of the photovoltaic system, which is the exergy of solar energy, can be calculated approximately as below

$$\dot{E}x_{in} = \dot{E}x_{solar} = S_T \cdot A \cdot \left(1 - \frac{T_o}{T_{sun}}\right), \quad (10)$$

where S_T is the solar radiation on an incident photovoltaic inclined surface, and T_{sun} is the sun temperature taken as 6000 K [8]. Therefore, exergy efficiency of the PVs can be expressed

$$\psi_{PV} = \frac{V_m I_m - \left(1 - \frac{T_o}{T_{cell}}\right) \cdot [h_c \cdot A \cdot (T_{cell} - T_o)]}{S_T \cdot A \cdot \left(1 - \frac{T_o}{T_{sun}}\right)}. \quad (11)$$

In the exergy efficiency analysis, energy efficiencies are assumed to be equal to exergy efficiencies for power conditioning units (charger and driver) and battery since electrical energy is a totally useful work. Consequently, for a PV powered refrigerator, exergy efficiency of the overall system can be formulated as

$$\psi_{system} = \frac{\dot{Q}_{evap} \left(1 - \frac{T_o}{T_{evap}}\right)}{\dot{E}x_{solar}} = \frac{\dot{Q}_{evap} \left(1 - \frac{T_o}{T_{evap}}\right)}{S_T \cdot A \cdot \left(1 - \frac{T_o}{T_{sun}}\right)}. \quad (12)$$

Results and discussions

For performance investigation of the PV powered refrigeration system, four cases are considered. The cases are determined with the respect to different cooling loads including no storage (empty), low storage (10 cans), nominal load (20 cans) and over load (30 cans) in the refrigerator. Cool-down behavior has been obtained at 1°C temperature set value in the refrigerator. Compressor consumes 49.1 W, 49.51 W, 50.34 W and 52.46 W in average for the no storage, low load, nominal load and over load cases. It is observed that compressor consumes more energy than others during over loaded condition to reach set value even it seems lower. Solar radiation values on the 45° tilted surface for four experiments days in May, 2009 are measured. Average energy efficiency values for PVs for the days 1, 2, 3, 4 are calculated to be 14.74%, 14.80%, 15.12% and 15.21%, respectively. Average ambient and cell temperatures are measured as in Table 1.

Energy and exergy analyses have been carried out for only refrigeration cycle and the whole refrigeration system for different cooling load. The energetic coefficient of performance (COP_R) for only refrigeration cycle is calculated to be 0.670 during the cool-down period with no storage items and 0.571 for the nominal load condition which is 20 cans (330ml/per can) in the refrigerator. Moreover, COP_R is calculated to be 0.477 for the over loaded condition which is 30 cans. Also, cool-down period is increased significantly. Energetic and exergetic coefficient of performance values of the refrigeration cycle, exergy efficiency of the whole refrigeration system and exergy destructions from the system components for the different cases are shown in Table 2. The exergetic coefficient of performance (COP_{R,ex}) for only refrigeration cycle is calculated to be 0.048 during the cool-down period with no storage items and 0.063 for the nominal load condition. It is obtained to be 0.040 for the over loaded condition. It can be said that exergetic performance decreases when the refrigerator is over-loaded. Total

exergy destruction at the over loaded case is also the highest with the value of 366.33 W. At the condition of the nominal load, total exergy destruction has the lowest value, 352.58 W.

Table 1. Average ambient and cell temperatures for the cases conducted on different days

Temperature (°C)	Day 1 No Storage	Day 2 Low Load	Day 3 Nominal Load	Day 4 Over Load
Ambient Temperature (°C)	26.9	29.19	31.05	30.34
Cell Temperature (°C)	56.89	61.61	61.89	63.64

Table 2. Energetic and exergetic performance coefficient values of the refrigeration cycle, exergy efficiency of the whole refrigeration system and exergy destructions from the system components for the different cases

Case	COP _R	COP _{R,ex}	ψ_{sys} (%)	Component	$\Sigma \dot{I}$ (W)
No Storage	0.670	0.048	0.604	PVs	287.87
				Batteries and Charger	11.71
				Compressor	39.01
				Condenser	6.08
				Expansion Device	1.41
				Evaporator	8.56
Low Load (10 cans)	0.574	0.068	0.859	PVs	291.06
				Batteries and Charger	11.80
				Compressor	39.62
				Condenser	5.57
				Expansion Device	1.73
				Evaporator	7.85
Nominal Load (20 cans)	0.571	0.063	0.810	PVs	285.00
				Batteries and Charger	12.00
				Compressor	40.75
				Condenser	6.06
				Expansion Device	1.65
				Evaporator	7.12
Over Load (30 cans)	0.477	0.040	0.514	PVs	296.76
				Batteries and Charger	12.51
				Compressor	44.64
				Condenser	5.15
				Expansion Device	1.30
				Evaporator	5.96

For all cases, exergy is destroyed highly in the PVs as seen in Table 2. Of the total exergy input (solar exergy), nearly 82% is destroyed in the PVs.

Secondly, 11% of the total exergy input is loss in the compressor. The overall exergy efficiency of the system is also very low since energy conversion efficiency (about 12%) and exergy efficiency (about 11%) of the PV is low.

For the over loaded case, the overall exergy efficiency of the system has the lowest value, 0.514%.

Conclusions

In this study, it is shown that a small household refrigerator with DC compressor can be operated PV power without any inverter. These decrease initial cost of the system since inverter is big cost for the solar energy powered systems. For performance investigation of the PV powered refrigerator with DC compressor, exergy analysis has been carried out. Experiments at different conditions have been conducted.

According to energy analysis the highest COP_R (0.670) is observed during the no storage condition. Also,

compressor power consumption is low for that operation. However, the highest exergetic coefficient of performance is 0.068 at the low load condition.

At the low load condition, the overall exergetic efficiency of the refrigeration system is 0.859%. The overall exergy efficiency of the system is also very low since energy conversion efficiency (about 12%) and exergy efficiency (about 11%) of the PV is low. It is also clearly seen from exergy destruction values. For all cases, exergy is destroyed highly in the PVs.

Acknowledgement

The authors gratefully acknowledge the support provided by the Council of Scientific Research Projects of PAU.

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Received 2011 02 09

O. Ekren, A. Yilanci, E. Cetin, H. K. Ozturk. Experimental Performance Evaluation of a PV-Powered Refrigeration System // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 8(114). – P. 7–10.

This paper presents cool-down, and steady state performance of a 76 W direct current operated household refrigerator powered by a photovoltaic (PV) solar panel and a battery bank. Exergy method has been conducted to investigate of the performance of the PV powered household refrigerator. Experiments are conducted with different cooling loads. In use of this type system, it can be said that over-loaded condition in the refrigerator should be avoided. From the obtained results, it is seen that exergy efficiency of the system is very low due to the low energy conversion and exergy efficiencies of the PVs. This situation is also seen from exergy destruction values. For all cases, exergy is destroyed highly in the PVs. Ill. 1, bibl. 8, tabl. 2 (in English; abstracts in English and Lithuanian).

O. Ekren, A. Yilanci, E. Cetin, H. K. Ozturk. Naudojančios vėsinimo sistemos Fotogalvaninius elementus eksperimentinis našumo tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 8(114). – P. 7–10.

Aprašoma kaip veikia plokštė, sudaryta iš fotogalvaninių elementų, ir baterijų pritaikymas buitiniam šaldytuvui. Didinant fotogalvaninių elementų našumą, buvo atliktas eksperimentinis tyrimas, esant skirtingoms vėsinimo apkrovoms. Nustatyta, kad, naudojant tokią sistemą reikia, vengti didelių sistemos apkrovų. Sistemos eksperimentinis efektyvumas, įskaitant ir fotogalvaninių elementų našumą, yra labai mažas. Il. 1, bibl. 8, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).