An experimental study optimization of a solar assisted D.C refrigerator under Iraqi climate.

Dalya Amjed Omer¹  Mahmoud Mustafa Mahdi²  Ahlam Luaibi Shuraiji³

University of Technology \Electromechanical Engineering Department

¹em.19.13@grad.uotechnology.edu.iq.
²50295@uotechnology.edu.iq.
³50053@uotechnology.edu.iq.

Abstract. Solar photovoltaic to derive a small dc domestic refrigerator is becoming beneficial for remote areas where electricity is not available. This article presents an experimental energetic and exergetic analysis for a small dc refrigerator driven by a solar photovoltaic (PV) panel. The performance parameters, such as exergy losses compressor, exergy losses condenser, exergy losses expansion valve, exergy losses evaporator, efficiency exergy refrigerator, average optimum exergy efficiency (refrigerator), efficiency system (PV panel plus dc refrigerator) were investigated. The mentioned parameters were measured along the time of the day under the climate of Baghdad city. The experimental test has been carried out with load refrigerator (5 liters of water), to the evaluate the average optimum value of the refrigerator exergy efficiency under different thermostat. this work aims to identify an optimal average exergy loss for D.C refrigerator during the day, which can work at the optimum condition in evaporator temperature. The average exergy losses optimum value in evaporated temperature (-6) is 24.63

Keywords: Energy analysis, Exergy analysis, Efficiency, Exergy losses, DC domestic refrigerator.

1. Introduction

Renewable electricity such as wind, water, and sunlight, is well regarded for being extracted from natural resources that are inexhaustible and constantly renewed, and available in the most countries. Photovoltaic converters, or solar cells transfer direct sunlight hours into the electricity. They are semi-conductive and photosensitive pulses and are surrounded by the front's talent and extra cover that conducts electricity. Undebatable, electrical power is very important for any house, as most household devices are working by electrical power. A refrigerator is one of the essential domestic house devices. [1] Therefore, refrigerator powered by solar cells has been of interested in many literature such as J. U. Ahamed, Geppert et.al
presented a comparison of a domestic refrigerator's energetic and exergetic performances using pure butane and isobutane as refrigerants. The calculated result at varied operating conditions, Exergy and energy efficiencies of isobutane were found to be 50% and 75% higher than that of R-134a, maximum exergy loss occurred in the compressor, it formed about 69% of the whole losses in the system; the higher the temperature differences between evaporator and condenser, the higher the exergy losses. 

Jasmin Geppert et al. (2013) [3] Studied the sensitiveness of refrigerators’ energy consumption, the test was applied on four different refrigerators in a laboratory using Box–Behnken design with three variables (thermostat setting position, ambient temperature, and additional heat load by storing warm food). Each test device daily energy consumption ranged from a few watt-hours to 2000 Wh, depending on the working conditions and the used devices. The ANOVA revealed that the ambient temperature was responsible for the overwhelming part of an appliance's energy consumption. The energy use was also affected, to a minor degree, by the internal compartment temperature and an additional heat load. 

S. D. Deshmukh, et al. (2015) [4] Experimentally analyzed the performance of photovoltaic driven vapor compression refrigeration system. The experimental outcomes were used for the PV systems energy and exergy efficiencies calculation. It was found that load had no impact on the photovoltaic panel performance. On the other hand, the PV panel temperature had a great effect on the exergy efficiency, i.e., exergy losses increased with increasing the panel's temperature. Ami Shukla, et al. (2015) [5]: evaluated thermal, electrical, and exergy output of the PV panel (Tata BP 184459) at Energy Centre, MANIT Bhopal. The experimental information had been used for the energy and exergy efficiencies calculation of the PV panel. Energy effectivity was varying between 6% and 9% at some point of the day. In addition, for the electrical energy, exergy efficiency is reduced by using the well-known PV panel, which ranges from 8% to 10%. ShajiSidney, et al. (2016) [6]: Studied exergy analysis of refrigerator. The result showed maximum exergy loss in the compressor decided through a way of the evaporator. As in the condenser the exergy loss was in minimal levels. All the exergic losses in the refrigeration unit have been barring extend proportional to the ambient temperature, and minimal exergy loss was noticed at 25°C. 

K. O. Daffallah, et al. (2016) [7] experimentally evaluated the performance of photovoltaic DC refrigerator with and without loading under different conditions. The test includes (PV) the panel, 12 V battery, charge controller, and 158-liter DC refrigerator. The test showed that a significant amount of power consumption increased when the thermal load increased. Depending on the different thermal loads, about 15% to 41% higher power consumption has been observed in comparison to the no-load condition. 

N. D. Shikalgar, et al. (2019) [8] compared the performance of the refrigerator with hot wall condenser, and cold water condenser Experimental result examined that COP 18-20% and the exergy effectivity of fridge with water-cooled condenser Comparison with a hot-wall air-cooled condenser. Energy consumption reduced with the use of a water-cooled condenser 17% of the daily refrigerator consumption. Erhan Arslan et.al (2020 [9] analyzed the effect of energy and exergy measurements of a naturally ventilated PV roof solar. The system's thermal, electrical, and overall energy efficiencies were 18-50 %, 13-18 %, and 35-67 % respectively, overall exergy competencies of the the-RSC system ranged from 0.1-0.9 %, 14-20 %, and 15-21 %. 

Shailendra Kasera, et.al (2021) [10] analyzed the performance a solar DC refrigerator using R290 variable speed mode. It was noticed that the cooling capacity decreased as temperature increased and the power consumption increased when the temperature increased. Moreover, COP of the system decreased with the increasing of the temperature. The higher temperature of condensed is also a reason for low COP at high room temperature. 60.61 ◦C and 68.76 ◦C are the highest compressor temperature.

2. Methodology

Solar cell is the building block of a solar panel. A photovoltaic panel is formed by connecting many solar
cells in series and parallel.

The energy efficiency of a PV system can be calculated from the ratio of the energy output of the system to energy input received on the surface of photovoltaic as:

\[ \eta_{en} = \frac{V_{oc}I_{sc}}{S} \quad \text{(1)} \]

The energy efficiency is limited to hypothetical cases. In eq. 1, S is solar flux absorbed, and it is given by:

\[ S = G \cdot A_{mod} \quad \text{(2)} \]

The maximum power point of fill factor (FF), which is given as:

\[ FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \quad \text{(4)} \]

The PV system's energy efficiency at maximum power is defined as the ratio of the actual electrical output to the incidence of solar energy input on the PV surface area as [11,12].

\[ \eta_{el} = \frac{V_{mp}I_{mp}}{S} \quad \text{(5)} \]

Efficiency of conversion of solar power as follows:

\[ \eta_{pco} = \frac{FF \cdot V_{oc}I_{sc}}{S} \quad \text{(6)} \]

**Exergy Analysis**

The exergy is a thermodynamic case function which enables the exemplarily maximum obtainable part of any form of energy to be calculated, with maintaining the first and the second laws of the thermodynamic [11,12]

\[ \dot{E}_{x_{in}} - \dot{E}_{x_{out}} = \dot{E}_{x_{dest}} = \dot{E}_{x_{loss}} \quad \text{(7)} \]

Where \( \dot{E}_{x_{in}}, \dot{E}_{x_{out}} \) and \( \dot{E}_{x_{dest}} \) are inlet, outlet and Exergy loss, respectively, in the control volume.

PV panel exergy efficiency is the ratio of total exergy output to exergy output obtained by PV to solar radiation exergy is also known as PV exergy efficiency [13].

\[ \eta_{ex} = \frac{\dot{E}_{x_{out}}}{\dot{E}_{x_{in}}} \quad \text{(8)} \]

The PV system's inlet exergy only contains the solar radiation intensity exergy. As for the theorem of the patella, as: [13,14].

\[ \dot{E}_{x_{in}} = G A_{mod} \left[ 1 - \frac{4}{3} \left( \frac{T_{amb}}{T_{sun}} \right)^{3} + \frac{1}{3} \left( \frac{T_{amb}}{T_{sun}} \right)^{4} \right] \quad \text{(9)} \]

Outlet exergy of PV system determined by [15]

\[ \dot{E}_{x_{out}} = \dot{E}_{x_{th}} - \dot{E}_{x_{out}} \quad \text{(10)} \]

Exergy of the thermal energy

\[ \dot{E}_{x_{th}} = Q \left( 1 - \left( \frac{T_{amb}}{T_{mod}} \right)^{4} \right) \quad \text{(11)} \]

\[ Q = UA_{mod} \left( T_{mod} - T_{amb} \right) \quad \text{(12)} \]
The overall coefficient of heat loss PV panel includes losses of conversion and radiation.

\[ U = (h_{canv.} + h_{rad}) \]  

Coefficient of Convective Heat Transfer [16]

\[ h_{canv.} = 2.8 + 3V_w \]  

Irradiative coefficient of heat transfer between the PV panel and the surrounding environment [17]

\[ h_{rad} = \varepsilon \sigma (T_{sky} - T_{mod})(T_{sky}^2 - T_{mod}^2) \]  

Effective temperature of sky [13]

\[ T_{sky} = T_{amb} - 6 \]  

Exergy electrical in output power electrical of PV panel [17]

\[ \dot{E}_x = V_{oc}I_{sc} FF \]  

The main component of condenser, compressor, evaporator, and capillary tube. This paper, made assumption are as following:

1. Condition prevailing steady-state in every component.
2. Loss of Pressure in a pipeline is neglected.
3. Heat gains Unnecessary, and heat losses of the system aren’t measured.
4. Potential Kinetic and losses energies are not measured.
5. Refrigerant is the unity of mass flow rate.[8]

The equation of exergy balance of each components is represented as:

Compressor

\[ (E_{xD})_{\text{comp}} = (E_x)_1 + W_{\text{actual}} - (E_x)_2 = m_r (T_o(s_2-s_1)) \]  

Condenser

\[ (E_{xD})_{\text{cond}} = (E_x)_2 - (E_x)_3 = m_r (h_2-T_oS_2) - m_r (h_3-T_oS_3) \]  

Expansion Device

\[ (E_{xD})_{\text{exp}} = (E_x)_3 - (E_x)_4 = m_r (T_o(s_3-s_4)) \]  

Evaporator

\[ (E_{xD})_{\text{evap}} = (E_x)_4 + Q_{\text{evap}} (1- \frac{T_o}{T_r}) - (E_x)_4 \]  

The total exergy loss in systems are define as sum of exergy loss in different component for system as:

\[ (E_{xD})_{\text{Total}} = (E_{xD})_{\text{comp}} + (E_{xD})_{\text{cond}} + (E_{xD})_{\text{exp}} + (E_{xD})_{\text{evap}} \]  

Exergy efficiency compute efficiency for process at second law of thermodynamic as:

\[ \eta_{\text{ex(refrigerer)}} = \frac{\dot{E}_{\text{out}} - Q_c(1-\frac{T_o}{T_r})}{W_{\text{compressor}}} \]  

\[ \eta_{\text{ex(system)}} = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}} = \frac{Q_c(1-\frac{T_o}{T_r})}{\dot{E}_{\text{in}}} \]
3. Experimental set up

The Experimental setup consists of PV, controller charge, battery, and load. In the winter season. The overall experimental setup of a PV system is shown in Fig. (2). The system consists of a Mono-Crystalline Solar Panel PV panel with 50 W, charge controller connected with 12V solar battery, and instrumentation device. A normal common model domestic refrigerator of 50W rated power consumption was used in this experiment. Table (1) lists the manufacturer specifications of the PV, while Table (2) shows the specifications of the battery and the voltage regulator. Moreover, the refrigerator specifications are shown in Table (3).

| Parameter                   | Specification          |
|-----------------------------|------------------------|
| Model                       | Mono Crystalline Solar Panel |
| Maximum power (W)           | 50W                    |
| Maximum power t voltage/Vmp(V) | 18V                 |
| Maximum power current/Imp(A) | 2.77A                 |
| Short Circuit Current/Isc(A) | 2.99A                 |
| Short Circuit Voltage/Vsc(V) | 21.6V                 |
| Maximum power Tolerance     | ± 5%                   |
| Product Size                | 680*510*30 mm          |

Table (2): Specifications for the battery, the charger regulator

| Items            | Specifications          |
|------------------|------------------------|
| Battery          | Battery, 12V, 100Ah    |
| Charger regulator| 12V, 30A               |

Table (3): Specification for the Refrigeration Unit.

| Model                      | CX30/CX40/CX50         |
|----------------------------|------------------------|
| Voltage / frequency / phase| 12V-24V/50 /1         |
| Operating current          | 3.75A/1.875A           |
| Power input                | 45W                    |
Table (4): constants inputs.

| Constants                                | Value                      |
|------------------------------------------|----------------------------|
| Stefan Boltzmann constant ($\sigma$)     | $5.67 \times 10^{-8}$ W/m²·K |
| Emissivity of the panel ($\varepsilon$)  | 0.9                        |
| Sun temperature (Tsun)                   | 5780 K                     |
| Maximum power (vmp)                      | 18v                        |
| Open circuit voltage (Voc)               | 21.6v                      |
| Short circuit current (Isc)              | 2.99A                      |
| Dimensions                               | 680*510*30mm               |
| Fill factor (FF)                         | 0.77                       |
| maximum power current /imp(A)            | 2.77A                      |
Table (5): Specification of all measuring instruments

| Serial No. | Name of measuring instrument | Manufacturing and model No. | Rating | Application               |
|------------|------------------------------|-----------------------------|--------|---------------------------|
| 1          | Solar power meter SM206_solar| 0.1_1999.9w/m²              |        | Solar radiation intensity |
| 2          | DIGITAL Multimeter DT9205A   | 2m_20A,2V_1000V             |        | PV module characteristics |
| 3          | DIGITAL Multimeter DT 33C    | (-40°C_+1000°C)             |        | Ambient temperature&Temperature cell |
| 4          | Thermocouple Type k          | -270 to 1260°C              |        | Temperature cell,Temperature cell |

Results and Discussions

The refrigerator's performance is tested at different working conditions: 1. with no load. The thermostat used in this system has been labeled from 0 to -20 on its control knob, 0 for switching off, and -3 to -20 for setting up. The thermostat setting is varied by turning the knob to the desired setting position to study the effect of the thermostat setting position on ampere-hour consumption. Fig. (3) demonstrates the behavior of the exergy losses in the compressor during the day. As result of the difference between high to low temperature which proportional with to the exergy losses compressor, the maximum exergy loss is 15.7603 KJ/Kg in the thermostat (-9) at 3:00 pm. The minimum exergy loss compressor was 5.5474 KJ/Kg when setting the thermostat to (-6) at 9:00 am resulted from the temperature difference between high to low is almost equal when the refrigerator is started at that time.
Fig. (4) demonstrates the behavior of the exergy losses in the condenser during the day. The maximum exergy losses is about 17.3329 KJ/Kg in the Thermostat (-3) at 12:00 pm. While the minimum exergy losses in condenser is 9.6 KJ/Kg at 12:00 pm. The reason behind this reading is the difference of approximately 4 degrees Celsius between the temperature entering the condenser and the temperature outside it at that time.
Fig (5) Variation of exergy losses in expansion valve for clear days.

Fig. (5) shows the results of the exergy losses of expansion valve during the day. The maximum exergy losses in thermostats (-20) is 8.0824 KJ/Kg at 1:30 pm the reason comes back to the difference between the temperature coming out of the condenser and the point outside of the expansion is approximately 2.7 because of the high room temperature.

Fig (6) Variation of exergy losses in evaporate valve for clear days.
The variation of exergy losses in evaporates valve for clear days is shown in Fig. (6). The minimum exergy loss is 23.53 KJ/Kg in thermostat 0 at 10:00 am.

![Fig (6) Variation efficiency exergy refrigerator for clear day.](image)

The Variation of the refrigerator efficiency exergy during the day is shown in Fig. (7). The minimum efficiency exergy for (0, -3, -6, -9, -20) thermostats are 40.65%, 54.01%, 54.01%, 40.39%, 42.98%, respectively.

![Fig (7) Variation efficiency exergy refrigerator for clear day.](image)

The Variation of the refrigerator efficiency exergy during the day is shown in Fig. (7). The minimum efficiency exergy for (0, -3, -6, -9, -20) thermostats are 40.65%, 54.01%, 54.01%, 40.39%, 42.98%, respectively.

![Fig (8) Variation of average efficiency exergy refrigerator &T evaporate.](image)
In fig (8), this work aims to identify an optimal average exergy loss for D.C refrigerator during the day, which can work at the optimum condition in evaporator temperature. The average exergy losses optimum value in thermostats (-6) is 24.63 %.

Conclusion

An experimental exergetic and energetic analysis of a small dc domestic refrigerator driven by solar PV panel are studied to check the exergy efficiency and average exergy losses optimum in all test thermostats under local climate. Experimental studies were carried out on small dc domestic operating refrigerator at load condition under the same operating conditions. Based on the experimental result obtained; the following calculation is drawn firstly, The maximum recorded exergy losses (Kj/kg) of the thermostats in the compresses 0, -3, -6, -9 and-20 were 7.442, 8.9102, 8.4075, 15.7603, 10.3545, respectively. At the same time, the exergy losses (Kj/kg) results of the same thermostats in the condenser case were 16.08, 17.3329, 14.3668, 16.63, 16.346, respectively. As for the exergy losses (Kj/kg), the results of the same thermostats in the expansion valve (calipray tube) case were 4.0434, 6.2282, 5.8608, 6.2878, 8.0824, respectively. And finally, the exergy losses (Kj/kg) results of the same thermostats in the evaporator case were 25.97, 212.2184, 203.4584, 203.83, 203.546, respectively. Secondly, The maximum refrigerator efficiency exergy under the same previous conditions were 40.65%, 54.01%, 47.38%, 42.46%, 41.75%, respectively. Thirdly, The minimum recorded efficiency of the system (DC refrigerator, Photovoltaic) of the thermostats in the 0, -3, -6, -9 and-20 were 0.9%, 1.01%, 1.2311%, 0.9013%, 1.3441%, respectively. Finally, the optimum average value (refrigerator) Thermostat (0) was 21.33%, Thermostat (-3) was 21.69%, Thermostat (-6) was 24.83%, Thermostat (-9) was 22.5%. The thermostat (-20) was 22.1%.

Nomenclature

| Symbol | Description |
|--------|-------------|
| h      | Enthalpy (J/kg) |
| m      | mass flow rate |
| Qevap  | cooling capacity |
| s      | Entropy (J/kg.k) |
| ExD    | Exergy destruction |
| T      | Temperature(k) |
| comp   | Compressor |
| cond   | Condenser |
| Exp    | Expansion device |
| evap   | Evaporator |
| To     | Tambeint (k) |
| Tr     | T evaporator (k) |
| W copresser | work compressor (k) |
| Qc     | cooling capacity (kw) |
| Exout  | exergy out |
| Éxin   | exergy in |
| Amod   | Area of Module (m2) |
| ÉX(pv)out | Solar Module Exergy Output Rate |
\( \dot{E}_{\text{Xdes}} \) Exergy Destruction Rate (W)
\( \dot{E}_{\text{exel}} \) Electrical Exergy Rate (W)
\( \dot{E}_{\text{ixin}} \) Inlet Exergy Rate (W)
\( \dot{E}_{\text{Xloss}} \) Exergy Loss (W)
\( \dot{E}_{\text{Xout}} \) Outlet Exergy Rate(W)
\( \dot{E}_{\text{exth}} \) Thermal Exergy Rate (W)
FF Fill Factor
G Solar Insolation (W/m2)
\( h_{\text{conv}} \) Convection Heat Transfer Coefficient ( W/m2k)
\( h_{\text{rad}} \) Radiation Heat Transfer Coefficient ( W/m2)
\( \text{Imp} \) Current at Maximum Power Point
\( I_{\text{O}} \) Saturation Current (A)
\( I_{\text{sc}} \) Short Circuit Current (A)
k Boltzmann’s Constant
L1, L2: Length and Width of Module (m)
\( T_{\text{amb}} \) Ambient Temperature (ºK)
\( T_{\text{mod}} \) Module Temperature (ºK)
\( V_{\text{oc}} \) Open circuit voltage
\( T_{\text{sun}} \) Sun temperature
\( \sigma \) Stefan Boltzmann constant
\( \varepsilon \) Emissivity of the panel
\( T_{\text{sky}} \) Sky Temperature (ºK)
\( U \) Overall Heat Loss Coefficient (W/m2.K)
\( V_{\text{mp}} \) Voltage at Maximum Power Point
\( \eta_{\text{el}} \) Electrical Efficiency (%)
\( \eta_{\text{en}} \) Energy Efficiency (%)
\( \eta_{\text{ex}} \) Exergy Efficiency (%)
\( V_{\text{w}} \) wind speed (m/s)

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