IJCPE
Iraqi Journal of Chemical and Petroleum Engineering

Iraqi Journal of Chemical and Petroleum Engineering
Vol.14 No.1 (March 2013) 39- 46
ISSN: 1997-4884

University of Baghdad
College of Engineering

Studying the Performance of Refrigeration Units Powered by Solar Panel

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Abstract
An experimental study was conducted to determine the performance of a solar electric refrigeration system. The system contained flat photovoltaic solar panel which absorbs the solar energy and convert it to electrical energy, used to run the refrigeration cycle. Two refrigeration cycles with electrical solar panel were used over a period of 12 months, the first one with classical parts known in refrigeration cycle, while the second one introduced heat exchanger which improves the coefficient of performance by saving the consumed energy. The coefficient of performance of these refrigeration cycles with compressor efficiency 85% are 2.102 and 2.57 respectively. The overall efficiency of the two systems are 18.9% and 23.13%.

Keywords
Solar Panel, solar electric refrigeration, Refrigeration system, photovoltaic cell, coefficient of performance

Introduction
During the last few decades energy consumption for cooling has increased dramatically in most countries. The main reasons for the increasing energy demand for summer air- conditioning and Refrigeration are the increased thermal loads, increased living standards and comfort demands in conjunction with architectural characteristics and trends. During the summer the demand for electricity increases due to the extensive use of Refrigeration systems, which increase the peak electric load, causing major problems in the electric supply. The last few years exhibited an increasing interest, based on research and development, has been concentrated on utilization of energy sources, like solar energy, wind energy, hydrogen energy, etc, due to the increasing of oil price. Among these sources, solar energy is a highly popular source due to the following facts: direct and easy usability, renewable and continuity, being safe, being free, environment friendly and not being under the control of anyone [1]. The use of solar energy to drive refrigeration systems has a great interest, this type of solar energy is called solar electrical refrigeration, which consists mainly of photovoltaic panels and an electrical refrigeration device. Whose efficiency and cost vary widely depending on the material and the manufacturing methods they are made from. The photovoltaic cells produce electricity

without noise or air pollution from a clean source [2].

In this work solar electrical panel are used to drive an improved refrigeration system and improve electrical refrigeration system, and then estimated the overall efficiency in the two cases.

Refrigeration System

Prior to discussing how solar energy could potentially provide refrigeration, it is appropriate to review the basic principles of operation for vapor compression refrigeration cycles that form the foundation for nearly all conventional refrigeration. In the vapor compression cycle, as can be seen in figs.(1) &(2), cooling is provided in the evaporator as low temperature refrigerant entering the evaporator as a mixture of liquid and vapor at State 1 is vaporized by thermal input from the load. The remaining equipment in the system reclaims the refrigerant and restores it to a condition in which it can be used again to provide cooling. The vapor exiting the evaporator at State 2 in a saturated *(2s)* or slightly superheated (*3s*) condition enters a compressor that raises the pressure and, consequently, the temperature of the refrigerant. The high pressure hot refrigerant at State 3 enters a condenser that uses ambient air to cool the refrigerant to its saturation temperature prior to fully condensing to a liquid at State 4. The high-pressure liquid is then throttled to a lower pressure, which causes some of the refrigerant to vaporize as its temperature is reduced. The low temperature liquid that remains is available to produce useful refrigeration[3]. A schematic of the vapor compression cycle is shown in Fig. (1) and a corresponding enthalpy –pressure diagram for the refrigerant is shown in Fig. (2).

The coefficient of performance (COP) of vapor compression refrigeration system is taken as a method of performance efficiency of any refrigeration cycle which defined as: [A. Klein2005]

$$COP=\frac{Q}{W} \qquad ...(1)$$

Where:

Q is the evaporator heat energy (kJ)

W is the compressor input work (kJ)

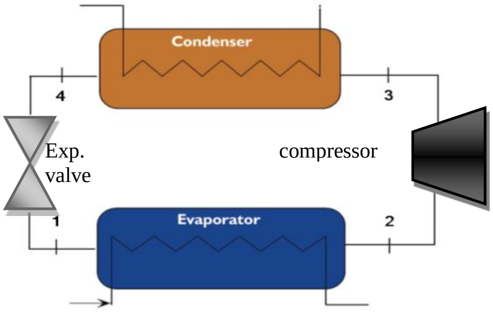

Fig. 1, Schematic of a vapor compression refrigeration cycle

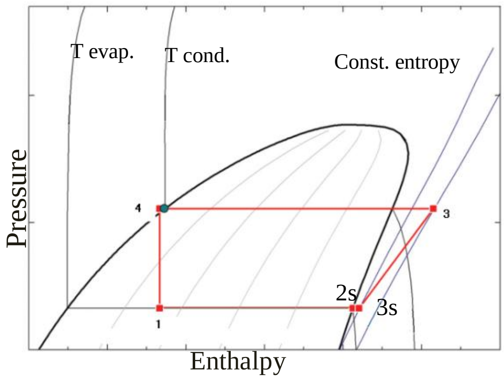

Fig. 2, Pressure-enthalpy diagram

Solar Electric Refrigeration

The Solar electric refrigeration is the refrigeration that runs on the solar energy. The solar system of the solar refrigerator comprises of the solar panel that collects the solar energy. The solar panels are fitted with photovoltaic (PV) cells that convert the solar energy into electrical energy and store it in the battery. During the normal running of the solar refrigerator the power is supplied directly by the solar panel, but when the output power of solar panels is less, the additional power is supplied by the battery. The battery is recharged when excess amount of power is produced by the solar panels [4]. The rate of electrical power capable of being generated by a PV system is typically provided by manufacturers of PV modules for standard rating conditions, i.e., incident solar radiation of 1,000 W/m2 and a module temperature of 25°C. Unfortunately, PV modules will operate over a wide range of conditions that are rarely as favorable as the rating condition. In addition, the power produced by a PV array is as variable as the solar resource from which it is derived. The performance of a PV module, expressed in terms of its current-voltage and power-voltage characteristics, principally depends on the solar radiation and module temperature.

Efficiency of solar panel is defined by the ratio of power W (Watt) to the product of solar panel surface area $A_s(m^2)$ and the direct irradiation of solar beam I_P (W/m^2) [5].

$$eff. = \frac{W}{I_P \times A_s} \qquad \ldots(2)$$

Experimental Work

Many parts are connected together in order to operate the refrigeration system. The experimental parts of a solar refrigeration system are illustrated in fig. (3).

There are two main parts in the experiment, the first part introducing the energy. This part is responsible for producing power or electrical energy:

a) PV Panel

The voltage and the power of PV cells are very small in order to supply a device. For this reason, many cells are combined together in a PV panel with common electrical output. One of the main features of the panel is the peak power. The peak power is the power from the photovoltaic when the solar irradiance is 1000 W in every square meter.The operating voltage and current are another important characteristic of the panel. The photovoltaic panels today are constructed in a way that they produce power equal to 12 V in order to charge the 12 V batteries.

PV panel which is used in this work has a specifications illustrated in table (1).

Table 1, PV panel specification

Photovoltic system specifications	
dimensions	1600×1300×35
Output peak power	180 W
Max.voltage	35.3 V
Max. current	5.36 A
Test condition	1000 W/m^2, 25C^o
Panel type	Fixed tilt
Panel tilt	35^o, 55^o

b) Voltage Regulator

This device controls the current flux from the PV to the batteries and allow to overcoming the change in the voltage supply by the sun through the PV panel from the sunrise to sunset. When the battery is fully charged, the voltage regulator decreases the current not to overcharge the battery. When the battery is overcharged, the operational life is decreased.

c) Battery

The electrical energy is stored to the batteries in order to be provided in intervals with minimum solar irradiance (during nights, cloudy days). Generally the batteries used for PV systems are the same as the ones used in cars (lead type). The output supply of batteries is DC with voltage about 12 V.

d) Inverter

Since the refrigerator driven motor is operated on A.C, an inverter is needed. This device converts D.C to A.C. to operate the refrigerator.

e) Load

The term load indicates the total number of electrical appliances that they will be operated with the electrical energy provided by the PV. For a PV system to be well designed the electrical energy that these appliances consume in a time interval of one month, should be equal or less to the energy produced by the system in the same time interval. For every electrical appliance, various parameters should be known before connecting them the PV system:

- The type of the operational current
- The value of the operational voltage
- The power dissipated during its operation.

Fig. 3, solar electricrefrigeration system

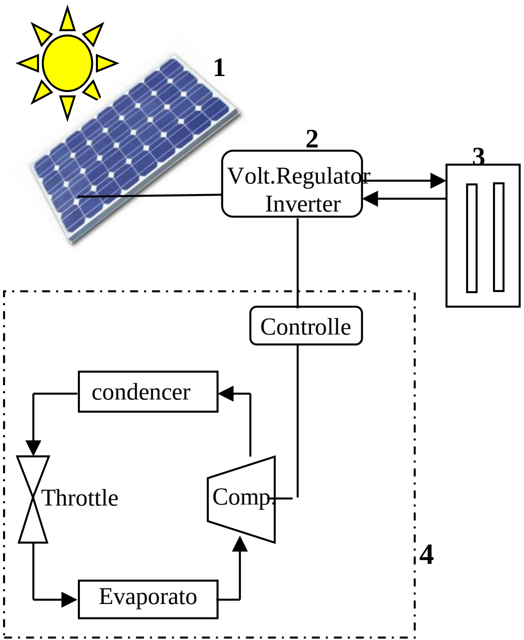

Fig. 4, Schematic diagram of solar electric refrigeration

Experimental Analysis

1. (PV) Panel Data

In order to study sun radiation for Baghdad city its location should be known as shown in table (2).

Table 2, Location identification

Location identification	
City	Baghdad
Latitude	33.35°
Longitude	44.4167°

Fixed PV panel are chosen for this study with two different tilts. The selected angles are 35° and 55° since they give the biggest radiation collector angles. The study is taken over a year with average radiation intensity for a month as shown in table (3).

Table 3, Monthly solar radiations

Month	Results: Solar Radiation (kWh/m^2/day) @35°	Solar Radiation (kWh/m^2/day) @55°
1	4.9	5.25
2	5.4	5.51
3	5.91	5.62
4	6.47	5.69
5	5.97	4.98
6	5.88	4.73
7	6.16	4.99
8	6.55	5.62
9	6.0	5.57
10	5.93	5.95
11	5.23	5.56
12	4.67	5.19
Avg.	5.76	5.39

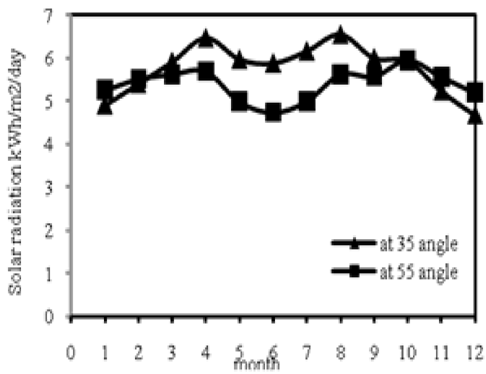

Fig. 5, Solar radiation vs. month at 35° and 55° tilt

To calculate the efficiency of the used solar panel maximum voltage should be calculated first as follows:[5,6]

$$W_{max}=I_{max}\times V_{max} \qquad ...(3)$$

$$= 5.36 \times 35.3 = 189.2 \text{ W}$$

The solar panel area: A_s= 2.08 m^2
The solar panel output power(Wo*) is* calculated from:

$$Wo = W_{max} \times \frac{I_p}{I_r} \qquad ...(4)$$

Where: I_p= solar radiation in W/m^2
I_r= reference solar radiation which equal (1000 W/m^2)
Wo= output power

So the efficiency of the solar panel:

$$eff. = \frac{W_o}{I_p \times A_s} = W_{max} \cdot \frac{I_p}{I_r \times I_p \times A_s}$$

$$= \frac{W_{max}}{I_r \times A_s} = \frac{W_{max}}{1000 \times A_s}$$

$$= \frac{189.2}{2080} = 9.091\%$$

The calculated results for the whole year is shown in table (4).

Table 4, Results of solar panel

month	Solar Radiation, I_P, (W/m^2) @35°	Work (W)	Solar Radiation, I_P, (W/m^2) @55°	Work (W)
1	490	92.7	525	99.33
2	540	102.16	551	104.24
3	591	111.81	562	106.33
4	647	122.41	569	107.65
5	597	112.95	498	94.22
6	588	111.24	473	89.49
7	616	116.54	499	94.41
8	655	123.92	562	106.33
9	600	113.52	557	105.38
10	593	112.19	595	112.57
11	532	100.65	556	105.19
12	467	88.35	519	98.19
Avg.	576	108.97	539	101.97

The obtained PV panel current and power can be shown in fig.(6) and fig.(7) respectively.

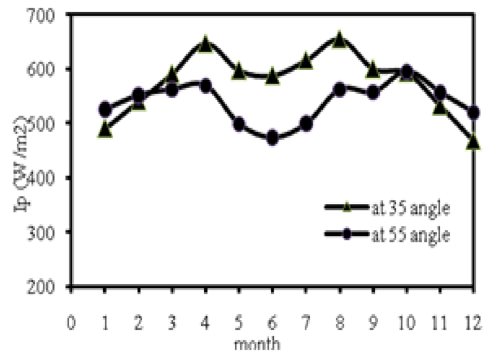

Fig. 6, Relationship between PV panel current produced for every month over a year at 35° and 55° tilt

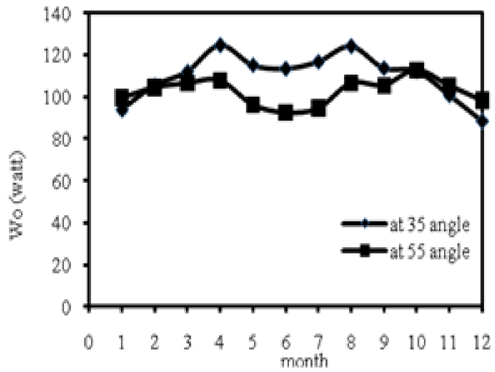

Fig. 7, Relationship between PV panel power produced for every month over a year at 35° and 55° tilt

2. Refrigeration System Operating Conditions and Performance

Two refrigeration cycles are used in this work as following:

2.1. Classical Refrigeration Unit

Freon (12) is used as a working fluid, as shown in fig. (8).

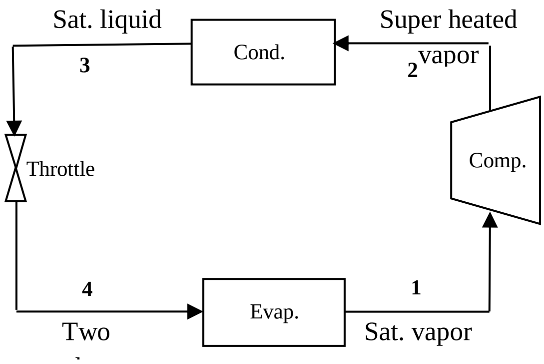

Fig. 8, Classical refrigeration cycle

Suction line T_1= 266.65K , P_1=24 psi
Discharge line T_2=324.85K,P_2=200 psi
Liquid line T_3=320.45KP_3=P2=200 psi

❖ From PH chart (R12)

h_1=353 KJ/Kg
h_2=393 KJ/Kg
h_3=h_4=254 KJ/Kg
Q-W=Δh (5)

The process between point 3 and 4 is isenthalpic throttling process, there is no work [7]

$\Delta h=0 \longrightarrow h_4=h_3$

The compressor is operated adiabatically, and its efficiency is 85%

Compressor: $-W_{comp.} = \Delta h = (h_2 - h_1)/0.85$
$W_{comp.} = (393 - 353)/0.85 = 47$ KJ/Kg
Evaporator: $Q_{evap.} = \Delta h = h_1 - h_4$
$Q_{evap.} = 353 - 254 = 99$KJ/Kg

$$COP = \frac{Q_{evap.}}{W_{comp.}} = \frac{99}{47} = 2.102$$

A modification on the refrigeration system is introduced with the same supplying amount of electrical energy but increasing the refrigeration performance.

2.2. Improvement of Refrigeration System

A heat exchanger is introduced in order to save energy. The location of heat exchanger is shown in fig. (9):

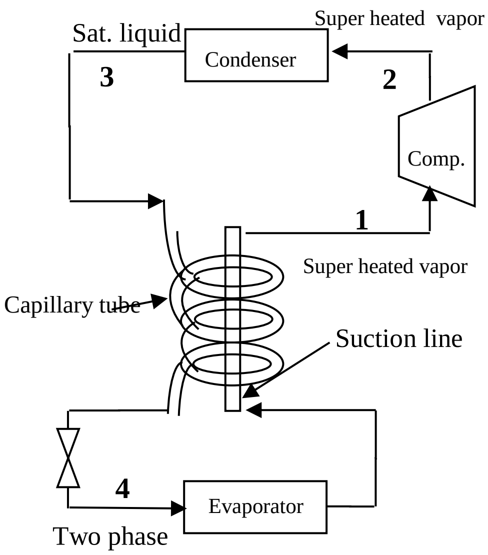

Fig. 9, Improved refrigeration cycle by introducing a heat exchanger

Suction line T_1= 269.35 K, P_1=21 psi
Discharge line T_2=323.35K,P_2=170 psi
Liquid line T_3=318.35K,P_3=P_2=170 psi

❖ From PH chart (R12)

h_1=360 KJ/Kg
h_2=398 KJ/Kg
h_3=h_4=245 KJ/Kg
Q - W = Δh

The process between point 3 and 4 is isenthalpic throttling process and there is no work

$\Delta h=0 \longrightarrow h_4=h_3$

The compressor is adiabatic, and the condenser and evaporator do no work

Compressor: $-W_{comp.} = \Delta h = (h_2 - h_1)/0.85$
$W_{com} = (398 - 360)/0.85$
$= 44.7$ KJ/Kg
Evaporator: $Q_{evap.} = \Delta h = h_1 - h_4$
$Q_{evap.} = 360 - 245 = 115$ KJ/Kg

$$COP = \frac{Q_{evap.}}{W_{comp.}} = \frac{115}{44.7} = 2.57$$

3. The Overall Systems Efficiencies

The biggest advantage of using solar panels for refrigeration is the simple construction and high overall efficiency when combined with a conventional vapor compression system. Combination of the efficiencies in Eq.(1) and Eq.(2) gives the overall efficiency of a solar electric cooling system: [5]

Overall eff.= $PV_{effe} \times COP$

1- Effe. of the systemwith classical refrigeration unit = 9 ×2.102 =18.9%
2- Effe. of the system with improved refrigeration unit = 9× 2.57 = 23.13%

Discussion

A solar panel was used to supply about 100 W to operate a refrigeration cycle in two cases. This test was made over 24-hour period during 12 months in Baghdad, with 10 hour as an average light day time and 576 W/m^2 as an average radiation. The efficiency of the used solar panel is 9%, which was calculated from the data obtained. On the other hand the COP for the refrigeration cycle in two cases was calculated, the first case consists of classical parts for refrigeration unit as shown in fig. (8). In this case the evaporator temperature between -6.5 and -18 C° and the condenser temperature between 47.3 and 51.7 C°. In the second cycle a heat exchanger was introduced between the throttle and the suction line as shown in fig. (9). This modification increased the COP of the cycle by decreasing the consumption of energy, for the second cycle the evaporator temperature between -3.8° and -15 C and the condenser temperature between 45.2 and 50.2°C. Thus, the COP of the classical refrigeration cycle is 2.102 and for the improved cycle is 2.57.

For the two cycles above the refrigerant vapor was compressed using 100 Watt piston compressor with an approximated of efficiency 85%.

To increase the cycle efficiency, there is another PV panel with better performance but an optimization between price and power produces must be done.

Refrigeration with energy produced from PV panel is environmental friendly and avoid the electrical shut down through the day and without any monthly depts for the use of electricity. Also, it decreases the public electrical peak load through the day.

Conclusion

The overall system efficiency can be defined as the combination of the coefficient of performance (COP) for refrigeration cycle with solar panel efficiency. The COP of the first refrigeration cycle was low, therefore an improved was made in the second refrigeration cycle by introducing a heat exchanger between the section line and expansion valve. Inspite of the lower photovoltic panel efficiency, it was found that the used of solar power to drive the refrigration cycle had many advantage.

Nomenclature

A	Area (m^2)
COP	Coefficient Of Performance
h	Enthalpy (KJ)
I	Current (A)
I_p	Solar radiation perpendicular to collector surface (W/m^2)
I_r	reference Solar radiation equal 1000 (W/m^2)
P	Pressure
PV	Photovoltaic Panel
Q	Heat energy (W)
V	Voltage (V)
W	Work (W)

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