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Thermodynamic and economic analysis of solar photovoltaic operated vapour compressor refrigeration system

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ABSTRACT : A large number of people in developing countries still live in rural and remote area like India where the grid electricity is yet unavailable or not envisaged by the people. Vaccine preservation has become an important issue and the basic needs in rural areas. Solar power refrigeration is the one of promising option to resolve such burning problem. This paper describes the thermodynamic and economic results of developed solar photovoltaic panels operated 20 litre refrigerator system. No load and full load test were carried out to study the performance of the system. The co-efficient of performance (COP) was observed to decrease with time from morning to afternoon and average COP 3.39 and 3.29 was observed for no load and full load condition, respectively. The exergetic efficiency of both photovoltaic and refrigerator systems were also evaluated for both no load and full load conditions. The overall system energy efficiency was found low because of energy conversion efficiency and exergy efficiency of the photovoltaic system was low. The payback period of the SPV refrigerator was found approximate 6 months.

KEY WORDS : Vapour compression refrigerator, Photovoltaic, Battery bank, UPS, COP, Exergy, Payback period

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In the current situation the energy demand is increasing with increasing in the population and improvement in the living standard. Energy is the crucial input to the social, economical, industrial and technological development of any country. A rational use of energy brings both economic and environmental benefits, by reducing consumption of fossil fuels, electricity and pollutant emissions. The International Institute of Refrigeration in Paris (IIF/IIR) has estimated that approximately 15 per cent of all the electricity produced in the whole world is employed for refrigeration and air-conditioning processes (Abdulateef *et al.*, 2009). In a tropical country, like India, refrigeration is most widely used and generally the most energy consuming process (Modi *et al.*, 2010). In general, refrigeration is defined as any process of heat removal from a place for preserving foods and medicines by enhancing their shelf life (Rathor and Panwar, 2010). Immunization prevents illness, disability and death from vaccine preventable diseases including diphtheria, measles, pertussis, pneumonia, polio, rotavirus diarrhoea, rubella and tetanus. Immunization currently averts an estimated 2 to 3 million deaths every year but an estimated 22 million people from remote area of developing country worldwide are still missing out their routine vaccination programs due to the lack in availability of the safe vaccine (WHO, 2013). According to WHO guidelines, vaccine should be kept in the temperature range of 0-8^0 C.

For the storage of life saving drugs or vaccines in the innumerable area of the developing country where the power supply is still irregular renewable has to be a central part of energy solution. Out of the various renewable sources of energy, solar energy proves to the best candidate for cooling because of the coincidence of the maximum cooling load with the period of greatest solar radiation input (Syed *et al.*, 2012). Cooling from solar energy has great potential for lower running costs, greater reliability and a longer working life than other conventional cooling systems where as it may also contribute in the reduction of global warming. Hwang *et al.* (2011), Kim and Infante (2007) broadly classified different technologies that are available to use solar energy for refrigeration. The review covers solar electric cooling, solar thermal cooling and solar combined power cooling. A comparison between these different technologies is also described with individual COP value. Salah (2006) briefly discussed on application of solar power for producing refrigeration effect. Possible solar power refrigeration system as discussed by him are- absorption cycle, adsorption cycle, desiccant cycle, ejector cycle, solar mechanical and solar PV operated refrigeration system. From the review, it was evident that solar refrigeration system depends on major two principles- thermodynamic and photovoltaic. Cooling system based on solar thermal technologies are having less thermodynamic efficiency as compared to vapour compression refrigeration system (NASA, 2009) because it is very difficult to keep the solar thermal system operating at steady state condition throughout the day. Solar thermal based cooling systems are commercially available but mostly having capacity of more than 20TR (Technical Bulletin CSIR, 2011) because solar collector can't scale down in size. Further the small capacity of cooling system, solar photovoltaic vapour compression refrigeration system is deemed to be most viable route.

Therefore, an attempt has been made to design and development of solar vapour compression refrigeration system at the Department of Renewable Energy Engineering, Udaipur. The principle objective of this paper was to describe the result of thermodynamic test conducted on the developed solar vapour compression refrigeration system.

METHODOLOGY

The present study was carried out at performance of the refrigeration system by Deparment of Renewable Energy Engineering, Udaipur.

Refrigerant :

Refrigerant is a heat carrying agent that absorbs heat from another body or substance during the refrigeration cycle (Khurmi and Gupta, 2011). It is known fact that the refrigerants are to be phase out material. Resulting from the ozone depletion potentials of these working fluids and the consequences effects of the phasing out of these fluids, researchers are focused on identifying alternative working fluids. In the areas of certain refrigeration needs 1,1,1,2-tetrafluoroethane (R-134a) has been considered as a possible alternate to the use of dichloro-difluoromethane (R-12), the most commonly used refrigerant. R-12 is estimated to have a higher potential for ozone depletion20. Researchers have also shown their keen interest of using R-134a refrigerant as compared to other refrigerants. Bolaji *et al.* (2011) proposed an experiment on three ozone-friendly Hydrofluorocarbon (HFC) refrigerants (R32, R134a and R152a) in a vapour compression refrigeration system and their performance were compared. The results showed that R32 yielded undesirable characteristics, such as high pressure and low Co-efficient of Performance (COP) as compare to R152a and R134a. Dalkilic and Wongwises (2010) studied on a traditional vapour-compression refrigeration system with refrigerant mixtures based on HFC134a, HFC152a, HFC32, HC290, HC1270, HC600, and HC600a. The performance was done with various ratios and their results were compared with CFC12, CFC22, and HFC134a as possible alternative replacements. Their results showed that all of the alternative refrigerants investigated in the analysis have a slightly lower performance co-efficient (COP) than CFC12, CFC22, and HFC134a for the condensation temperature of 50 °C and evaporating temperatures ranging between - 30 °C and 10 °C. Therefore, R-134a was selected as a refrigerant to operate the system.

System description :

The solar photovoltaic based refrigeration system was designed, developed and evaluated by Department of Renewable Energy Engineering, Udaipur (27° 42' N, 75° 33'E) under no load and full load conditions. A PV panel consisting of three modules (125 Watt peak each) connected in series was used to obtain the desired voltage and current, respectively. Three 12 V, 7 Ah sealed lead acid battery was used to supply the power at starting time and ensure for the smooth operation. The refrigerator operates on an alternative current based compressor (Make: Godrej) unlike the ac compressor used in the common domestic refrigerators.

Technical specifications of the solar refrigerator and balance of system (BOS) for the power supply are given in Table A and B. For evaluating the thermal performance, pressures were measured at inlet and outlet of the refrigerant at compressor. Simultaneously temperatures were also measured at several locations, these are; compressor body, inlet and outlet pipe surface of the refrigerant at compressor and condenser, ambient condition, cooling chamber and outer side of front opening door (Thomachan and Srinivasan, 1999). The digital thermometer of make M/s. HYtech Instruments

Table A : Technical specification of solar refrigerator

Sr. No.	Parameters	Specification
1.	Storage capacity	20 litres
2.	Door	Front opening
3.	Type of refrigeration	Vapour compression refrigeration system
4.	Compressor	
	Make	Godrej 90
	Power consumption	90W
	Refrigerant	R134a
	Operating voltage	230V AC
5.	Maximum and Minimum internal temperature	-4°C to 4°C
6.	Thermostat	3 setting
7.	Cut in temperature	9 °C
8.	Cut out temperature	2 °C
9.	Insulation	PUF, 2.5 cm thick
	Dimension	37×19×20 cm
	Weight	21.2 kg

was used to measure the temperature at various points in refrigerator. The range of instrument was from -50 to + 300^{0}C.

Table B : Technical specification of the components for the power supply

Sr. No.	Parameters	Specification
1.	Number of panels	3
2.	Make	REIL, Jaipur
3.	Max. power output	125Wp
4.	Size of the array (L×B)	1.67×3 meter
5.	Battery bank	
	Make	Rocket ES7-12
	No. of battery	3
	Rated voltage	12V DC
	Rating	7Ah
	Type of the battery	Sealed lead acid
6.	Inverter cum charge controller	
	Make	Radetron UPS
	Rated capacity	1KVA
	Input voltage	36V

System performance :

Co-efficient of performance :

The co-efficient of performance is an index of performance of a thermodynamic cycle or a refrigeration system. COP is used instead of thermal efficiency. For the vapour compression refrigeration cycle, COP is defined as the amount of cooling produced per unit work supplied on the refrigerant. For a reversible or Carnot refrigeration cycle it is expressed as (Thomachan and Srinivasan, 1999).

$$COP_{carnot} = \frac{T_e}{T_o - T_e} \qquad .....(1)$$

T_e = Evaporator temperature (^{0}C)

T_o = Ambient/room temperature (^{0}C).

But all the real processes are irreversible process. The actual COP of the refrigeration system was calculated with the help of pressure enthalpy curve produced by Hansen and Artu (Rathore and Panwar, 2010). The COP can be evaluated by using the formula :

$$C.O.P. = \frac{\text{Refrigeration effect}}{\text{Input compressor work}}$$

$$C.O.P. = \frac{h_1 - h_4}{h_2 - h_1} \qquad .....(2)$$

h_1, h_2, h_3 and h_4 are the enthalpies value at point 1, 2, 3 and 4, respectively in kJ/kg (Fig. A).

Several researches in this field have been done and a lot more is still undergoing. For instance, Axaopoulos and Theodoridis (2009), designed a solar photovoltaic powered ice-maker of 175 litre in volume which operates without the use of batteries. Four hermetic type reciprocating DC

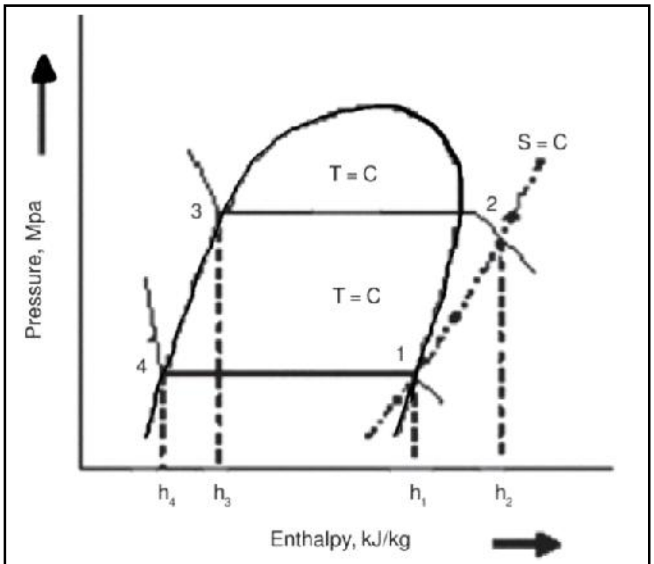

Fig. A : Pressure enthalpy diagram of operating system

compressors (Danfoss BD35F-Solar) were used which were connected to a photovoltaic array of 440 Wp, through a controller. The system was capable to start at the solar radiation of 150W/m^2. The solar to compressor power efficiency as measured was 9.2 per cent.

Modi *et al.* (2010) powered a 165 litre domestic electric refrigerator by 140Wp solar photovoltaic array. The system also includes a six terminal charge controller, a transformer based inverter and two 12V-135Ah lead acid battery. The co-efficient of performance (COP) was observed to decrease with time from morning to afternoon and a maximum COP of 2.102 was observed at 7 AM. RET screen 4 was used for simulating the economic feasibility of the system for the climatic condition of Jaipur city.

Rathor and Panwar (2010), studied on the performance evaluation of 80 litre 'SPRERI-TECH' solar PV refrigeration (developed by SPRERI, Gujrat) at C.T.A.E., Udaipur. The system was tested at no-load and full-load conditions. The COP of the system was calculated as 3.0, 2.6 and 2.0 when thermostats are set at positions 2, 4 and 6, respectively during no load conditions whereas 1.8, 1.6 and 1.2 was calculated when five litre of water was placed in the chamber and thermostats were set at positions 2, 4 and 6, respectively.

Mehmet (2011) designed and developed a PV powered multi-purpose refrigeration system at Harran University. The performance of the developed system was evaluated on daily and seasonal basis. The developed refrigerator system was connected with 80Wp solar array, a charge controller and two unit of 12V- 100Ah battery bank. The PV system was found 12-14 per cent efficient. Loads put into the refrigerators are 5, 10 and 15L, respectively. The highest amount of energy consumption was found to be 75W for 15L load. On seasonal basis experiment, it was found that the system consumes average energy of 347Wh/day.

Photovoltaic efficiency :

The efficiency of the solar panels, defined as the ratio of the electrical power produced to the incident radiation.

$$\eta_{pv} = \frac{P_{max}}{S \times A_{pv}} \quad .....(3)$$

where

η_{pv} = efficiency of photovoltaic system

P_{max}: Maximum power from photovoltaic system (W)

S = Solar irradiance (W/m^2)

A_{pv} = Area of the photovoltaic system (m^2).

Exergy analysis :

Exergy is defined as the maximum amount of work that can be done by a system. Unlike energy, exergy is not subject to a conservation law; exergy is consumed or destroyed, due to the irreversibility's present in every real process.

Hepbasli (2006) comprehensively studied on the exergetic aspects of renewable energy resources (RERs) *i.e.* solar, wind, geothermal and biomass based gadgets. This paper describes about the exergy analysis which is a very useful tool. It can be successfully used in the performance evaluation of RERs as well as all energy-related systems. Based on the review results of the RERs, the exergy efficiency values of PV system were found to be 11.2per cent. by the use of exergy tool, investigator can knowledge about how effective and efficient a country uses its RESs. Kumar *et al.* (2003) studied and observed as the exergetic method of analysis was a useful tool in explaining the various energy flows in a process.

Yumrutas *et al*. (2002) studied on the exergy analysis for the investigation of the effects of the evaporating and condensing temperatures on the pressure losses, the exergy losses, the second law of efficiency, and the co-efficient of performance (COP) of a vapour compression refrigeration cycle. It was found that the evaporating and condensing temperatures had strong effects on the exergy losses in the evaporator and condenser, on the second law of efficiency and COP of the cycle but little effects on the exergy losses in the compressor and the expansion valve. The second law efficiency and the COP increases, and the total exergy loss decreases with decreasing temperature difference between the evaporator and refrigerated space and between the condenser and outside air.

Hernandez *et al*. (2003) carried out the thermodynamic behaviour of a hybrid compressor and ejector refrigeration system with the help of two selected refrigerant as 142b (HCFC142b) and R134a (HFC134a). The ideal efficiency, the enthalpy-based co-efficient of performance, the exergy efficiency and the supplied energy ratio were obtained. With this information, at a moderate condenser and generator temperature of 30 and 85^{0}C, respectively, the developed cooling system working with R134a had the best operation with a highest co-efficient of performance of 0.48 and an exergy efficiency of 0.25.

Ekren and Yilanci (2011), fabricated a 50 litre PV powered R134a refrigerant based refrigeration system with 76 watt DC operated hermetic compressor. 80W_p photovoltaic array were connected to 80 Wh lead acid battery to power the cooling system. According to energy analysis the highest COP 0.67 was observed at no load condition where as the highest exergetic COP was 0.068 observed at low load conditions.

Reddy *et al.* (2011), investigated a study on the exergetic analysis of a vapour compression refrigeration system with selected refrigerants. The various parameters were computed such as COP and exergetic efficiency of the system, effects of degree of condenser temperature, evaporator temperature and sub-cooling of condenser outlet, supper-heating of evaporator out let and effectiveness of vapour liquid heat exchanger. It was found that R134a had the better performance in all respect, whereas R407C refrigerant had poor performance.

Photovoltaic exergy :

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 :

$$Ex_{out} = V_m I_m - \left[1 - \frac{T_0}{T_{cell}}\right] h_c \times A_{pv} \, (T_{cell} - T_0) \quad .....(4)$$

where V_m, I_m h_c , A ,T_{cell} and T_o are the maximum voltage and current of the photovoltaic system, convective heat transfer co-efficient from the photovoltaic cell to ambient, area of the photovoltaic surface, cell temperature and ambient temperature (dead state temperature), respectively.

The convective heat transfer co-efficient from the photovoltaic cell to ambient can be calculated by using correlation :

$$h_c = 5.7 + 3.8 \times v \quad .....(5)$$

where,

v = wind velocity (m).

The module or cell temperature is used to predict the energy production of the photovoltaic module. Cell temperature is a function of ambient temperature, wind speed and total irradiance. The cell temperature can be determined by the following relationship :

$$T_{cell} = 0.943T_a + 0.028\ \text{Irradiance} - 1.528\ \text{Windspeed} + 4.3 \quad ...(6)$$

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

$$Ex_{in} = Ex_{solar} = A_{pv} \cdot S \cdot \left[1 - \frac{4}{3}\left(\frac{T_O}{T_{SUN}}\right) + \frac{1}{3}\left(\frac{T_O}{T_{SUN}}\right)^4\right] \quad ...(7)$$

where, T_{SUN} = temperature of the sun taken as 5760 K.

Exergy efficiency of the photovoltaic system is defined as the ratio of total output exergy (recovered) to total input exergy (supplied). It can be expressed as :

$$\eta_{PV} = \frac{Ex_{out}}{Ex_{in}} \quad ......(8)$$

Refrigeration exergy :

The exergy analysis is usually aimed to determined the maximum performance of the system and identify the sites of the exergy destruction. The exergy efficiency of the refrigeration system also called the second law efficiency of the refrigeration cycle can be defined as the ratio of the minimum work requirement to the actual work input. The exergetic co-efficient of performance of a refrigeration system is as below :

$$COP_{R\ ex} = \frac{Q_{eva}\left(\frac{T_o}{T_{eva}} - 1\right)}{W_{comp}} \quad ......(9)$$

RESULTS AND DISCUSSION

The results obtained from the present investigation as well as relevant discussion have been summarized under following heads :

No load test :

The no load test was conducted on 5th May 2012. The solar insolation was measured as 7.695 kWh/m^2/d. Short circuit current and open circuit voltages were measured during the off cycle of the refrigerator. At the peak time, maximum the PV array and solar radiation was recorded as 311W and 1141W/m^2, respectively power output from. The short circuit current produced by PV array was found linearly function of solar intensity. Open circuit voltage was found maximum in morning and low during the peak time due to increased in cell temperature. As the cell temperature increases, the carrier recombination in the cell will also increase. It is suggested that voltage of the module is a logarithmic function of the solar intensity Solanki (2009).

Starting current went up to as high as 1.1A; this is because the compressor overcame the suction to discharge pressure differential at start where as the running current was stood at 0.77A. In the present case the refrigeration cut-in point was set at 9^{0}C and the cut-out point of the refrigeration system was set at 2^{0}C. Initial cool down of the cabinet box of the refrigerator occurs in about 40 min from ambient temperature of 30^{0}C to cut out temperature at 2^{0}C (Fig. 1). The on-off cycle was about 1:1 during the test period. Voltage across the battery terminal was measured in ON-OFF cycle of the refrigerator. During ON cycles, voltage went down because compressor consumes power slightly from the battery bank while in OFF cycles, voltage across the battery terminal was increased which means the PV array charge the battery bank. The compressor body temperature is an important parameter towards knowing the performance characteristics of the refrigerator because the higher it is, lesser will be refrigeration effect. During the ON cycles, the compressor body temperature reaches upto 48^{0}C and after that remains in steady state condition which shows a part of heat is continuously leaked from ambient. During the OFF cycle, the compressor body temperature gets cool down to ambient. During the ON cycle, temperature at the outside of the front door found lower than the ambient temperature which tell us about the improper insulation at door. During the first temperature pull down period, the rate of temperature falling was observed high at initial position and after reaching 10^0 C the falling rate decreases and takes time to reach at cut-out point. The warm up test was done in which the temperature inside the refrigerator was observed to stabilize to a common values nearing the ambient. The refrigerator temperature rose from 2^0 C to 28^{0}C within one and half hour which suggest that either the insulation or ambient operating condition needs to be improved.

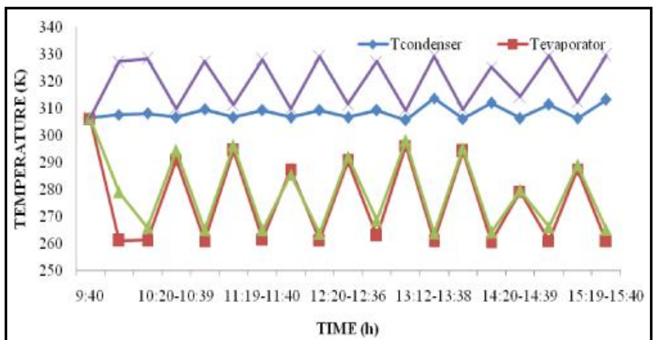

Fig. 1 : Cool down and warm characteristics of the refrigerator

The performance of the photovoltaic system was evaluated in terms of photovoltaic energy and exergy efficiencies. The energy efficiency is relatively higher during the early and late hours of the day as compared to midday as a result of thermal effects. It was found that, the conversion efficiency is inversely proportional to the module temperature. The average efficiency of the photovoltaic system was observed 10.19 per cent. The shape of the exergy-in curve follows that of the irradiance, and the greater the value of the irradiance, the greater the difference between the two which illustrates solar radiation's great capacity for useful work (exergy) due to the high temperature of the sun (Fig. 2). The exergy efficiency of the PV array stays at around 8.50 per cent throughout the day, far from the 100per cent that would correspond to the ideal or reversible process. Increasing PV array temperature determines the sensible decrease of this efficiency from 10.6 per cent to 7.36 per cent. In order to have maximum exergy efficiency, PV array temperature should be kept near the ambient temperature or in other words, PV array temperature should be controlled. In order to control PV array temperature, there are some practical methods such as spraying water on the top surface of photovoltaic modules or combining of PV modules in photovoltaic/thermal (PV/T) collectors etc.

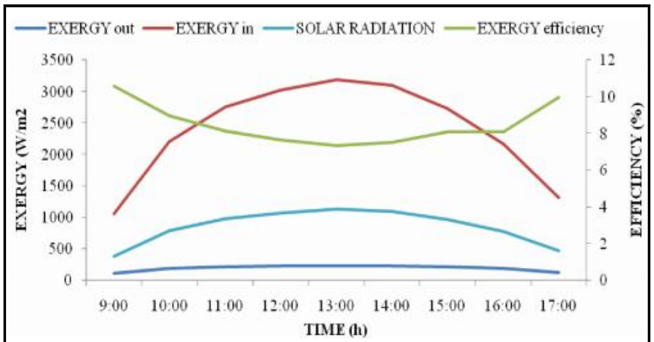

Fig. 2 : Variation of solar photovoltaic exergy efficiency with time and solar intensity

The energy consumption of a refrigeration system is determined by the refrigeration capacity and the difference between the condensation and evaporation temperatures. The maximum energy consumption was recorded at the start time and noon hours, while minimum energy consumption by the load was recorded at evening hours. The average daily overall energy consumption of the cooling system during no load condition was 0.405 kWh/d.

The COP of the refrigeration cycle is also shown in the Fig. 3, it shows that the compressor of the refrigeration system was tripped 8 times during the no load condition. This indicates the better performance of the whole system. The maximum pull down time 40 minutes were observed during the test and that time the COP of the system was 3.41 observed. The energy consumed during this period was 0.07 kWh. As the noon approaches the COP of the system decreases, it may be due to the high temperature difference between the condenser coil and the evaporator coil. The value of the COP again rises as passing the noon. The zero value of the COP denotes the cutoff the compressor which means the refrigeration effect and work input both were zero during the period. At that time COP cannot be defined hence, represented by zero in the plot. The Carnot COP of the system is varying from 6 to 6.52. The actual COP of the refrigerator system which was calculated from experimental value with pressure enthalpy chart and it stays in between 3.13 to 3.58.

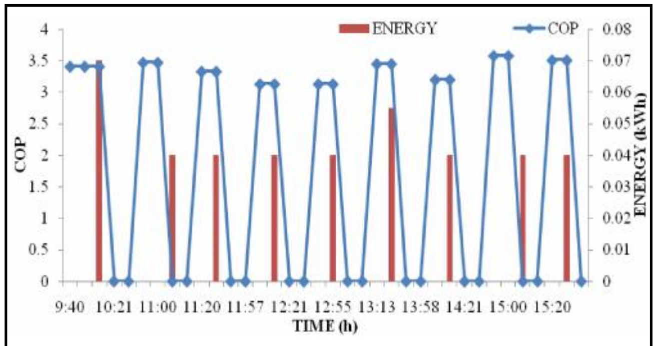

Fig. 3 : Variation of energy consumption and COP with time

The second law efficiency or the exergy efficiency of the refrigerator system remains close to the 50 per cent. It was analyzed that the second law efficiency increases with the increasing the evaporative temperature and decreasing the condensing temperature. It was found that evaporating and condensing temperatures have strong effects on the second law efficiency and COP of the cycle. It was found that the second law efficiency and the COP increases with decreasing in temperature difference between the evaporator and refrigerated space and between the condenser and outside air.

The overall energy of the SPV refrigerator was evaluated by multiply both avg. COP and PV efficiency and it is around 34.33per cent which are found very low because the photovoltaic energy efficiency are low.

Full load test :

In the present model at a time we can place 100 nos. of 10ml vaccine for preservation. So the 1kg water which is the cumulative weight of 100 doses; was selected for the full load test having properties similar to the vaccine.

AC current is continuously consumed by the compressor for the first four hours which means there was no tripping and the compressor worked continuously for first four hours. The voltage was continuously dropped at the battery terminals during first on-cycle. The voltage of battery increases only during the off-cycle. Deep discharge condition was not found during the first on-cycle which means the photovoltaic system continuously charge the battery as well as power the compressor during the on cycle. The temperatures of evaporator and suction line observed to fall when the compressor is running and rises during the cutoff period where as the temperature of condenser and discharge line rise during the on-cycle. It is clear that the initial cool down of the cabinet box of the refrigerator occurs in about 4h and 8 minutes. Form the Fig. 4, it can be easily observed that the on-off cycle was observed about 1:1 during the test period which means refrigerator operates well in condition. The compressor body was continuously leaking the heat from compressor. Heat leakage was not found from front door as the insulation was improved after the no load test. The water temperature was continuously losses its temperature which means heat is continuously rejecting from the water. It was also analyzed that the thermostat cut-in and cut-out happens according to the air temperature in the cabinet box.

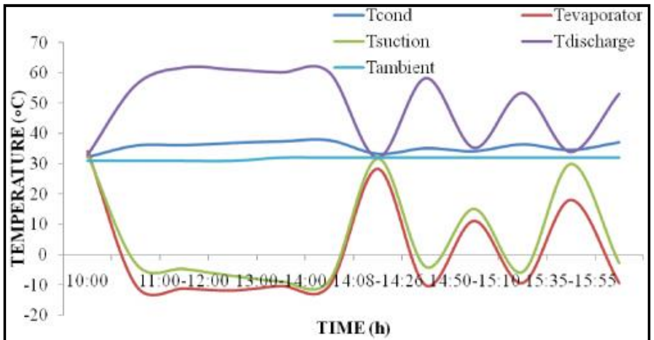

Fig. 4 : Cool down and warm characteristics of the refrigerator

After completion of full load test the warm up test was conducted. The air and water temperatures inside the cabinet box were recorded. In fact the refrigerator temperature remains below the preservation point for one and half hour. The test was conducted for 3h and the water temperature reached up to 14.5^{0}C which means insulation thickness and room condition both were well for the vaccine storage.

The photovoltaic energy and exergy efficiency were evaluated with time, solar radiation and cell temperature (Fig. 5). The energy and exergy efficiencies were found high as 10.53 per cent and 9.48 per cent, respectively in early morning because the cell temperature is near to the ambient temperature. The avg. energy and exergy efficiencies were found low as 9.71 per cent and 8.56 per cent, respectively.

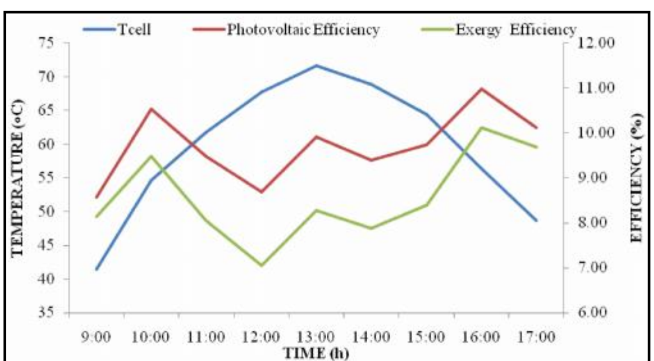

Fig. 5 : Energy and exergy efficiency with time and cell temperature

The COP of the refrigeration system analyzed with the help of p-h chart and it was found that the maximum COP was found when the solar radiation low. The maximum COP was found in the evening time which is due to the better room condition and less difference in between condenser and room temperature. The COP of the first on-cycle was started from 3.2 and decreasing continuously to 2.75. The average COP of the system test day was found 3.37.

The exergy co-efficient or the exergy efficiency of the refrigerator remains close to the 55per cent. The exergy efficiency was affected by the ambient condition and it found minimum in the noon time. The overall system energetic efficiency and exergetic efficiency were evaluated 29.96per cent. The overall energetic efficiency of the system is very low since energy conversion efficiency (about 9.71%) of the PV is low. It is also clearly seen from exergy values that; exergy is destroyed highly in the PVs.

Techno- economics of solar refrigerator :

The hospital authorities informed that while keeping the vaccine and medicine such as Tetanus, Toxoid, Diphtheria, Bacillus, Measles, polio etc. in conventional refrigerator 50 per cent of these damages due to non-availability of electricity for 5-6 hours in a day. The cost of damaged medicine reported by hospital authorities was around Rs. 7000/- per litre vaccine per month. The cost economics of solar refrigerator has been calculated on the basis of cost of vaccine and medicine saved per month. The calculation of the payback period is shown in Table 1. Payback period of the SPV refrigerator was calculated as 6 month which means the SPV refrigerator is economically viable to use at hospital in remote and rural areas of developing countries.

Table 1 : Payback period calculation

Initial investment (cost of complete solar refrigeration system)	Rs. 40,250
Average maintenance cost	Rs. 200 per month
Conventional energy saved during 6h operation	Rs. 150/- per month
Total cost of vaccines which are being saved by use of SPV refrigerator	Rs. 7000 per month
Total savings (7000+150-200)	Rs. 6950/- per month
Payback period of refrigerator	5.7month

Conclusion :

This study indicates the necessity and usefulness of energetic and exergetic techniques to evaluate the performance of the SPV refrigerator with a view to get better information about useful work and lost work and design some remedial techniques in future to overcome on these losses. The installed system of solar photovoltaic refrigerator system is capable for cooling the vaccine for 7 hour in a day. The pull down test indicates that 375Wp photovoltaic capacity and 21Ah battery bank is the least possible configuration required for this converted system. The average COP during no load and full load tests were found high as 3.37. Second law efficiency of the refrigerator system remains close to 55 per cent at no load and full load conditions. The photovoltaic conversion efficiency and exergy efficiency was found nearer to 10 per cent and 8.5 per cent, respectively in both no load and full load condition. This indicates that the product load condition does not affect the PV system. The reason for low of overall efficiencies is due to both the energy conversion efficiency and exergy efficiency of the PV system is low so that it can be said that exergy are destroyed highly in PV. The payback period of the proposed system was found 6 months. It is suggested that the design procedure may be improved by a variable speed compressor to cope with the variation of the refrigeration load due to different modes of operation.

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