Journal of Basic and Applied Engineering Research
Print ISSN: 2350-0077; Online ISSN: 2350-0255; Volume 2, Number 8; April-June, 2015 pp. 671-675

http://www.krishisanskriti.org/jbaer.html

Solar Powered Vapour Compression Refrigeration System for Effective and Sustainable Vaccine Storage without using Battery

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Abstract—*The research paper aims to combat the issues related with improper storage and handling of vaccines. The research focuses on:*
" To design and fabricate a Clean and Environment friendly Solar Powered Refrigeration system which can be used in far flung areas where electricity supply is erratic and to devise a mechanism to maintain optimum temperature for vaccine storage using a phase changing material (CH3COOH + H2O)."
The use of Solar panel in refrigeration system replaces the conventional battery integrated solar refrigeration system. The design proves robust in the days of non-insolation where there is a lack of energy to power the refrigeration systems unlike the battery integrated system. The new system using phase changing material once achieves the temperature of 5 degree centigrade can act as a thermal reservoir and is found to be stable for more than four to six days depending on the non solar hours of the particular area, which hence keeps the vaccines at the stable optimum temperature.

1. INTRODUCTION

Vaccine preventable diseases like polio, measles, and hepatitis are a major cause of morbidity and mortality among children in developing countries. Vaccination is one of the most effective disease prevention strategies when implemented properly across all sections of the at-risk population. Immunization against a disease is achieved only if a potent vaccine in administered.

The system used for keeping and distributing vaccines in good condition is called the "cold chain." Cold Chain is a system of storing and transporting vaccine at the recommended temperature range (2-8°C) from the point of manufacture to point of use. Literature concerning vaccination rates in India indicates a considerable disparity between children in urban compared with rural areas. In addition, 75% of the health infrastructure, medical personnel, and other health resources are concentrated in urban areas of India, whereas only 27% of the population lives in the urban parts of the country. The weak health infrastructure and unsanitary conditions contribute to the increased incidence of diseases like polio, cholera, and hepatitis in rural compared with the urban areas. The rural manifestation of polio in India is confirmed by the number of polio cases reported in prevalence studies and independent reports on polio.

1.1 Simple Vapour Compression Refrigeration System:

The schematic diagram of the arrangement is as shown in Fig. 1. The low temperature, low pressure vapour at state B is compressed by a compressor to high temperature and high pressure vapour at state C. This vapour is condensed into high pressure vapour at state D in the condenser and then passes through the expansion valve. Here, the vapour is throttled down to a low pressure liquid and passed on to an evaporator, where it absorbs heat from the surroundings from the circulating fluid (being refrigerated) and vaporizes into low pressure vapour at B.

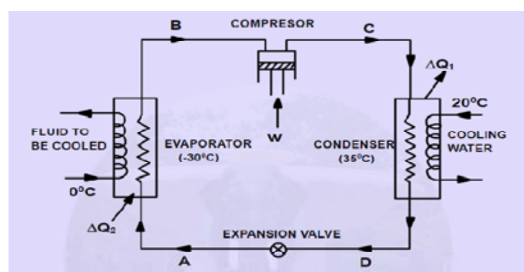

Fig. 1: Simple Vapour Compression System

2. SOLAR POWERED VAPOUR COMPRESSION REFRIGERATION SYSTEM:

A solar powered vapour compression refrigeration system is made pragmatic with thermal storage and new control techniques. In one embodiment, the refrigeration system includes a photovoltaic panel, a variable speed compressor, an insulated enclosure, and a thermal reservoir. The photovoltaic (PV) panel converts sunlight into DC (direct current) electrical power. The DC electrical power drives a compressor that circulates refrigerant through a vapour compression refrigeration loop to extract heat from the insulated enclosure. The thermal reservoir is situated inside the insulated enclosure and includes a phase change material. The conversion of solar power into stored thermal energy is optimized by a compressor control method that effectively maximizes the compressor's usage of available energy. A capacitor is provided to smooth the power voltage and to provide additional current during compressor start-up. A controller monitors the rate of change of the smoothed power voltage to determine if the compressor is operating below or above the available power maximum, and adjusts the compressor speed accordingly. In this manner, the compressor operation is adjusted to convert substantially all available solar power into stored thermal energy. The block diagram of solar refrigeration system is shown in Fig. 2.

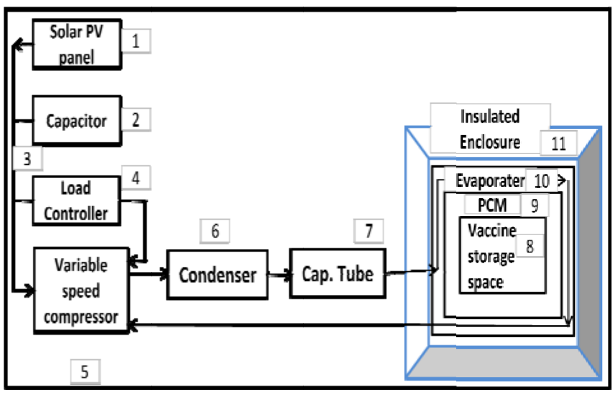

Fig. 2: Block diagram of solar Refrigeration System

2.1 Detailed Description of the Solar Refrigeration System

[1-4]Turning now to the Fig. 2 shows a first embodiment of a solar refrigeration system which includes a solar panel (1) connected to a power bus (3). Although a wide variety of solar panel types and styles may be employed, one suitable example is a 12 volt nominal PV panel that is capable of a peak power output of approximately 120 watts at approximately 15 volts under full solar insolation.

A capacitor (2) is connected to power bus (3) in parallel with solar panel (1). Capacitor (2) operates to provide temporary storage of electrical charge in order to smooth any voltage variations on power bus (3) and to provide extra current during demand periods. The voltage variations may be caused by a variety of sources including changes in light intensity on the solar panel and changes in the electrical load driven by the solar panel (1). The capacitor (2) may be varied in type and size as per requirement.

A variable speed compressor (5) with a load controller (4) is directly coupled to the solar panel (1) by power bus (3). In this context, "directly coupled" is defined to mean that no power converters are provided between the compressor (5) and solar panel (1). This design advantageously exhibits relatively high efficiency due to the direct powering of the compressor (5) by a PV panel. It is noted that systems which use batteries typically force the solar panel to operate below its peak power point to match the battery charging voltage. Powering the compressor directly from the solar panel allows the solar panel to be operated at the maximum power point.

As refrigerant is circulated through the loop, it is compressed by compressor (5), cooled to a liquid state by ambient air in condenser (6), evaporated to a gaseous state in evaporator (10), and recompressed and re-circulated by compressor (5). This circulation results in a net transfer of heat from the evaporator (10) to the condenser (6), thereby cooling the thermal reservoir (9) containing PCM.

A thermal reservoir (9) is preferably provided in the insulated enclosure .Thermal reservoir (11) preferably comprises a phase-change material that has a phase-change temperature at or slightly below the target interior temperature for the insulated enclosure. Particularly desirable phase-change materials are those having a solid-liquid phase change with a high heat of fusion, and which are inexpensive and relatively non-toxic. Water and water solutions are examples of suitable phase change materials. The size and phase change material of the thermal reservoir is preferably chosen to maintain the target interior temperature for several days in the absence of solar power.

In the embodiment of Fig. 2, the thermal reservoir (9) is contemplated as being adjacent to evaporator (10), and/or as being a part of evaporator (10). As refrigerant circulates through the evaporator (10) to cool the interior of the insulated enclosure(8), a direct transfer of heat energy occurs to evaporator (10) from thermal reservoir (9) to cool the thermal reservoir and induce a phase change of the phase-change material.

In operation, the solar panel (1) delivers power to power bus (3) during the day when the sun is shining. The load controller (4) runs the compressor (5) at a speed that maximizes the power extracted from the solar panel. The compressor (5) circulates refrigerant through a refrigerant loop to cool the insulated enclosure and to cool and induce a phase change of the material in the thermal reservoir. At night no power is delivered to the power bus (3), and the compressor (5) is inactive. The temperature in the insulated enclosure is maintained by the thawing of the material in the thermal reservoir. Advantageously, no fluid circulation or active heat pumping is required to maintain the enclosure temperature during these inactive time periods.

2.2 Phase Change Materials

A phase-change material (PCM) is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa; thus, PCMs are classified as latent heat storage (LHS) units.

PCMs latent heat storage can be achieved through solid–solid, solid–liquid, solid–gas and liquid–gas phase change. However, the only phase change used for PCMs is the solid–liquid change.

Initially, the solid–liquid PCMs behave like sensible heat storage (SHS) materials; their temperature rises as they absorb heat. Unlike conventional SHS, however, when PCMs reach the temperature at which they change phase (their melting temperature) they absorb large amounts of heat at an almost constant temperature. The PCM continues to absorb heat without a significant rise in temperature until all the material is transformed to the liquid phase. When the ambient temperature around a liquid material falls, the PCM solidifies, releasing its stored latent heat.

2.2.1 Desirable Properties of PCMs

[5-7] The desirable thermodynamics properties of PCM require its melting temperature to be in the desired operating temperature range. PCM should possess high latent heat of fusion per unit volume, high specific heat, high density and high thermal conductivity. It should contain small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce the containment problem. It should also have congruent melting. The kinetic properties of PCM sights high nucleation rate to avoid super cooling of the liquid phase, high rate of crystal growth, so that the system can meet demands of heat recovery from the storage system. The chemical properties of PCM demands for chemical stability, complete reversible freeze/melt cycle and there should not be any degradation after a large number of freeze/melt cycle. PCM should be non-corrosiveness, non-toxic, non-flammable and non-explosive materials.

3. EXPERIMENT ANALYSIS

[2-3] For a perfect design of our vaccine fridge, as earlier stated it require a PCM (phase changing material) of melting point in the range of 2-8 C, and a high latent heat so that it can keep the refrigerated space under the optimum temperature of vaccine storage during non-solar hours. According to the properties required the various options available were organic and inorganic material. Based on the decision matrix two materials were selected to test for the melting point with the objective melting point temperature of 5C. The material is as follows inorganic mixture (Na2SO4+NaCl+KCl+H2O) composition by weight (31+13+16+40) and Organic mixture (CH3COOH+ H2O) composition by weight (91.65+8.35).

The experimental analysis aims at determining the melting point of the PCMs: Inorganic mixture (Na2SO4+NaCl+KCl+H2O) composition by weight (31+13+16+40) and Organic mixture (CH3COOH+ H2O) composition by weight (91.65+8.35).

3.1 Experimental Procedure

The required chemical weight was carefully taken in weighing machine. The chemical were mixed and stirred in stirrer machine so as to have a proper mixing. Then the chemical is transferred in small 50ml beaker. The ice were crushed and were kept in larger beaker so as to place the ice as such that the whole small beaker in surrounded with ice. To increase the cooling effect the bigger beaker was surrounded with ice as well as shown in the Fig. .The thermometer was inserted at different section so as to monitor the temperature change in the sample at different section. The experimental set up can be shown in Fig. 3.

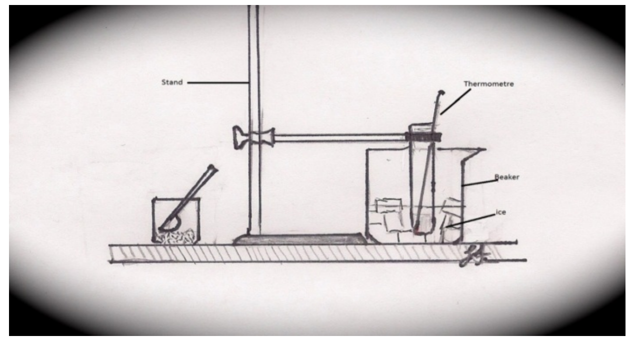

Fig. 3: Experimental set up

3.1.1 Experimental Result

The experiment performed with inorganic PCM has not shown the sign of effective PCM for the referigeration of vaciines as it settles down the beaker undissolved and melting temperature was varying below 0 degeree centigrade. The results totally changes with the organic PCM of acetic acid with stable required temperature of 5 degree centigrade.

3.2 Experimental Analysis

The cooling copper box has been very rigorously designed as it is the section which holds the vaccine and it also need to be ensured that it maintains the temperature in the required temperature range of 2-8 C and the objected temperature of 5 degree C. So it is very important to ensure that the thickness of the box be maintained so that the cooling effect reaches from the cooling coil to the internal section with less temperature lag and the solidification of the PCM is throughout the container i.e. on the time of charging the whole of PCM solidifies and provide it during the non-insolation hour with the temperature stability.

Experiment aims to determine the layer wise temperature distribution of the PCM container containing the PCM acetic acid.

3.2.1 Experimental Procedure

The chemical was poured into the copper container. The thermostats were pasted in different section. First thermostat were placed at the container inner face (T3) i.e. the other side of the cooling coil, second thermostat placed at the containers other side i.e. at the other cooling space (T1) and one in the middle (T2) . As shown in the figure. The temperatures were tabulated.

3.2.2 Observation Table

Time	T1	T2	T3
0	25.1	25.4	25.4
15	22.2	21.6	22.2
30	19.8	19.6	20
45	17.8	17.5	17.9
60	16.95	16.1	16.5
75	14.55	14.5	14.9
90	13.45	13.4	13.6
105	12.05	12.1	12.5
120	11.3	11.5	11.8
135	10.2	10.4	10.8
150	9.3	9.5	9.8
165	8.4	8.8	9.1
180	7.6	8.2	8.2
195	7	7.4	7.5
210	6.5	7.1	7
225	5.9	6.3	6.4
240	5.5	6	6
255	5.3	5.8	5.8
270	5.1	5.5	5.5

3.2.3 Experimental Graph and Results:

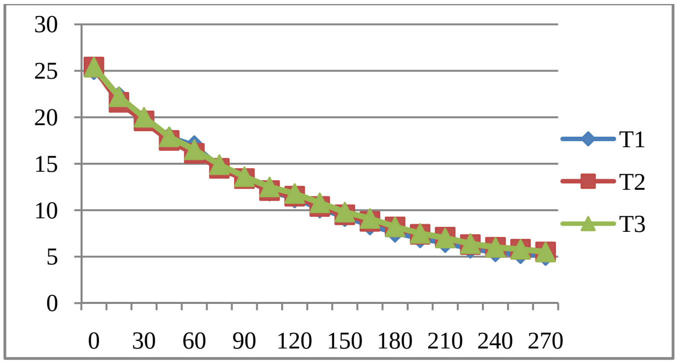

Fig. 4: (Time Temperature graph for PCM)

From the graph above it is inferred that temperature T1, T2, T3 at three different section of the reservoir shown below in Fig. 5, saturates approximately 5 degree centigrade and becomes stable as the time passes.

Fig. 5 (T1, T2, T3 section of Thermal Reservoir)

3.4 Experimental Calculation

Design parameters:

- Capacity = 15 litres
- Ambient Temperature = 30 degrees
- Inside Temperature = 4 degrees
- Total sun hours = 6 hrs
- Insulating Material = Thermocol (k=0.033 W/mK)
- Insulation Thickness = 7cm
- PCM Material = Aqueous solution of Acetic Acid (LHF=256KJ/Kg)
- Refrigerant = R134a
- COP = 4
- Mass of PCM=m

Autonomy Time = 3 days

3.4.1 Calculation of heat loss

Dimension of Refrigerated Space = 30.5x18x 27.5(in cm)
Dimension including PCM storage space = 35.5x23x27.5 (in cm)

Total Area = 0.485 sq. mtr
Assuming Steady State Heat Conduction through walls and applying Fourier's Law
i.e Q = k*A*(dT/dX)
Heat loss from both sides (left and right) will be
A1 =0.063 sq. mtr
Q1 = 1.54 W
Heat Loss from Front and Back side will be
A2 =.0976 sq mtr
Q2 = 2.39 W
Heat Loss from Top and Bottom will be
A3 = 0.0816 sq.mtr
Q3= 2 W
Hence Total Heat Loss is: Q = 5.93 W
Accounting for Opening and Closing of gate,
Q = 1.25*5.93
Q = 7.4125 W
Heat Loss per day will be : Q = 0.1779 KWhr /day

3.4.1 Estimation of PCM volume required:

Volume of PCM required for 1 day preservation

Heat Loss per day = 640.44 KJ/day
Latent Heat of aq. Acetic Acid (LH) = 256 KJ/Kg
m*LH = Q => m = 2.5 Kg
Therefore for 3 days we require = 0.0075 cu.mtr

3.4.2 Compressor Power Calculation

Considering that whole PCM will melt completely in 3 days (during this time it helps to sustain the required temperature in refrigerated space by acting as a thermal reservoir), total heat to be extracted during sun hours would be,

(Heat Extracted)/(COP)
= {(Heat loss)*(Autonomy time +sun hrs)}/ {(COP)*(sun hrs)}
= 24 W

Hence, Compressor power required = 24 W

4.5 Calculation of size of solar panel

Power required to run the compressor = 24 W
Running time= 6 hrs

Total DC Load required in watt-hr = 144 W-hrs per day
After taking into account De-Rating factor,
Total DC Load required would be = 144+ 20% of 144
= 172.8W-hrs per day
Total sun hrs available per day = 6 hrs
Required Solar Panel Input = 28.8 W
After taking into account Solar Radiation fluctuation,
Required Solar Panel Input = 28.8+15%of 28.8
= 33.12 W

4. WORKING MODEL

4.1 Specifications of component used

The working model for solar powered refrigeration system with integrated PCM as thermal reservoir can be shown in Fig. 6.

- COMPRESSOR – 220V , 50 Hz , 1PH R134a
- CONDENSOR – 165ltrs commercial condenser
- THERMOCOL SLAB – 5cm and 2cm thick slabs
- SUB-ZERO (Temp. Controller) – Range -50 degrees to 99 degrees
- ACETIC ACID – CH3COOH >=99%

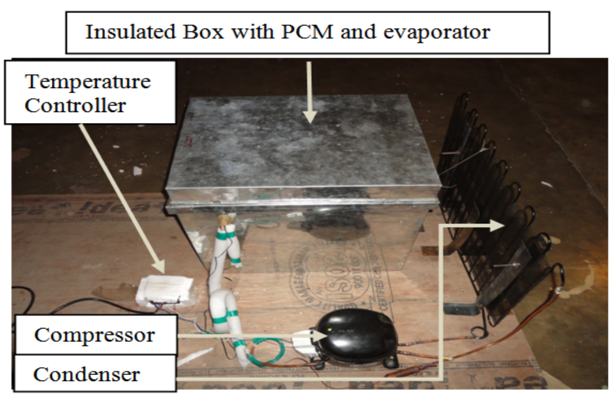

Fig. 6: (Working Model)

5. CONCLUSION:

An experimental analysis to find the best suitable PCM between organic and inorganic hub is carried out and suitable organic phase changing material was found with high latent heat and melting point in the range of 2-8 degrees. Based on various criteria of availability, cost, and maintenance and so on, aqueous acetic acid with water (91.65+8.35) by weight composition is chosen.

The working model of solar powered refrigeration system incorporates a thermal reservoir surrounded by acetic acid PCM, compressor section, condenser section and thermocol slab. A practical model is presented with calculation of the volume of PCM material required for three days to preserve the vaccines along with compressor power to operate the model. The temperature around the reservoir section is found to be approximately 5 degree for almost two days and fourteen hours for the working model shown. The design of the solar powered refrigeration system varies for different insolation zone and the PCM calculation has to be done for worst case as the failure to serve in worst cases would defeat the very purpose of the innovation. The time temperature graph of organic PCM around the vaccine storage place shows up the stable temperature of PCM around the reservoir for two days and fourteen hours which serve the purpose in far-flung devoid of electricity.

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