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Design and realization of a vaccine refrigerator powered by photovoltaic Energy

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***Abstract*— Recently, there is a large demand for cooling system of food and vaccines in developing countries. Such equipment mainly vaccine refrigerator require electricity supply which is often only available in urban regions. However solar intensity is abundant in many countries. This paper investigates a photovoltaic vaccine refrigerator based on absorption cooling system for remote areas when grid connection is not feasible.**

We carried out a method of modeling and sizing the vaccine refrigerator. Which allows obtaining the temperatures that prevail in the various compartments of the cold room as well as the average power necessary for its operation. The system is powered through a photovoltaic energy. The photovoltaic generator is connected to the vaccine refrigerator by means DC-DC converter, he is controlled to obtain maximum power from the variation of solar intensity. A Perturbation and Observation control method is developed to achieve maximum power to the load. The modelling of proposed system was done using MTLAB/Simulink. The simulation results demonstrate the effectiveness of the developed system.

***Keywords*— vaccine refrigerator, absorption cooling, R717 refrigerant, photovoltaic energy, buck converter,**

I. Introduction

The objective of such health organization is to provide a good health, reduce health risks and promote healthy lifestyles. They are working with countries to increase and sustain access to prevention, treatment and care for tuberculosis, malaria and neglected tropical diseases. They moved towards remote regions and inaccessible areas to control population health and prevent them from diseases. In such cases, they had a problem to preserve vaccines where grids are not feasible or electricity is available just for few hours in a day. So the use of renewable energy is the alternative solution to deal with the energy needs [1], [2].

In fact many projects have been developed for a stand-alone solution for vaccine refrigerator. Indeed several studies including different technologies of cooling systems are founded in literature. Solar cooling can be categorized into solar thermal and solar electric cooling system. In the first category, the cooling effect can be achieved through solar thermal gain based on adsorption or absorption system. The second category considers a mechanical compressor.

The photovoltaic energy appears as the most studied alternative source which the solar irradiation is transferred into electrical energy through the photovoltaic effect. Recently, thanks to the reduction of the manufacturing price of photovoltaic PV panel, it is possible to consider the photovoltaic vaccine refrigerator as a very interesting option where a high level of solar radiation is present [3].

Many works deal with solar thermal to provide cooling system other authors considered solar electric compression with conventional refrigeration system.

To contribute to the development of efficient photovoltaic refrigeration systems, a conceptual study of a refrigerator intended for vaccine storage and whose refrigeration unit operates with R717. The electrification of the vaccine refrigerator is achieved by a photovoltaic system which is consists of PV device connected to the power electronic converter controlled through the maximum power point tracking and related to the vaccines refrigerator.

II. Description of the vaccine refrigerator

The proposed system of the vaccine refrigerator is consisting of:

- PV panel
-DC-DC buck converter with MPPT control
-Battery and vaccines refrigerator.

The synoptic of the vaccine refrigerator is presented by the Fig.1.

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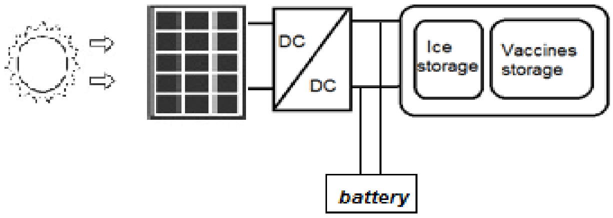

Fig. 1 Synoptic of the vaccine refrigerator

The vaccine refrigerator consists of two compartments; one for vaccine storage and the other is used to produce ice for the unfavourable climatic conditions. The ice section behaves an auxiliary cold source by the latent storage.

Most vaccines should be keeping at temperature from 0 to 8°. Even though such of them required long term storage at -20°C and short term storage at 4-8°C. Table 1 shows different types of vaccines temperature [4], [5].

TABLE I: Vaccines temperatures

Vaccine types	Transport to region	Regional store
Measles	-20°C to 8°C	at -20°C
Oral Polio	-20°C to 8°C	at -20°C
BCG	4 to 8°C	at 4-8°C
DPT	4 to 8°C	at 4-8°C
Tetanus	4 to 8°C	at 4-8°C

The vaccine refrigerator is a absorption system admits a substance who changes from one state into different states. It contains four heat exchanging devices; a vapour generator, an absorber, an evaporator and a condenser. For its operation a solution pump and two throttling devices are required. Fig. 2 shows the structure of absorption cooling system. For the absorption system, a fluid or gas in vapour state is absorbed by a liquid to form a binary solution. In order to release the absorbent the heat is supplied to this binary solution. Then the heat is dissipated to the surrounding medium when the release refrigerant passed through the condenser, and it reached the evaporator to receive heat from the medium to refrigerate [6], [7], [8]. The criteria of the choice of the suitable absorbent/refrigerant pair included large number of parameters, mainly the temperature of vaporization, the chemical stability and low cost. Most experimental studies show that NH3/H20 system provides evaporation at the temperature below 0°C. So it became a more attractive solution to use it in industrial application [1], [4].

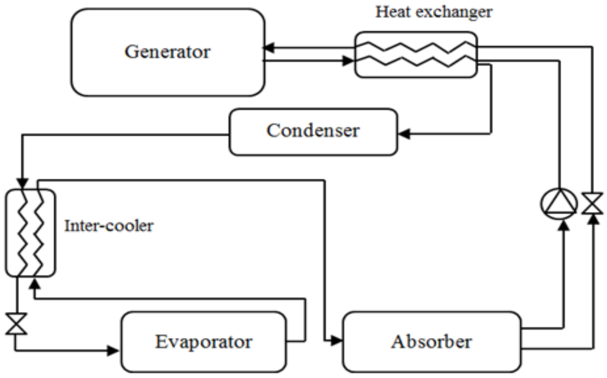

Fig. 2 structure of absorption system

III. Dynamic Modelling of the Vaccine Refrigerator

Generally, the ammonia / water refrigeration mixture is the most suitable for refrigeration installations at low temperatures. This mixture has good thermodynamic properties; high miscibility, low heat capacity, low viscosity and good coefficient of performance.

R717, which is ammonia, is used successfully as a refrigerant in absorption refrigeration cycles. It is a colorless, particularly toxic gas with no ozone depletion potential (ODP = 0) and no direct global warming potential (GWP = 0) [9].

The dynamic modelling of the refrigerant circuit makes it possible to determine the electrical energy required to operate the compressor to meet a maximum thermal load. It is established for a reference thermodynamic functional cycle, very precise. A thermodynamic cycle is defined by two important factors namely: the condensation temperature and the evaporation temperature.

- ❖ The evaporation temperature depends mainly on the nature of the products to be refrigerated. In the case of our preservative, the refrigeration compartment must be at a temperature of 12°C. On the other hand, for the freezing compartment intended to produce ice, its temperature must be - 2 °C. So for the choice of the evaporator, it is important to choose a ΔT_{ev} as low as possible. For this, the T_{evap} evaporation temperature chosen for our study is -15 °C.
- ❖ The condensation temperature generally depends on the environment. As well as the evaporator, for the choice of the condenser, it is imperative to set the total ΔT_{cd} between the ambient and the condensing temperature as low as possible to have the lowest possible energy consumption. For this, the ΔT_{cd} chosen is 42 °C.

From these two temperatures, the functional cycle of the refrigerant circuit operating at R717 is established as follows: Evaporation temperature T_{evap}=-15°C; Condensation temperature $T_{cond}=T_{amb}+15$°C; Overheating=5°C; Subcooling = 5°C.

Fig. 3 represents the enthalpy diagram of the fluid R717.

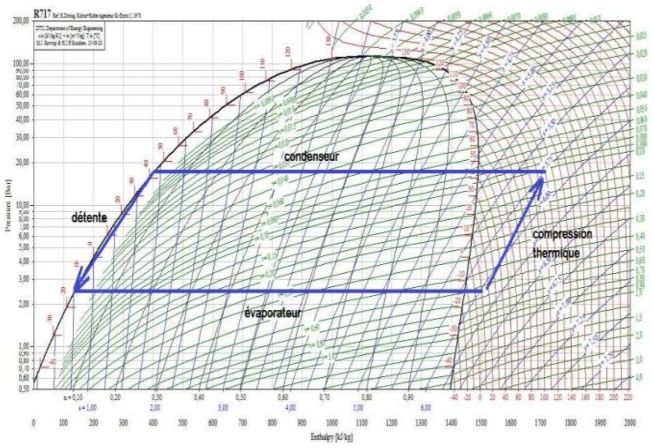

Fig. 3 enthalpy diagram of the fluid R717

To generate this functional cycle, one must make use of the thermodynamic and physicochemical properties of the fluid. In practice, these properties are in the form of graphs giving all the indicative parameters, such as the pressure P, the temperature T, the specific volume V, the enthalpy H and the entropy S.

IV. Sizing of the Vaccine Refrigerator

Several method sizing of the system are allowed, mainly depending on the product introduced. In particular, consider of insulating materials is feasible to realize an over insulation of the envelope [6], [7]. So insulating material used is the expanded polyurethane when thickness is assumed about 30cm with a transmittance of about 0.0027w/m²K. Then the net dimension of the vaccine refrigerator is defined by (LxHxP) 40x60x40.

Thus, it could be seen that the parameters which influence the quantity of cooling are;

- Isolation thickness
- Ambient temperature
- insulating material

Modelling of the refrigerating conservator makes it possible to determine the electrical energy required for the operation of the machine as well as the temperatures of the different compartments of the refrigerator.

A. Calculation of the cooling load

The modelling of this system is realized by the establishment of the heat balance:

- Heat transmission by infiltration

$$Q_i = TFA\left(w_e - w_i\right)0.84 \quad (1)$$

where $TFA = \text{air exchange rate}.\frac{1000}{3600}$, $w_{e,i}$ is the humidity

- Heat transmission through the facades

$$Q_f = k.S.\Delta T \quad (2)$$

where k is the thermal transmission coefficient, S the surface T the temperature

- Heat transmission by products

$$Q_p = m.c_p\left(T_{ex} - T_{in}{}^{p}\right) \quad (3)$$

where c_p is the Specific heat, m is the mass, T_{ex} the external temperature, $T_{in}{}^{p}$ the product temperature

- Heat transmission by lighting

$$Q_l = \frac{P.t}{24} \quad (4)$$

where, P : power, t : operating time

B. Energy balance of the refrigeration system

The thermal coefficient of performance of the refrigeration machine can be calculated using [7]

$$COP = \frac{Q_e}{Q_g + P_{el}} \quad (5)$$

Neglecting the work received by the pump, we can write the previous equation as follows:

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g} \quad (6)$$

The heat balance is written in the following way [10], [11]:

$$\dot{Q}_{gen} + \dot{Q}_{ev} = \dot{Q}_{con} + \dot{Q}_{abs} \quad (7)$$

Where

$\dot{Q}_{gen}$: Quantity of heat received by the absorbent

$\dot{Q}_{ev}$: Cooling energy

$\dot{Q}_{con}$: Quantity of heat yielded by the condenser

$\dot{Q}_{abs}$: Quantity of heat yielded by the adsorbent during absorption.

$$\dot{Q}_{gen} = \dot{m}h_7 + \dot{m}_p h_6 - \dot{m}_r h_5 \quad (8)$$

$$\dot{Q}_{ev} = \dot{m}\left(h_3 - h_2\right) \quad (9)$$

$$\dot{Q}_{con} = \dot{m}\left(h_1 - h_7\right) \quad (10)$$

$$\dot{Q}_{abs} = \dot{m}_r h_4 - \dot{m}h_3 - \dot{m}_p h_8 \quad (11)$$

Where:

$\dot{m}$: mass flow of the refrigerant [kg/s]

$\dot{m}_r$: mass flow of NH3 rich solution [kg/s]

$\dot{m}_p$: Mass flow rate of the NH3 poor solution [kg/s]

h: enthalpy [J/kg]

C. Calculation Result

The calculation results example is done for the case of the absorption refrigerator which is under construction in laboratory. The COP values were calculated is equal 0.3. The electrical power of medical conservator is 60 Watts

The characteristics of this installation are;
- Indoor temperature: 12 °C
- Evaporator temperature: -15 °C
- Condenser temperature: 42 °C
- Generator temperature: 120 °C

TABLE II: Parameters of the refrigeration machine

Evaporator area (m^2)	0.0118
Condenser area (m^2)	0.0675
Generator area (m^2)	0.0201
Absorber area (m^2)	0.0543
Thermodynamic COP	0.3

Fig. 4 presents the real prototype of the vaccine refrigerator.

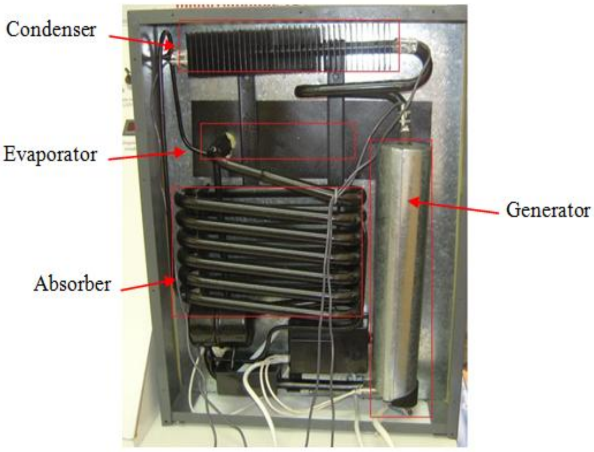

Fig. 4: prototype of a vaccine refrigerator

V. SIZING OF THE PHOTOVOLTAIC SYSTEM

A. Modelling and characteristic of the photovoltaic panel

The electrical diagram of a photovoltaic cell in this case comprises a current generator delivering a current I_{pv} corresponding to the generated photo current, a diode and a series resistor R_S which depends on the resistance of the semiconductor used, the contact resistance of the collective grids and the resistivity of the grids. Its value must be as low as possible to limit its influence on the cell. To account for the leakage current, a parallel resistor R_{sh} has been reduced to this model [12], [13].

The equivalent diagram of this model is shown in Fig. 5

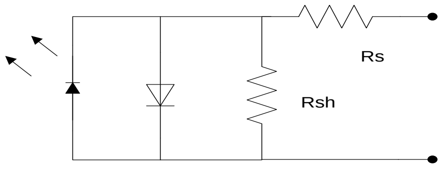

Fig. 5 Single diode equivalent circuit of PV cell

The mathematical model can be expressed as

$$I_{pv} = I_{ph} - I_d - I_{rsd} \tag{12}$$

The generated photocurrent I_{ph} is given by:

$$I_{ph} = \left[I_{cc} + k_i\left(T - T_r\right)\right]\frac{G}{G_n} \tag{13}$$

where I_{cc} is the short circuit current, k_i is the temperature coefficient of I_{cc} , T is the surface temperature of the photovoltaic cell, T_r is the reference temperature of the photovoltaic cell, G is the solar irradiation on the device surface, G_n is the nominal irradiation.

The diode current I_d equation can be expressed as

$$I_d = I_0\left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{V_t}\right) - 1\right] \tag{14}$$

where V_{pv} is the output voltage, R_s is the series resistance , I_0 is the module reverse saturation current which is given through (4)

$$I_0 = I_{rr}\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_g}{n}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \tag{15}$$

$$V_t = \frac{knT}{q} \tag{16}$$

where q is the electron charge, E_g is the energy of the band gap, n is the ideality factor, I_{rr} is the reverse saturation current is expressed by the following equation (17)

$$I_{rr} = \frac{I_{cc}}{\left[\exp\left(\frac{qV_{oc}}{nkTc}\right) - 1\right]} \tag{17}$$

where V_{oc} is the open circuit loop ,c is the number of PV cell

The current crossing the resistance is given by the following equation:

$$I_{rsd} = \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \tag{18}$$

The photovoltaic PV array is consist of N_s cell in series and N_p cell in parallel, his mathematical model is given by the following equation [14].

$$I_{pv} = N_p I_{ph} - N_p I_0 \left[\exp\left(\frac{q}{nkT} \left(\frac{V_{pv}}{N_s} + \frac{R_s I_{pv}}{N_p} \right) \right) - 1 \right] - \frac{N_p V_{pv} + N_s R_s I_{pv}}{N_s} \quad (19)$$

For the electrification of our prototype vaccine refrigerator, we have chosen the photovoltaic panel of the BP module MSX-60 whose parameters are grouped in table 3 [15]:

TABLE III: PV Module Parameters

Panel type	BP MSX-60
Maximum voltage V_{mp} [v]	17,1
Maximum power P_{pv} [w]	60
Maximum current I_{mp} [A]	3,5
Voltage in open circuit V_{oc}[V]	21,1
Short circuit current I_{cc} [A]	3,8
Current coefficient short circuit [V/°C]	0.065
Ideality factor	1.2
Number of cells in series	36

B. MPPT CONTROL ALGORITHM

The MPPT command (Maximum Power Point Tracking) is an essential control for optimal operation of the photovoltaic system. The principle of this control is based on the automatic variation of the duty cycle α by bringing it to the optimal value so as to maximize the power delivered by the PV panel [16], [17].

The principle of this algorithm is to disturb the voltage of the PV panel while acting on the duty cycle α . Indeed, following this disturbance, the power supplied by the PV panel is calculated at time k, then we compare it to the previous one of the instant (k-1). If the power increases, we approach the point of maximum power (PMP) and the variation of the duty cycle is maintained in the same direction. On the contrary, if the power decreases, we move away from the PMP. Then, we have to reverse the direction of the variation of the duty cycle [18], [19]. Fig.6 shows the P & O algorithm

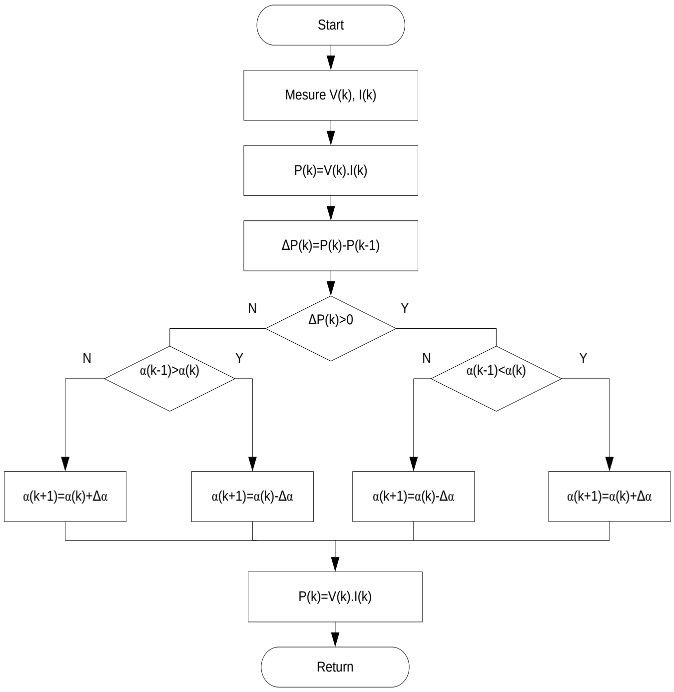

Fig.6 P&O algorithm

C. SIZING AND CONTROL DC/DC BUCK CONVERTER

The DC-DC converter is an interface that allows adaptation between the PV panel and the load (a mobile vaccine refrigerator) to extract the maximum power of the panel. The mathematical model of buck converter is derived from the basic schematic block shown in Fig.7 [20], [21].

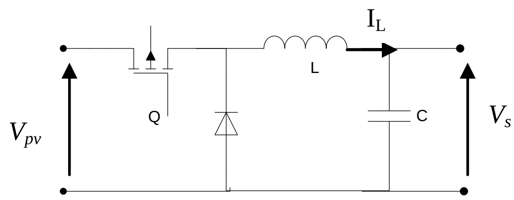

Fig.7 Electrical diagram of the Buck Converter

The operation of the buck converter can be decomposed into two phases according to the state of the switch Q;

- During a period (αT) of the switching period of T, the switch Q is closed. The supplied source of energy at the load R and the inductance L, the voltage $V_s = V_{pv}$.
- During a period (1-αT) of the switching period T, the switch opens and the voltage across the inductor is reversed. The freewheeling diode D ensures the continuity of the current and the discharge of L in R, the voltage $V_s = 0$.

The state representation of the buck converter model is given by the following equation

$$\overset{\bullet}{x} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} I_L \\ V_s \end{bmatrix} + \begin{bmatrix} \frac{\alpha}{L} \\ 0 \end{bmatrix} V_{pv} \qquad (20)$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} I_L \\ V_s \end{bmatrix} \qquad (21)$$

The size of the converter is depending on the characteristics of the photovoltaic generator used. In this case, the desired system must ensure the constraints of the following specifications:

- The output voltage of the converter is about 12V.
- The output current of the converter is equal to 2A.
-The output voltage is 1%.
-The output current is 1%.
-The switching frequency of the chopper is fixed at 2 kHz.

In order for the converter to operate in continuous conduction mode, the inductance L and the capacitor C must satisfy the following equations [22]:

$$L = \frac{\alpha(1-\alpha)\mathrm{V}_{pv}}{\Delta I_L f} \qquad (22)$$

$$C = \frac{\alpha(1-\alpha)\mathrm{V}_{pv}}{\Delta V_0 L f^2} \qquad (23)$$

VI. Realization and Test of the Vaccine Refrigerator Prototype

The characteristic of the panel, at a temperature of 25 ° C, as a function of sunlight G = 200, G = 400, G = 600, G = 800 and then G = 1000 W / m² are represented in Fig.8. The maximum power corresponding to the maximum power varies only slightly according to the illumination. Our photovoltaic panel delivers 60w for our vaccine refrigerator.

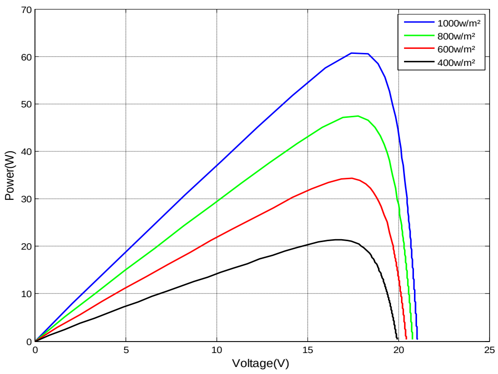

Fig.8 P-V curves in different solar irradiations

Fig. 9 shows the evolution of the output current of the buck converter as a function of time, the value of the current is stabilized at its set value which is 2A without oscillation and overshoot.

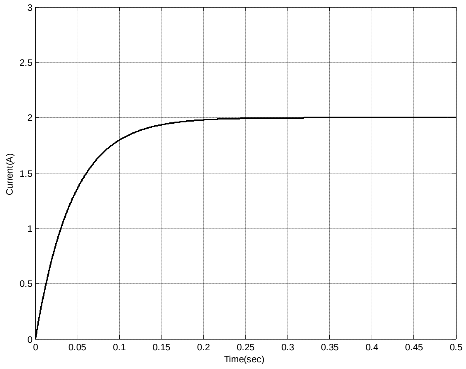

Fig. 9 Current output Buck response

Fig.10 shows the characteristic of the output voltage of the buck converter. The voltage value, in steady state, is equal to the reference value which is of the order 12V.

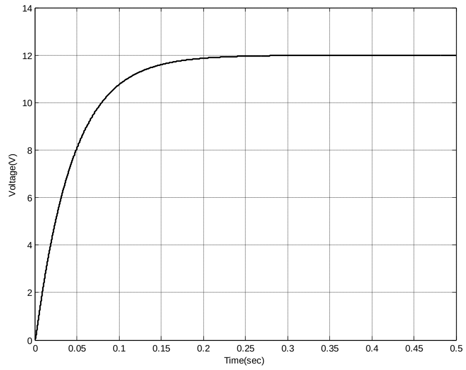

Fig.3 Voltage output Buck response

Fig. 11 presents our prototype vaccine refrigerator which is connected to the photovoltaic system its power 60w.

The refrigerator consists of an electrical cabinet, displays that display the different temperatures of the refrigerator which are the temperature of the congelation and the temperature inside

Fig. 11 structure of absorption system

VII. CONCLUSIONS

This paper presents a study and a realization of a new prototype of refrigerators photovoltaic which largely respects our environment, intended for the refrigeration of the vaccines in the desert and isolated places or the remote places in the mountains.

We analyzed various parameters that could affect the proper functioning of our refrigerator allowed to estimate and evaluate the power consumption of our refrigerator in several sites, and finally set the power of our refrigerator to 60 watts for remote sites and desert. Finally, we proceeded to a sizing of the complete system to determine the size of our photovoltaic system.

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