

# A PORTABLE DIRECT-PV THERMOELECTRIC VACCINE REFRIGERATOR WITH ICE STORAGE THROUGH HEAT PIPES

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## ABSTRACT

The objective of this work is to design a portable solar refrigeration system capable of maintaining vaccine temperatures between 2 and 8 °C for at least 4 days of operation without access to grid electricity, and to test the feasibility of using the system in different remote locations having a high number of unvaccinated children and lacking electricity.

The basic concept is to integrate direct-coupled PV thermoelectric modules (TEMs) with latent heat energy storage (LHES) using water as the phase change material along with heat pipes. In this concept, a photovoltaic panel (PV) directly powers thermoelectric modules (TEMs) to generate a cooling effect during the day. LHES is integrated into the refrigerator design as a cooling backup to maintain the cooling at night. Heat pipes are utilized in the system to passively control the temperature for vaccine storage.

The coupling of PV and TEMs was verified by mathematical models. The results showed that sufficient cooling could be produced from the coupling. The heat pipe attached to TEMs appeared to be able to improve COP of TEMs. An experiment showed that it is possible to use the heat pipes to maintain acceptable vaccine temperatures above that of ice as the energy storage medium.

A feasibility field study of the system was then performed. Three remote sites: the villages of Raypa, Malvas, and Cochapeti in Peru were selected as typical areas where the system would be needed. The results showed that the direct-coupled PV-TEM combined with latent energy storage (using ice) was fully adequate in providing cooling for the vaccines throughout the year.

## 1. INTRODUCTION

The World Health Organization (1) reported that in 2002,

an estimated 2.1 million people around the world died of diseases preventable by widely available vaccines. In addition, in 2003, approximately 27 million children worldwide were not reached by the vaccines. Most of these children who missed out on routine vaccination programs tended to be people living in remote locations where there is no grid electricity. While it is true that there are varied causes for these deaths, one unacceptable cause stems from vaccine storage deficiencies resulting in loss of vaccine potency. It was also reported that about 50 % of transported vaccines (2) are wasted in the developing countries.

Presently, many cooling systems, such as a vapor compression refrigerators, cold boxes, and thermoelectric systems, are used to maintain the quality of vaccines during transportation to remote areas. The vapor compression system and cold boxes are the most common cooling systems in use in remote areas. The advantage of the vapor compression system is its ability to handle large loads with good efficiency. However, the system is heavy because of the compressor, noisy during operation, and costly. The cold box (vaccine carrier) is much lighter, low in cost and simply uses an ice pack to cool the vaccines. However, it has very limited reliability because of inconsistent cooling, causing the vaccines to freeze in some instances. Also, it provides cooling for a limited time period.

An alternative cooling technology that is becoming increasingly popular uses the principle of thermoelectric modules (TEMs). These modules are made of semiconductor materials connected in series electrically and in parallel thermally to create cooling. Although they are less efficient than the vapor compression systems, they are very light, low in cost, quiet, and environmentally friendly.

Several thermoelectric refrigerator designs (3 -9) have been introduced, some even patented. However, most of these designs were developed for large cooling loads and intended to improve the coefficient of performance (COP) of the TEM by utilizing different approaches such as conventional



of the pipe is considered to be the evaporator to which heat is added. This part was exposed to ambient air inside the insulated container. The middle part is adiabatic, and is insulated with cotton; hence there is little heat input. The top part acts as the condenser, from which heat is extracted (using ice). The lengths of the evaporator, adiabatic, and condenser sections are 45 mm, 103 mm, and 30 mm, respectively.

### 3.1.2 Test Methodology

The experimental setup is shown in Fig. 3. The heat pipe was operated under ambient temperature ( $T_a$ ) and three temperatures were measured at various positions including evaporator ( $T_{eva}$ ) and condenser ( $T_{cond}$ ) of the heat pipe by a type T thermocouple and recorded by a CR23X data logger.

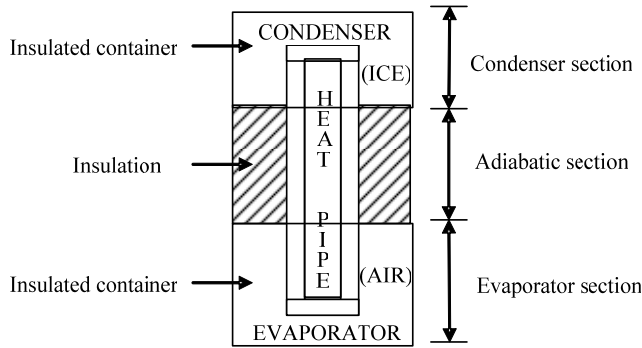


Fig. 3: Schematic description of the experimental heat pipe

### 3.1.3 Results and Discussion

The variation of condenser ( $T_{cond}$ ), evaporator ( $T_{eva}$ ), ambient ( $T_a$ ), and temperature difference ( $T_{diff}$ ) with time when the condenser was located above the evaporator is shown in Fig. 4. It was observed that during operation of the heat pipe, the heat was transferred from the higher temperature of the evaporator to the lower temperature of the condenser. Consequently, the evaporator temperature dropped rapidly at the beginning and soon after reached the steady state at 7 °C at a time of 50 minutes to 150 minutes. These results showed that the heat pipe could maintain a temperature difference constant between condenser and evaporator, which is suitable for passive control of temperature for vaccine storage. It was also observed from the experiment that if the condenser temperature were maintained at 0 °C, the evaporator temperature would be at 2 °C, which satisfies the design criteria.

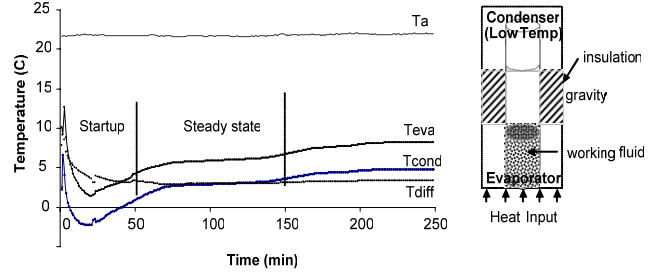


Fig. 4: Temperature variation of heat pipe (with condenser located above evaporator)

### 3.2 Coupled PV-TEM Operation

According to the concept of the PV coupling, if the voltage and the current of the PV do not intersect with that of the TEMs, there will be no cooling produced. Therefore, it is important to make sure that the coupled PV and TEMs are well matched.

In this section, two system models: the coupled PV and TEMs with and without a heat pipe (No.1), were used to identify the possibility of coupling these components to generate cooling. A mathematical model of PV and TEMs and the results from simulation are presented below.

#### 3.2.1 Component Models

##### 3.2.1.1 PV model

A PV model of  $I$  vs.  $V$  is nonlinear. The output current and voltage depend on the solar radiation and ambient temperature. The four parameters of the PV model proposed by Townsend (12) are used in the simulation. These parameters ( $I_L$ ,  $I_o$ ,  $R_s$ , and  $A$ ) were calculated by a method summarized by Duffie and Beckman (13).

$$I = I_L - I_o \left[ \exp\left(\frac{V + IR_s}{A}\right) - 1 \right] \quad (1)$$

##### 3.2.1.2 TEM model

The theoretical equations for the thermoelectric module performance include the voltage equation (14):

$$V = 2N \left[ (I\rho) / G + \alpha\Delta T \right] \quad (2)$$

and the cooling capacity equation:

$$Q_L = 2N \left[ \alpha IT_L - (I^2 \rho) / (2G) - k\Delta T \right] \quad (3)$$

### 3.2.1.3 Results of Coupled PV-TEM Operation

In the simulations, the TEM model was assumed to maintain the temperature of the cold side at 0° C while that of the hot side varied with the ambient temperature. A 20-Watt solar panel integrated with thermoelectric module (Model CP0.8-254-06) was chosen to simulate the effectiveness of the coupling. The simulation results are presented in Fig 5.

In Fig. 5, the first graph presents hourly I-V curves and the operating points of the coupling during the previous 24 hours; the second graph presents the useful cooling provided from the coupling without heat pipe (No.1) integrated; the third graph presents the useful cooling provided from the coupling with heat pipe (No.1). The results from the first graph indicated that whenever solar radiation changes, the cooling effect produced will change also. Whenever there is no electricity supplied by PV, there will be some heat gain from the ambient temperature through TEMs as indicated by the negative value on the second graph. This heat gain will be protected by a heat pipe which acts like a diode. The negative values of the useful cooling in the third graph still appear because during TEMs operation, the cooling produced is not sufficient to remove the heat gain through TEMs. This effect is very small, however.

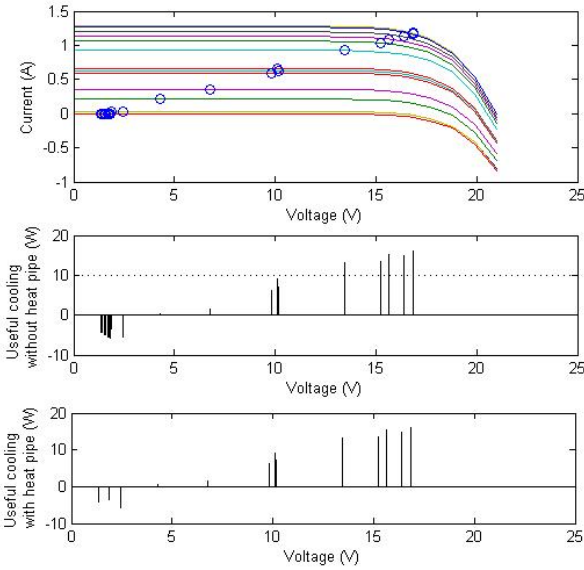


Fig. 5: Hourly I-V curve variation of a PV module and useful cooling of TEM at Raypa, Peru on January 1, 2005

## 4. PRELIMINARY SIZING OF THE REFRIGERATOR

In this section, the initial sizing of the refrigerator is shown. The main determinants of size selection are vaccine

capacity, ice storage, PV, and thermoelectric modules except for the heat pipe.

### 4.1 Vaccine and Ice Storage

The vaccine storage was designed to contain at least 54 vials; each of which has a base diameter of 2 cm and a height of 4 cm and contains 5 ml of vaccine. These vials can save approximately 45 children from polio or 90 children from yellow fever/measles/tuberculosis, according to the World Health Organization (15). The mass of ice storage was determined in order to ensure vaccine potency for at least 4 days, at 43 °C ambient temperatures. The heat gain through the system at steady state was calculated by using a thermal network model (Fig. 6). In that model, the arrows represent the direction of the heat fluxes; the diode block indicates that the heat pipe transfers heat in one direction only; each block represents the net thermal resistance between two nodes; and each node represents a control temperature of the system.

#### 4.1.1 Mathematical Formulation

The energy balance of each node at steady state can be derived as follows:

At node  $T_{ice}$  :

$$Q_{hg\_ice} = Q_{a\_tem} + Q_{a\_ice} + Q_{hp2} + Q_{vac\_ice} \quad (4)$$

At node  $T_{vac}$ :

$$Q_{hg\_vac} = Q_{a\_vac} - Q_{vac\_ice} - Q_{hp2} \quad (5)$$

where

$$Q_{a\_ice} = \frac{T_a - T_{ice}}{R_{a\_ice}}; Q_{vac\_ice} = \frac{T_{vac} - T_{ice}}{R_{vac\_ice}};$$

$$Q_{a\_vac} = \frac{T_a - T_{vac}}{R_{a\_vac}}; Q_{hp2} = \frac{T_{vac} - T_{ice}}{R_{hp2}};$$

$$Q_{a\_tem} = k \times \Delta T \times G;$$

In addition to heat gain from the outside to the vaccine chamber and the ice chamber, the heat gain from door-opening should also be taken into account. It is assumed that the door will be opened three times a day and that the heat gain from the outside (43° C) to the inside (2° C). Given that, the heat gain from each door opening can be expressed as:

$$Q_{OD} = f \times \rho_a \times V_{vac} \times C_a \times (T_o - T_i) \quad (6)$$

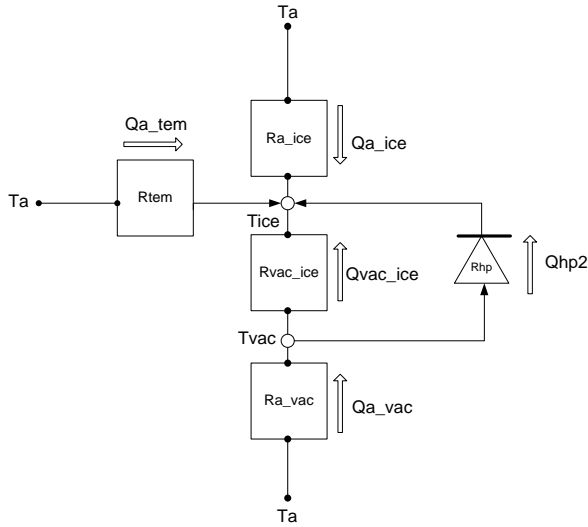


Fig. 6: Thermal network model of the refrigerator

#### 4.1.2 Results of Sizing

In sizing the components, the cooler was assumed to be made of FiberGlas reinforced plastic (FRP) for the outside frame, vacuum panel as insulator (Ins), and aluminum (AL) for the chambers for optimal heat conductivity. In sizing the storage chambers, the ambient, ice and vaccine temperatures were assumed to be 43 °C, 0 °C, and 2 °C, respectively. Moreover, several thermal resistances of the model were estimated and the heat gains calculated. The results of storage sizing are shown in Fig. 7. From the calculation, in order to maintain the potency of vaccine products, 24 hours a day for 4 days, the required amount of water is 1.9 liters.

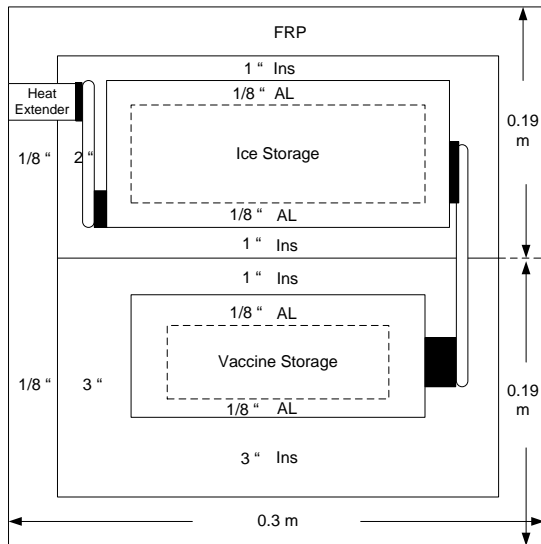


Fig. 7: Diagram of prototype of portable refrigerator

#### 4.2 Direct –PV Thermoelectric Modules

TEM selection is dependent upon the required cooling (heat gain) needed and the operating voltage of the PV-TEM unit selected (Table.1).

TABLE 1: SPECIFIC INFORMATION OF TEMs

SELECTED TEM	CP 0.8-254-06
Max. Voltage ( $V_{max}$ )	30.8/15.4 V
Max. Current ( $I_{max}$ )	2.1/4.2 A
Max. cooling ( $Q_{max}$ )	36.2 W

Note: The specifications are obtained at 25 °C of hot side

The photovoltaic panel (BP SX 20) is chosen to power the TEM during daytime. To size the required number of PV panels, the worst case scenario of solar radiation from Cochapeti during the month of March, (3.62 kWh/m<sup>2</sup>) (16), is used. The number of panels required can be estimated as:

$$no\ of\ PV = \frac{P_{TEM}}{H_c \times P} \quad (7)$$

The result of PV sizing is shown in Table 2.

TABLE 2: SPECIFIC INFORMATION OF THE PV

SELECTED PV	BP SX 20
No. of PV required	1
PV area ( $A_{pv}$ )	0.21 m <sup>2</sup>
Length	0.42 m
Width	0.5 m
Max. voltage ( $V_m$ )	16.8 V
Max. current ( $I_{L,m}$ )	1.19 A
Weight	2.5 kg

#### 5. PILOT STUDY

The objective here is to demonstrate the effectiveness of the refrigerator in selected remote locations. Three remote areas of Peru: Raypa, Malvas, and Cochapeti, where the system is critically needed were used as representative sites and where data loggers have recorded hourly incident global horizontal irradiation and ambient temperatures (17). The ambient temperatures in Raypa during several months commonly exceed 30 C. Three parameters (net energy, liquid fraction, and COP of TEMs) were estimated with the above weather data as inputs to evaluate the effectiveness of the system.

### 5.1 Calculation Steps

The calculations are shown in Fig. 8. The phase change state of water in the ice chamber can be determined as follows:

$$\begin{aligned}
 & \text{if } \frac{Q_{net\_dsum}}{V_w} \leq 0; fli = 0; \\
 & \text{elseif } \frac{Q_{net\_dsum}}{V_w} < \rho_l \times L_w; fli = \frac{(Q_{net\_dsum} / V_w)}{\rho_l \times L_w}; \\
 & \text{else } fli = 1;
 \end{aligned}
 \tag{8}$$

Note:  $fli = 0$  means the water is in solid form;  
 $fli = 1$  means the water is in liquid form:

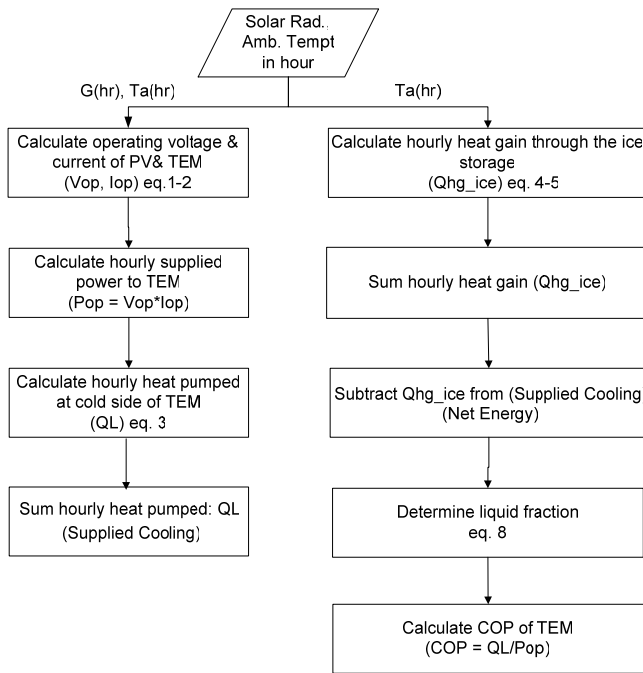


Fig. 8: Flow Chart

### 5.2 Results of the Study

The steps to calculate net energy, liquid fraction, and the COP of the TEM were explained in the last section. The results of simulations are presented in Figs. 9, 10, and 11.

The simulation results from three locations: Malvas, Cochapeti, and Raypa, indicate that the designed system can maintain the temperature of ice storage at 0° C as shown in the liquid fraction graphs. This results in properly maintaining the temperature for effective vaccine storage. The design system appears to achieve a high COP of TEMs with assistance of the heat pipe (No.1).

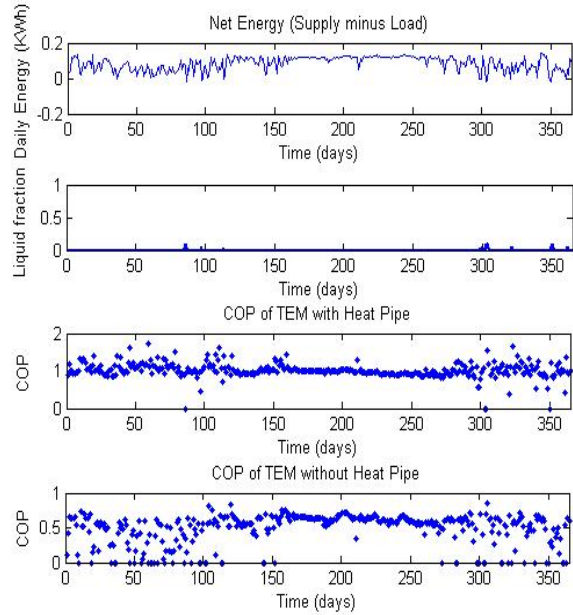


Figure 9: A 20 W PV and CP0.8-254-06 at Malvas, Peru

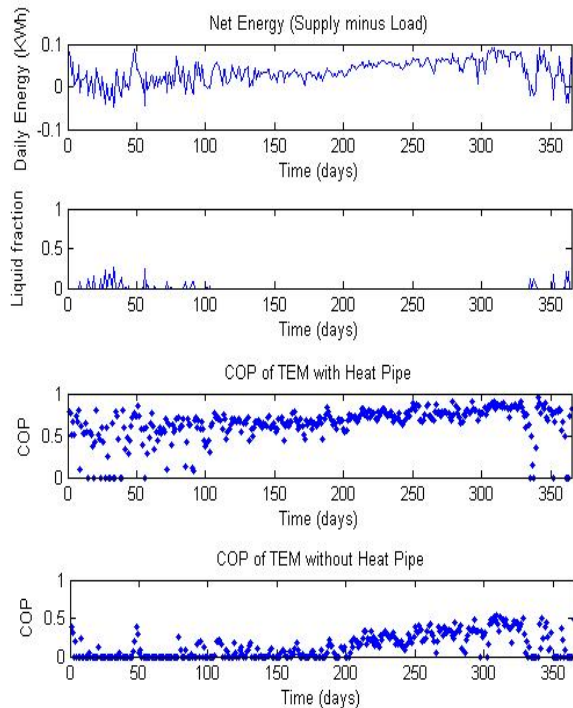


Fig. 10: A 20 W PV and CP0.8-254-06 at Raypa, Peru

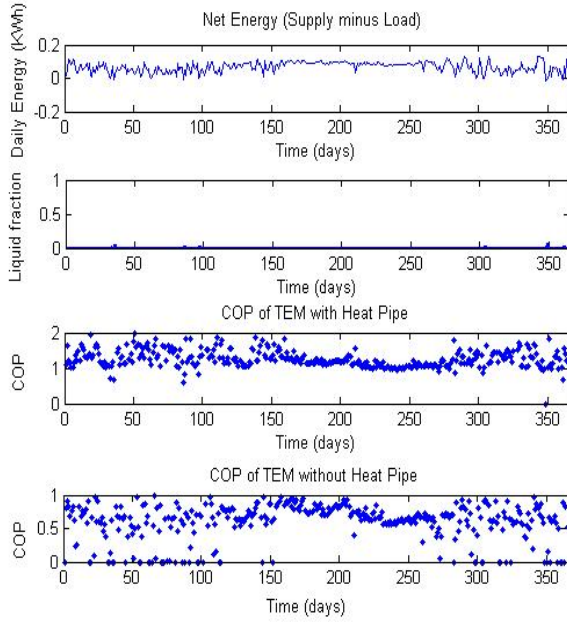


Fig. 11: A 20 W PV and CP0.8-254-06 at Cochapeti, Peru

## 6. CONCLUSION

The concept of a direct coupled PV-TEM refrigerator with latent energy storage using water as cooling backup has been proposed and shown to be functionally competitive with compressor refrigerators and the vaccine cold boxes. The light-weight of the TEMs, the non-toxicity (no working fluid), low-cost, the independence of energy source provided by the PV panel, and the longer period of cooling (using LHES) are additional advantages of this system. Some of the critical concepts of the new system, the heat pipe and direct-coupled PV and TEM performance, were evaluated. The results revealed that the low melting point issue of the water could be solved by installing a cylindrical heat pipe between LHES and vaccine storage, the low COP of TEM could be improved by a heat pipe, and the cooling could be produced from coupling PV and TEMs. Moreover, the feasibility study showed that the system can potentially operate in different locations.

For future work, a dynamic, complete model of the system will be developed to simulate the system performance in hotter climates, and the prototype will be fabricated to validate the model.

## 7. NOMENCLATURE

I	Operation current (A)
$I_o$	Dark current (A)
IL	Light current (A)

V	Operation voltage (V)
$R_s$	Series resistance (ohm)
A	Thermal voltage (V)
N	Number of thermocouples
$\rho$	Resistivity (ohm-cm)
G	Area/Length (cm)
$\alpha$	Seebeck coefficient (V/K)
$\Delta T$	Temp. difference between hot and cold sides (K)
TL	Cold side temperature (K)
K	Thermal conductivity of TEM (W/cm-K)
$Q_{hg\_ice}$	Total heat gain through the ice storage, (W)
$Q_{a\_tem}$	Heat transfer from ambient through TEM, (W)
$Q_{a\_ice}$	Heat transfer from ambient through five sides of the ice storage (W)
$Q_{hp2}$	Heat transfer through the heat pip, (W)
$Q_{vac\_ice}$	Heat transfer between vaccine and ice storage (W)
$Q_{a\_vac}$	Heat transfer from ambient through five sides of the vaccine storage (W)
$Q_{net\_dsum}$	Net energy (kWh/day)
$R_{tem}$	Thermal resistances of TEM, (K/W)
$R_{a\_ice}$	Thermal resistances through each of the five faces of the ice storage in parallel include: conduction from the ice in the ice storage, conduction through aluminum container, insulator, and fiberglass, and convection to the air, minus the areas that are in contact with the heat extender of TEM and the heat pipe condenser, (K/W)
$R_{a\_vac}$	Thermal resistances through each of the five faces of the vaccine storage in parallel include: convection from the air in the vaccine storage, conduction through aluminum container, insulator, and fiberglass, and convection to the air, (K/W)
$R_{vac\_ice}$	Thermal resistance between top face of vaccine storage and under face of ice storage include: air convection in the vaccine storage, conduction through aluminum container, conduction through insulation, and conduction from the ice in the ice storage (K/W)
$R_{hp2}$	Thermal resistances of heat pipe no. 2, (K/W)
f	Exchange rate, (air change/time)
$\rho_a$	Density of air, (kg/m <sup>3</sup> )
$V_{vac}$	Volume of vaccine chamber, (m <sup>3</sup> )
$C_a$	Specific heat of air, (J/kg-K)
$T_o$	Outside temperature, 43 (°C)
$T_i$	Inside temperature, 2 (°C)
$P_{TEM}$	Power required by the TEM
$H_c$	Daily incident solar irradiation, 3.62 (kWh/day);

P	Power output of one PV panel at 1 KW incident irradiation (W/panel/kW)
$\rho_l$	Density of water, 999 (kg/m <sup>3</sup> )
f <sub>li</sub>	liquid fraction
V <sub>w</sub>	volume of water required for cooling backup at steady state, (m <sup>3</sup> )
L <sub>w</sub>	Latent heat of the water, 333×10 <sup>3</sup> (J/kg);

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