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Design and Simulation of Solar Powered Vapour Compression Refrigeration System

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***Abstract*--- Due to the growing concern and awareness of environmental issues among the scientific community, power generation from renewable energy sources, particularly solar energy has become significantly important for the last few decades. Solar energy is abundantly available in India hence, it has a high potential to use as an alternative to non-renewable energy sources.Refrigerated storage, which is believed to be best method for storing the fruits and vegetablesin fresh form, is not available in rural or remote locations where grid electricity is almost not available.So, without having a conventional energy source at these areas, the present study was taken upto design and fabricate Solar powered VCR system.In this system electrical energy has been replaced with solar energy which will reduce the consumption of high grade electrical energy. It consists of solar panel, Lead-acid battery, inverter, charge controller and VCR system. We have selected all the solar components by calculating its capacities as per the capacity of compressor used for VCR system. VCR calculations have been done using *Coolpack* software which is an user friendly software.VCR system is simulated using *Aspen Hysys v11* software and the desired results were obtained. Solar PV panel system is simulated using *Matlab/Simulink* software from which current and power curves were obtained for different values of irradiance at a constant temperature.**

***Index Terms*— VCR, Solar PV system, Simulink, Aspen Hysys v11**

I. INTRODUCTION

This introductory chapter presents the Objectives, Scope and Methodology of the project. Our goal is to develop a Vapour compression refrigeration system which works on electricity provided from Solar energy.

II. OBJECTIVES

In this project, we will concentrate only on designing a refrigeration system that uses solar energy as its main source of power. The design will also see the implementation of a simulation so as to help us in determining the viability of the project. Solar powered refrigeration system has been a subject that has received a lot of publicity in the recent past. Several governments have put in place mechanisms of controlling harmful emissions to the environment and also devise ways of controlling the amount of energy consumed. Designing a system that relies on entirely solar energy will help in achieving some of the goals for the developing countries of having a clean source of energy and also reduce their reliance on fossil fuels and national electricity grid. Following are the objectives of our project:

- To learn and understand Vapour Compression refrigeration system.
- To learn and understand Solar power generation and its components.
- Design of Vapour compression refrigeration system.
- Design of Off-Grid Solar system.
- Simulation of VCR and Solar PV system.

III. SCOPE

On average nearly 300 days a year in India are sunny, with about 1,500–2,000 sunshine hours per year depending upon location. The daily average solar energy incident over India varies between 4 to 7 kWh/m2. This provides huge potential for projects that use solar energy to be implemented. Although there has been considerable progress in this field, a lot of scope remains to rework and improve existing ways of utilizing solar energy in a viable manner. At the same time, there is also room for creation of new ways to efficiently engage with solar power. The components of the system included solar panels, a maximum power point battery bank, vapour compression refrigeration system. Each component was sized and configured appropriately in order to optimise the performance of the system.

IV. METHODOLOGY

Our system is a solar powered VCR system. We have used electricity generated using photovoltaic energy i.e. solar energy. The project has been carried in the following

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pattern:

- Designing of Vapour compression refrigeration system (mini refrigerator) using Coolpack software.
- Designing of off-grid solar system to run the mini refrigerator.
- Cost estimation of the components for VCR system and off-grid solar system.
- Simulation of VCR system in Aspen Hysys v11 software.
- Simulation of Solar PV system using Matlab/Simulink software.

V. PROBLEM STATEMENT

Design and Simulation of a Solar Powered Vapour Compression refrigeration System. Given data:

- Evaporating Temperature = 7.4°C
- Condensing Temperature = 54°C
- Degree of Superheat = 5°C
- Degree of Subcooling = 7°C
- Pressure drop in Suction line = 0.80 bar
- Pressure drop in Discharge line = 3.10 bar

VI. DESIGN CALCULATIONS

- **Vapour compression refrigeration cycle calculations:**

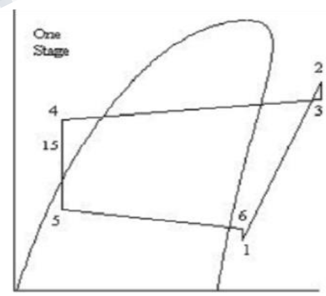
We have performed VCR system calculations using Coolpack software. Following are the steps performed on Coolpack to get the results:

- Step 1: Open Coolpack and click on Refrigeration Utilities.
- Step 2: Click on the P-h cycle icon.
- Step 3: An option will occur for selecting refrigerant.
- Step 4: Click on Options menu and then select Input Cycle.
- Step 5: Put the parameters in the dialog box which appears after selecting Input Cycle.
- Step 6: Click on Update button and then click on Show info which gives the results.

Following are the results obtained after following the above process:

```
Refrigerant: R134a
Data:
Te [°C]                   =     7.40
Tc [°C]                   =    54.00
DT subcooling [K]         =    47.00
DT superheat [K]          =    -2.40
Dp condenser [Bar]        =     0.00
Dp liquid line [Bar]      =     0.00
Dp evaporator [Bar]       =     0.00
Dp suction line [Bar]     =     0.80
Dp discharge line [Bar]   =     3.10
Isentropic efficiency     =     1.00
------------------------------------------------
Calculated:
Qe [kJ/kg]                =   189.766
Qc [kJ/kg]                =   226.660
W [kJ/kg]                 =    36.894
COP [-]                   =     5.14
Pressure ratio [-]        =     5.889
------------------------------------------------
Dimensioning:
Qe [kW]                   =     0.772
Qc [kW]                   =     0.922
m [kg/s]                  =     0.00406575
V [m^3/h]                 =     0.9948
Volumetric efficiency     =     0.85
Displacement [m^3/h]      =     1.1704
W [kW]                    =     0.150
Q loss [kW]               =     0.000
```

Fig. 1: Screenshot of VCR system results 1



Point	T [°C]	P [bar]	v [m^3/kg]	h [kJ/kg]	s [kJ/(kg K)]
1	2.334	2.997	0.067964	399.132	1.7273
2	68.783	17.652	0.011511	436.026	1.7273
3	63.351	14.552	0.014539	436.026	1.7391
4	7.000	14.552	N/A	209.366	N/A
5	N/A	3.797	N/A	209.366	N/A
6	5.000	3.797	0.052808	399.132	1.7100
15	N/A	14.552	N/A	209.366	N/A

Fig. 2: Screenshot of VCR system results 2

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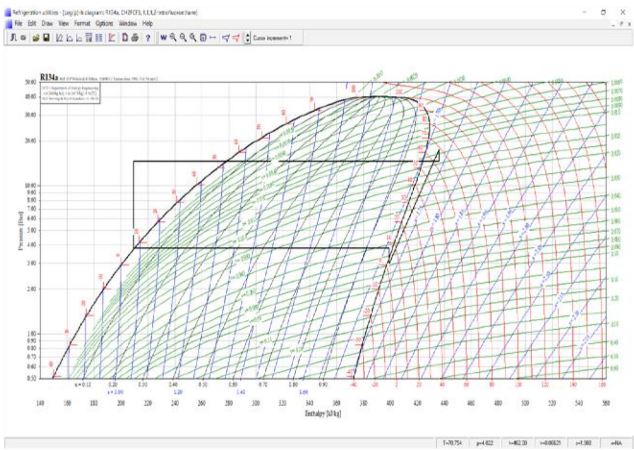

Fig. 3: Screenshot of VCR system P-h diagram

From the above calculations we had selected VCR components.

1. Selection of Compressor:

Fig. 4: Hermetically selaed compressor

From calculations we have selected 1/5 HP hermetically sealed D.C. compressor.

2. Selection of Condenser:

Fig. 5: Natural convection Air cooled condenser

In Natural convection Air cooled condensers heat transfer is by buoyancy effect hence they are suitable for small refrigerators. Therefore, we have selected Natural convection Air cooled condenser.

3. Selection of Expansion valve:

Fig. 6: Capillary tube

Considering low capacity refrigeration and economical aspect we have selected capillary tube made of copper as expansion device for our refrigeration system. From standard charts we got length of capillary tube as 1500 mm and inside diameter as 0.7 mm.

4. Selection of Evaporator:

Fig. 7: Roll bond evaporator

From calculations we have got 0.22 TR cooling capacity of evaporator for which we get 30 litres capacity evaporator compartment. So we have selected roll bond evaporator of length 320 mm and width 300 mm.

➢ **Solar system calculations:**

The following 6 steps are required for building a DIY Off-Grid Solar System:

1. Calculate Daily Energy Consumption
2. Select the Battery
3. Select the Solar Panel
4. Select Charge Controller
5. Select Inverter

1. Calculate Your Daily Energy Consumption:

Energy Consumption (Watt-Hour) = Power (Watts) × Time (Hours) = 151 × 5

Energy Consumption (Watt -Hour) = 755 W-hr

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2. Select the Battery:
The following factors determine the battery bank size:

- Daily power consumption
- System voltage (12V / 24V /48V)
- Depth of Discharge (DOD) - The battery's Depth of Discharge (DOD) is the percentage of the battery capacity that can be safely drained without damaging the battery.

$$\text{Battery Capacity (Ah)} = \frac{\text{Daily Energy Consumption (Watt-Hour)}}{\text{(System Voltage x DOD)}}$$

$$\text{Battery Capacity (Ah)} = \frac{755}{12 \times 0.5} = 125.833 \text{ Ah}$$

Fig. 8: Battery

For Battery ,we have selected 150 Ah Luminuous Battery.

3. Select the Solar Panel:
The sizing of the solar panel used in an off-grid system depends on the following factors:

- Daily energy consumption
- Number of Peak sun hours – The peak sun hours is the number of hours per day during which the average solar irradiance (sunlight) is 1000 watts per square meter (W/m2) or 1 kilowatt per square meter (kW/m2).
- Solar panels efficiency

$$\text{Solar panel Watt} = \frac{\text{Daily Energy Consumption (Watt-Hour)}}{\text{Peak sun Hour} \times \text{System efficiency}}$$

$$\text{Solar panel Watt} = \frac{755}{4.5 \times 0.7} = 239.682 \text{ W}$$

Fig. 9: Solar Panel

For Solar Panel ,we have selected 250 Watt Polycrystalline Solar Panel.

4. Selection of Charge controller:
Voltage rating for charge controller is same as system voltage i.e. 12V

Current rating (A) = $\frac{\text{Solar panel wattage}}{\text{System Voltage}} \times$ Safety factor Current rating (A) = $\frac{239.682}{12} \times 1.3 = 25.965$ A

Fig. 10: Charge controller

For Charge Controller, we have selected 30 Amp MPPT(Maximum Power point Tracker) Charge Controller.

5. Selection of Inverter:

- Continuous Watts = 800 W
- Surge Watts = 1200 W
- Output voltage = 230 V (AC)
- Frequency = 50 Hz

Fig. 11: Inverter

For Inverter, we selected 1100 VA AC to DC Pure Sine Wave Microtek Inverter.

VII. SIMULATIONS

➢ **Vapour Compression Refrigeration Cycle Simulation:**

We have performed Simulation of VCR cycle in Aspen Hysys v11 software. We had selected refrigerant R134a and Property package as Peng Robinson. We had made the VCR cycle model shown in Fig. 12 by taking the components from Model Pallette and inputting the given values.

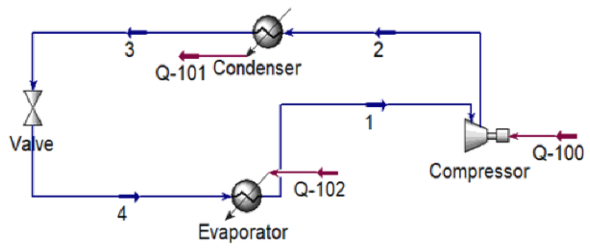

Fig. 12: VCR cycle model in Aspen Hysys v11

Results were obtained after simulation for each component shown in the following tables. The temperature and pressure values at the suction and discharge of the compressor are approximately equal to design calculations and indicates working of actual VCR cycle.

Table 1: VCR cycle simulation results

Material Streams					
		1	2	3	4
Vapour Fraction		1.0000	1.0000	0.0000	0.1601
Temperature	C	7.400	60.22	0.7756	-26.35
Pressure	kPa	80.00	310.0	300.0	100.0
Molar Flow	kgmole/h	0.1643	0.1643	0.1643	0.1643
Mass Flow	kg/h	16.77	16.77	16.77	16.77

Name	Compressor
Compressor Speed [rpm]	
Power [kW]	0.199782
Capacity (act feed vol flow) [ACT_m3/h]	4.70475
Adiabatic Efficiency	75
Polytropic Efficiency	76.595
Compressor Volume [m3]	0
Delta T [C]	52.8188
Delta P [kPa]	230

Name	Valve
Pressure Drop [kPa]	200
Percentage open [%]	50
Friction pressure Drop [kPa]	200
Holdup Temperature [C]	
Pipe k [kg/hr/sqrt(kPa-kg/m3)]	0
Resistance (Cv or K) [USGPM(60F,1psi)]	0.0241884
Cg	0.809498
C1	33.4664
Km	0.9

Name	Evaporator
Duty [kJ/h]	3520.24
Pressure Drop [kPa]	20

Name	Condenser
Duty [kJ/h]	4239.45
Pressure Drop [kPa]	10

Fig. 13: Parameters of each component

- **Solar Photovoltaic Array Simulation:**

We have simulated Solar PV Array in Matlab/Simulink software. Fig.14 shows Simulink model. We have used 1 Soltech 1STH-215-P module for our PV Array. PV Array has 5 parallel strings consisting of 1 series connected module per string. Simulink Model is equivalent to actual Solar PV system. The PV model is validated by simulating at different values of Irradiance and Temperature.

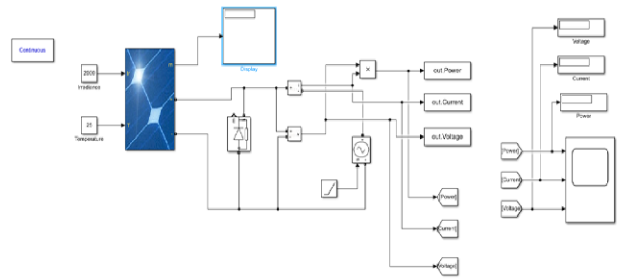

Fig. 14: Solar PV Array Simulink Model

In Fig. 15 are shown the current, voltage and power which are obtained at output of PV Array. These are the curves of current, voltage and power versus time obtained at value of 1600W/m2 Irradiance and 25°C Temperature as constant inputs to Solar PV Array. From the obtained curves we can conclude that current and power increases upto a certain point and then decreases rapidly whereas voltage increases linearly in a Solar PV Array. In order to produce maximum power from our selected Solar PV module it has operated at a voltage of 25V which is seen from the curves.

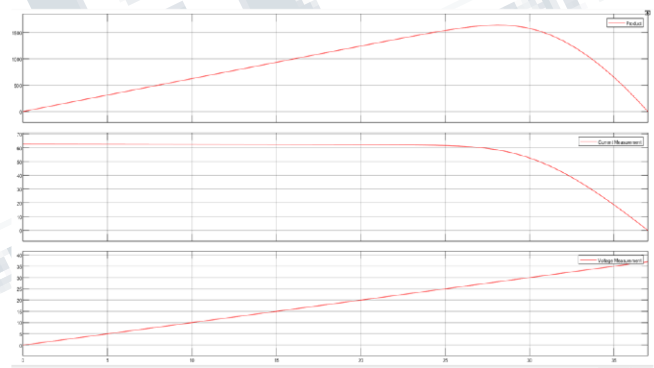

Fig. 15: Power, Current and Voltage curves for PV array

The MPPT (Maximum power point Tracker) points were obtained from following graph shown in Fig. 16

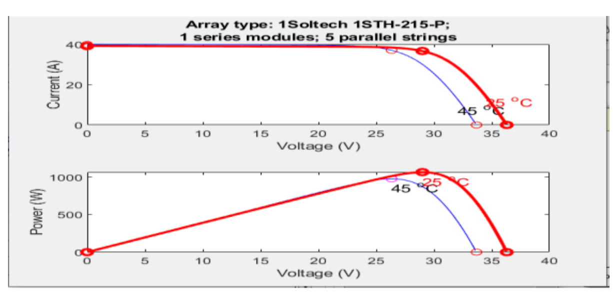

Fig. 16: MPPT point

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Power values were obtained for different values of irradiance from 0 W/m2 to 2000 W/m2 at a constant value of 25°C temperature. These values were inserted in Excel from where a graph of Power vs Irradiance was obtained which is shown in Fig. 17

It can be observed that as Irradiance increases the maximum power output also increases proportionally.

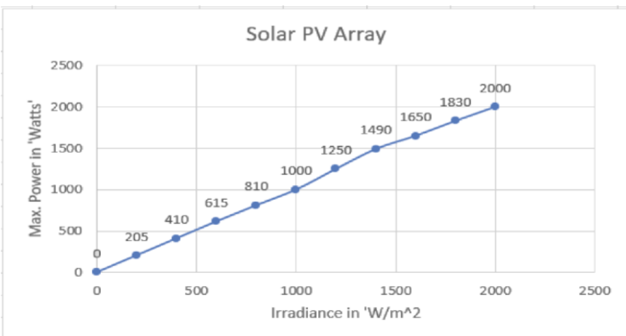

Fig. 17: Graph of Power vs Irradiance

Current vs Time graph for different values of Irradiance at constant temp. of 25°C was also obtained which is shown in Fig. 18. From graphs it is seen that current increases with increase in irradiance on solar PV panel.

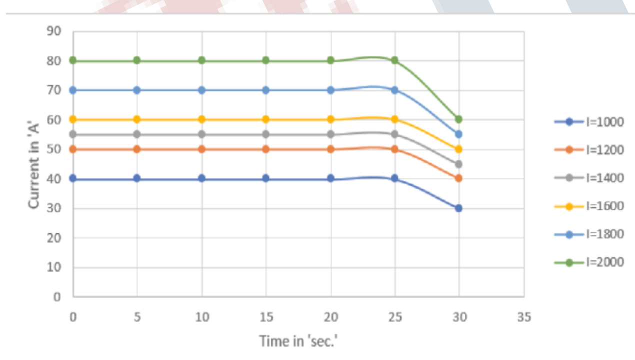

Fig. 18: Current vs Time for Irradiance values

VIII. COST ESTIMATION

➢ **Costing of VCR system:**

Table 2: Costing of VCR system

Sr. No.	Components	No. of Objects	Cost in '₹'
1)	DC Compressor	1	3000
2)	Natural convection Air cooled condenser	1	1000
3)	Roll Bond Evaporator	1	950
4)	Evaporator compartment	1	2000
5)	Capillary tube	1	300
6)	Structure for VCR	1	2000
7)	Copper pipes	4	500
	Total		**9800**

➢ **Costing of Solar PV system:**

Table 3: Costing of Solar PV system

Sr. No.	Components	No. of Objects	Cost in '₹'
1)	Battery	1	11900
2)	Solar Panel	1	9900
3)	Charge controller	1	2000
4)	Inverter	1	5500
5)	Solar cables	2	960
6)	Structure for solar panel	1	3000
7)	Solar connector (MC4)	4	500
	Total		**33760**

IX. ANALYSIS OF ELECTRICITY COST AND CO2 EMISSIONS

➢ **Electricity Cost saving calculations:**

- Daily Energy Consumption of VCR system = 0.75 kWh .
- Electricity rate per unit = ₹ 5.5 .
- Daily rate of running VCR system on Electricity grid = 0.75 x 5.5 = ₹ 4.125 .
- Yearly rate = 4.125 x 30 x 12 = ₹ 1485 .
- Life of Solar PV system is generally 20 years hence, Electricity cost saved for 20 years = 1485 × 20
  = ₹ 29700 .
- From above calculations we can conclude that with the use of Solar PV system a considerable amount of cost can be saved which is spent monthly on Electricity bills.
- Also for a Solar PV system maintenance cost is almost zero.

➢ **CO_2 Emission calculations:**

- Electricity generated from a coal based plant emits approximately 0.98 kg of CO_2/kWh
- Daily electricity consumption of VCR system = 0.75 kWh
- CO_2 emitted per day = 0.75 x 0.98 = 0.735 kg of CO_2
- CO_2 emitted in 20 years i.e. life of Solar PV system
  = 0.735 x 30 x 12 x 20
  = 5292 kg of CO_2
- From Solar PV system CO_2 is not emitted at all.
- Hence, we can avoid huge amount of CO_2 emission with use of Solar PV system.

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X. CONCLUSION

The aim of our project is to develop a Solar PV system which could run a Vapour compression refrigeration system. We were able to design and simulate a Solar PV system which could run a VCR system such that the load is always met.

Firstly a VCR system and Solar PV system was designed by doing the required calculations from the derived formulae.

VCR cycle was simulated in Aspen Hysys v11 software from which results obtained validate design calculation results.

A Matlab/Simulink model of Solar PV Array was developed to simulate its performance in accordance with Irradiance and Temperature. From simulation results it was observed that with increase in Irradiance the current and power output increases. We were also able to determine voltage to get maximum power from Solar PV array at a particular value of Irradiance and Temperature.

Hence, from computer simulation we were able to validate our calculations.

Usage of Electricity generated from Solar PV system saves monthly cost spent on Electricity bills.

Solar PV system helps in nullifying the CO_2 emission in comparison to electricity generated from coal based power plants.

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