DESIGN A THERMOELECTRIC COOLING HOLDER SUPPLIED BY PHOTOVOLTAIC PANELS

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Abstract: In this paper, the development of a portable solar power vaccine carrier box for local usage in Africa and South Africa is described. The purpose is to provide guidance to the design of a thermoelectric cooling holder. An overall design of a cooling holder was done in SolidWorks® and a thermal analysis of the complete systems was done in Flow Simulation. The thermal analysis was done to simulate the cooling capacity of the Thermoelectric Cooling Module (TECM) heat exchanger. Design of the solar power supply including photovoltaic panels, charge controller, and batteries were also done.

Keywords: Cooling holder, Thermoelectric Cooling Module (TECM), photovoltaic panels.

1. INTRODUCTION

Infectious diseases are the main course of deaths or disabilities among infants and young children in rural parts of Africa. The most effective and cheapest method to prevent infectious diseases is vaccine [1]. These vaccines are administered into the body of patients during routine immunization programs. The most important part of these immunization programs is the cold chain system. This system implies the storing and transporting of vaccine from the manufacturer to the patient in a certain temperature in order for it to stay in a potent state. All vaccines lose their potency if exposed to heat or when it is frozen. Obviously it is pointless to immunize with vaccine which has lost its potency [1]. The storing standards of vaccine set out by the World Health Organization (WHO) state that vaccine should be stored within 2 - 8°C [2]. In order to deliver vaccine to patients in a potent state, the most important tool is functioning freezers and refrigerators. These cooling containers must also be rugged and find a mean to power itself as it will be used in rural parts of Africa where no electricity is available.

In this paper, the design and development of a portable solar powered vaccine carrier box is described. In order to successfully design a vaccine cooling holder, that utilizes thermoelectric technology as a heat pump, it was necessary to determine if the cooling power of this type of technology would be satisfactory for the application. Thermoelectric Cooling Module (TECM) with different voltage, current and heat pumping capabilities are available and that is why it is important to determine the correct heat pumping capability needed for a given application. The hot side of the cooling holder is cooled by using a heat sink and fan assembly, due to the size and complexity when compared to water cooling. A heat exchanger with a very high efficiency should be used to cool the hot surface of a TECM. A design for the solar power supply including photovoltaic panels, charge controller and batteries were done. An overall design of the cooling holder was constructed in SolidWorks® and a thermal analysis of the complete system was done in Flow Simulation. These simulations ensure that the results are optimum and that a proper prototype of the design can be implemented. The simulation results were used to construct a prototype cooling holder with the exact dimensions as the designed cooling holder. The design of the model in SolidWorks®, a thermal analysis performed of the model in Flow Simulation and the design of the control circuit in OrCAD®, forms all part of the simulations.

2. DESIGN CONSIDERATIONS

The proposed design of this paper is to design and implement a cooling system for the storage of vaccine for the use in Africa. The efficiency of the cooling holder will be evaluated under normal operating conditions to determine if its cooling capacity is aliquant. In figure 1 all sections of the system are shown. The most important components of the project are the photovoltaic panel, charge controller, battery, cooling holder, temperature control circuit and the thermoelectric cooling modules. This is the functional architecture of the preliminary design of the project.

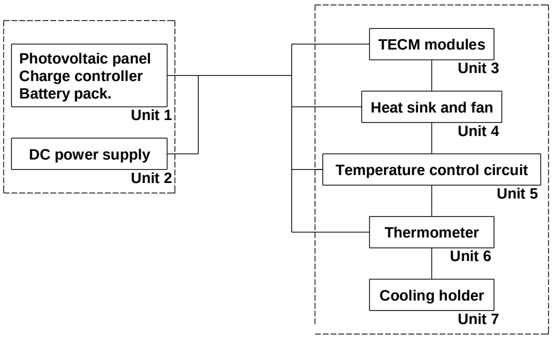


Figure 1: Preliminary design functional architecture

2.1. Photovoltaic panels

The rated power output is used to classify photovoltaic panels and it is measured in watts (W). It is expected of the photovoltaic panel to produce its rated amount of power in one peak hour of sun [3]. When making calculation the geological location must be kept in mind as it will affect the peak sun hours. In figure 2 the average annual solar radiation falling on one square metre surface from 2004 to 2010, measured in kilowatt hours is illustrated [4]. There is more than 2000 kWh/m^2 of energy available in the mid region of Africa to generate power. This justifies the use of solar energy to power the cooling holder.

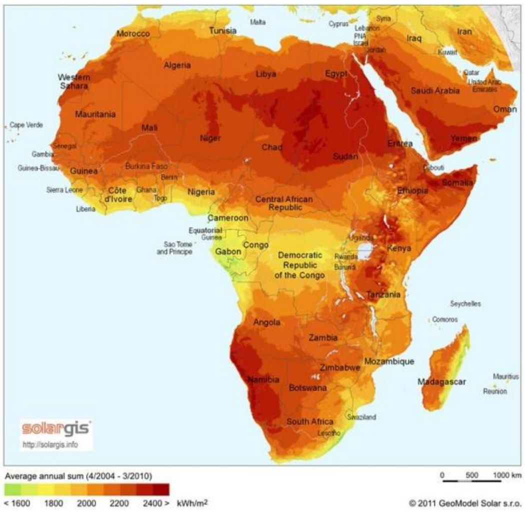


Figure 2: Average solar radiation in Africa [4]

In figure 3 the average annual solar radiation falling on one square metre surface from 1994 to 2010, measured in kilowatt hours is illustrated [4]. There is more than 2000 kWh/m^2 of energy available in the Potchefstroom region to generate power.

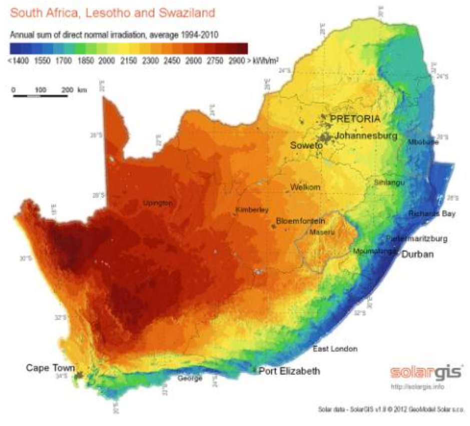


Figure 3: Average solar radiation in South Africa [4]

Photovoltaic panels can be wired in series or in parallel, to increase voltage or current respectively. When photovoltaic panels are wired in series the output voltage is increased and when they are wired in parallel the output current is increased [5]. Photovoltaic panels are rated according to their peak power (W), with the associated voltage (V) and the current (A) at this point of peak power. Photovoltaic panels normally have a rated terminal voltage of 17 V, while the cell operating temperature affects the output of the photovoltaic panel. Twenty five degrees Celsius is the nominal temperature at which the panels are rated, while their output can vary by up to 2.5% for every 5 degrees increase in temperature. The output of the photovoltaic panel decreases, as temperature increase [6]. It should be kept in mind when sizing a photovoltaic panel that the output is affected by the temperature. The output of the photovoltaic panel can be increased up to 25% above its nominal rated current with the increase in temperature. Due to this fact, the charge controllers must be sized to account for this increase in the output of the photovoltaic panels, hence it can withstand the increase in the short circuit current. Charge controllers are rated 125% higher to ensure that it can handle the short circuit [7].

2.2. Solar Power Supply

In order to provide power to the complete cooling holder, a solar panel, charge controller and battery are used. The size of the power supply is determined by the power consumption of the system. The total power consumption of the system is the sum of the power consumption of the TECMs with the two fans (P_1) and the temperature control circuit (P_1).

$$P_{total} = P_1 + P_2 = 134 + 1.2 = 135.2\ W \qquad (1)$$

The exact size of the photovoltaic panels, charge controller and batteries are determined in the rest of this section.

Determine the DC Load: The total load of 135.2 W will be operated for 24 hours per day, resulting in 3244.8 Wh per day. There will be energy losses to account for and therefor 20% has to be added to the load. The total load is therefor:

$$P_{load} + P_{losses} = 1.2\ P_{load} = 3893.8\ Wh/\text{day} \qquad (2)$$

Sizing the photovoltaic panels: Due to weather conditions in Africa a peak sunshine period of 6.6 hours is available. In order to determine the required solar panel input power, the total load must be divided by the peak sunshine period as follow:

$$P_{solar\ panel\ input} = \frac{3893.8\ Wh}{6.6\ h} = \ 589.97\ W \qquad (3)$$

This implies that solar panels that will generate 589.97 watts hour are needed.

Selecting the photovoltaic panels: A combination of photovoltaic panels must be selected to provide at least 589.97 W. Five 130 W photovoltaic panels will be used to generate 650 W. Each photovoltaic panel will provide an output of 130 W ($P_{\max}$) at 7.7 A (current at $P_{\max}$). It should be noted that any configuration of solar panels can be used to generate at least 600 W of power. In the Potchefstroom region there is more than 2000 kWh/m^2 of solar energy available to generate power, as it is mentioned above.

Selecting the charge controller (solar regulator): Charge controller is rated by the amount of current they can receive from the photovoltaic panels. Therefore it is necessary to know the exact rated short circuit current of the photovoltaic panels. The panels that are selected in the previous step, each has a rated short circuit current of 8.1 A. The charge controller should be capable of handling the total short circuit current. Thus the total short circuit current is:

$$I_{Total.S.C} = 5 \times 8.1 = 40.5\ A \qquad (4)$$

The output of photovoltaic panels vary with temperature and due to this an additional 25% must be added to the total short circuit current rating to allow for growth and the fact that the solar panels may exceed their rated output.

$$I_{Total.S.C} = 1.25 \times 40.5 = 50.63\ A \qquad (5)$$

This implies that a charge controller of at least 50.63 A is needed for the design. There is not a standard size of 50.63 A and due to this the developer propose the use of a 60 A charge controller. The charge controller must have a voltage rating of 24 Vdc as this is the operating voltage of the TECMs.

Sizing the batteries: It is recommended to shallow cycle batteries so that it last longer. This implies that the batteries are discharged to only 20% of its capacity. A conservative design will save the deep cycling for occasional usage, like when it is raining or cloudy. This implies that the battery bank should be about five times the daily load. This also means that the system will be able to provide power continuously for five days without any sun or recharging. The total battery amp-hours (Ahs) required is determined by the daily watt-hour requirements and the desired number of days of storage capacity required and the assumption that the battery will never be discharged more than 20% of its capacity. First the average Ahs per day are calculated by dividing the average daily load with the system voltage.

$$Average\ AH/day = \frac{3893.8\ Wh}{24\ V} = 162\ Ah/\text{day} \qquad (6)$$

The number of batteries connected in parallel (N) is determined by multiplying the average Ah per day with the number of battery storage days and dividing that with the battery discharge limit and the battery ampere capacity of the batteries that was chosen. The batteries must have two days of storage capacity and the discharging limit is 0.8 and the batteries to be used are 100 Ah batteries.

$$N = \frac{(162\ AH/day)(2\ days)}{(0.8)(100)} = 4 \text{ batteries in parallel} \qquad (7)$$

In order to get a system voltage of 24 Vdc it will be required to connect two 12 Vdc batteries in series.

Power supply requirements table: The design of the solar power supply was discussed in this section. The design decision requirements for each of the units in the solar power supply are summarized in the table 1. In the table the requirements for each unit is given as well as the quantity needed. There are many quality brands for each unit and the decision on which brand to use will be determined by each person's requirements; like cost, quality, availability ext. It is however important that the selected brand for each unit must adhere to the requirements as determined in table 1.

Table 1: Power supply requirements

Unit	Quantity	Requirements
Photovoltaic panel	5	130 W at 7.7 A
Charge controller	1	24 Vdc, 60 A
Battery	4	12 Vdc, 100Ah

Power supply connection diagram: The power supply must provide two output voltages, a 24 Vdc output for the TECMs with fans and a 12 Vdc output for the temperature control circuit. A graphical illustration of the power supply is shown in figure 4. This diagram illustrates the connection of the separate units.

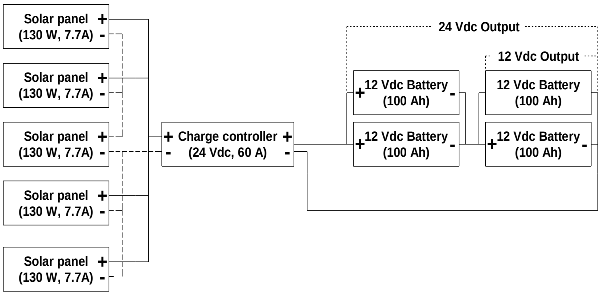


Figure 4: Power supply concept

2.3. Temperature Control

In order to regulate the temperature between 2 ˚C and 8 ˚C the KEMO M169 temperature switch supplied by Communica is selected. This temperature switch is the on/off cycle type temperature controller. This temperature switch, switches according to a pre-set temperature value a relay on or off. When the measured temperature is below the pre-set value the temperature switch, switches off the TECMs and when the measured temperature is above the pre-set value the temperature switch, switches on the TECMs. In this design the pre-set temperature value will be set at 5 ˚C. This allow for a temperature hysteresis band of 3˚C below and above the pre-set temperature value. The temperature switch has a temperature range of 0˚C to +100˚C, which cover the full range of temperature for the project. The output relay is able to switch 5 A at 25 V. The current rating is however to low as the TECMs will occupy 6.6 A starting current and 5.6 A running current at 24 V. This requires for an extra power switching stage to be built, ensuring that the TECMs get enough power to function properly. The output relay of the KEMO M169 temperature switch is used to switch another relay with ratings of 10 A at 24 Vdc. This relay is able to handle the amount of current needed by the cooling unit. In figure 5 the KEMO M169 temperature switch is illustrated [8].

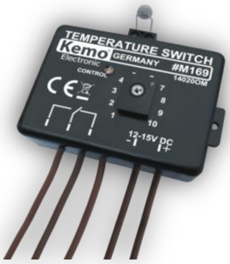


Figure 5: KEMO M169 temperature switch

In figure 6 the wiring diagram of the complete temperature control circuit is illustrated. Internal Relay is the internal relay of the KEMO M169 temperature switch and External Relay is the relay that has been added to compensate for the current used by the TECMs.

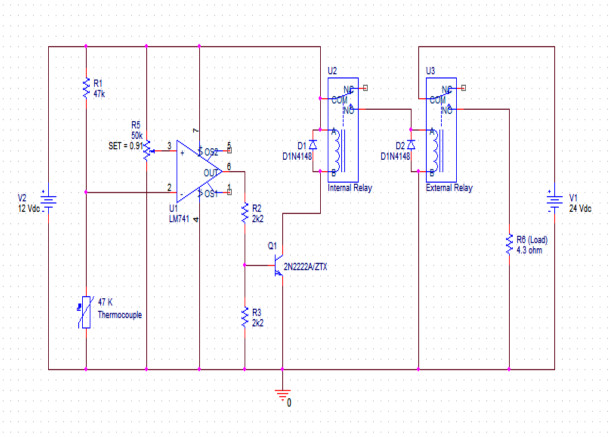


Figure 6: Wiring diagram of temperature control circuit

In order to evaluate if the temperature control circuit will be able to control the temperature of the refrigeration compartment between 2 ˚C and 8 ˚C a temperature sweep of the complete circuit was done in OrCAD®. The switching graph is illustrated in figure 7. This graph illustrate that the output of the control circuit is 0 Vdc for all the temperature values below 5 ˚C and the output is 24 Vdc for all the temperature values above 5 ˚C.

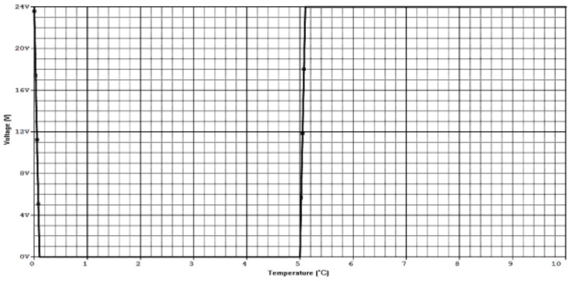
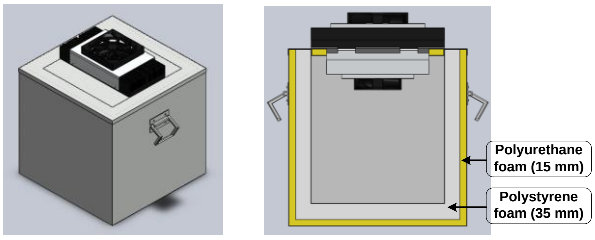


Figure 7: Switching graph of temperature control circuit

3. SOLIDWORKS® MODEL DESIGN

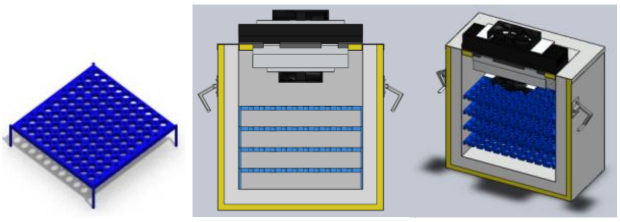
The design and construction of an accurate model for the cooling holder as well as the TECM and heat sink fan units was the first part of the SolidWorks® simulation. These models will then be used to perform a thermal analysis for the cooled operating condition of the cooling holder. In figure 8(a) the model designed for the cooling holder in SolidWorks® is illustrated. The main objective was to create an accurate model to be able to perform an accurate thermal analysis of the refrigeration compartment temperature of the cooling holder. The cooling holder consists of two layers of temperature isolation material that is covered in a thin layer of metal sheet to protect it. The temperature isolation material is polyurethane foam with a thickness 15 mm and polystyrene with a thickness of 35 mm, as indicated in figure 8(b). The polyurethane foam forms the outside layer and polystyrene form the inside layer. The combined thickness of the isolation is 50 mm. The reason for the choice of the two materials is that they have the lowest thermal conductivity values. The thermal conductivity of polyurethane foam is 0.039 W/m˚C and for polystyrene is 0.037 W/m˚C. To enhance the efficiency of the cooler box, it was decided that a top loading entry door to the cooler box would be used. This does not allow the heavy cool air to be drained from the cooler box each time the door is opened, as is the case with vertical cooler doors. The volume of the inside area of the cooling holder is 0.27 m^3. The total capacity of the cooling holder is 27 litres.



(a) (b)

Figure 8: (a) Final design of cooling holder; SolidWorks® model, and (b) Cooling holder enclosure.

Vaccine storage shelves for the cooling holder are designed as shown in figure 9(a). These storage shelves make it possible to store a total of 400 vaccine bottles, 100 on each shelve. Each one of the vaccine bottles is able to store 20 ml of vaccine. This count up to a total of 8 litres of vaccine. In figure 9(b) the position of the shelves inside the cooling holder's refrigeration compartment is shown.



(a) (b)

Figure 9: (a) Vaccine storage shelf and (b) Position of vaccine storage shelves in cooling holder

4. SIMULATION AND RESULTS

The aim of this simulation is to verify whether the design cooling holder has the necessary cooling capacity for an ambient temperature. As an example in this simulation the ambient temperature is considered 20 ˚C. The time period that the designed cooling holder takes to reach the desired temperature in the refrigeration compartment of the cooling holder is also determined through this simulation. The no-load simulation is done at temperature 20 ˚C. The results for these simulations are illustrated in three different formats: a table format, temperature profile format and graph format. The table format illustrates the minimum, average and maximum temperature of the surface and volume goals. The temperature profile gives a visual illustration of the temperature on the inside of the cooling holder. The graph format illustrates the temperature at a specific time period and this also shows the amount of time that the cooling holder takes to reach 5 ˚C on the inside of the cooling holder. The values shown in table 2 are the results for both the volume and surface goals of the thermal analysis at an ambient temperature of 20 ˚C while the TECMs are not in operation. The temperature throughout the cooling holder is uniform 20 ˚C as illustrated by the numerical results in table 2. It is important to ensure that the temperature in the cooling holder is at the same temperature as the ambient temperature at which the test is done to test the cooling power of the heat pumping unit correctly.

Table 2: Numerical results; No-operation of TECMs at 20˚C

Volume Goals	Value (˚C)	Surface Goals	Value (˚C)
Min air temp.	20.05	Min air temp.	20.05
Ave. air temp.	20.05	Ave. air temp.	20.05
Max air temp.	20.05	Max air temp.	20.05

The values obtained from the volume and surface goals show that the ambient temperature remains constant at 20.05 ˚C. In figure 10 the temperature profile of the cooling holder at ambient temperature of 20 ˚C is illustrated.

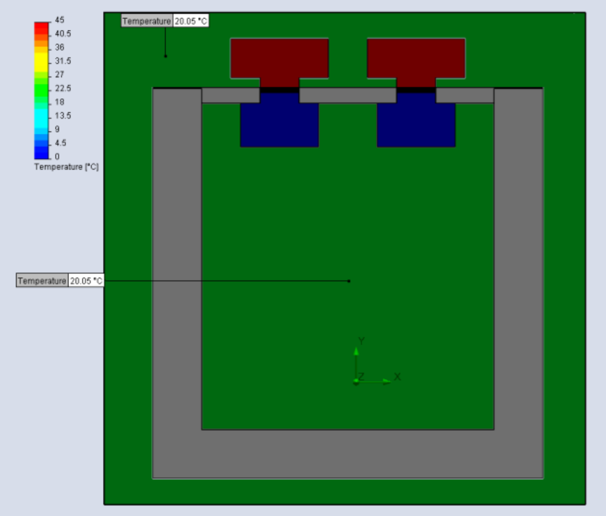


Figure 10: Temperature profile; No-operation of TECMs at 20 ˚C

The values shown in table 3 are the results for both the volume and surface goals of the thermal analysis at an ambient temperature of 20 ˚C, while the TECMs are in operation.

Table 3: Numerical results; Full operation of TECMs at 20 ˚C

Volume Goals	Value (˚C)	Surface Goals	Value (˚C)
Min air temp.	3.857	Min air temp.	3.999
Ave. air temp.	4.814	Ave. air temp.	4.603
Max air temp.	5.770	Max air temp.	5.206

In figure 11 the temperature profile of the cooling holder at ambient temperature of 20 ˚C is illustrated. Figure 12 illustrates that the design cooling holder takes about 17 minutes to reach 5 ˚C on the inside of the cooling holder when the ambient temperature is 20 ˚C.

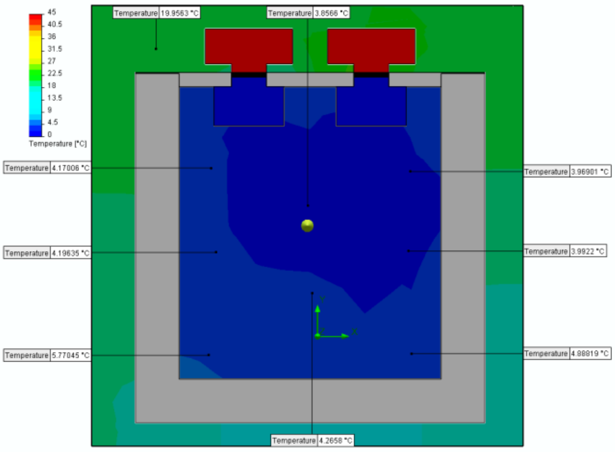


Figure 11: Temperature profile; Full operation of TECMs at 20 ˚C

The results of the no-load simulation verify that the design cooling holder has the necessary cooling capacity to cool the refrigeration compartment of the cooling holder to 5 ˚C while the ambient temperature is 20 ˚C. The time in which the desired temperature on the inside of the cooling holder is reached show a linear relationship with the ambient temperature, due to the increase in the heat load on the inside of the cooling holder when the ambient temperature increase.

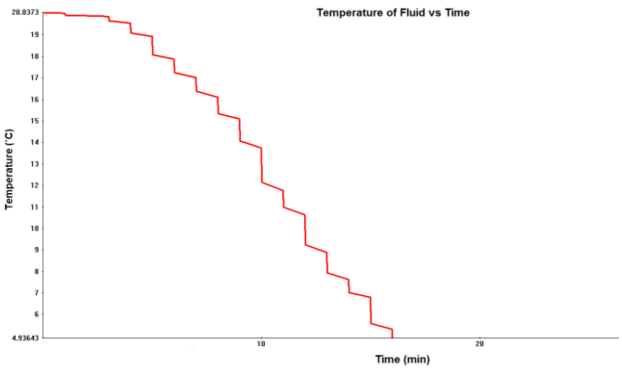


Figure 12: Time graph; Full operation of TECMs at 20 ˚C

The actual constructed model of the complete cooling holder system is illustrated in figure 13(a). This model was fabricated by making use of the designs done in SolidWorks®. The AA-100-24-22 thermoelectric heat pumping assembly is illustrated in figure 13(b). The heat sink fan assembly is illustrated in the top picture. The cold sink fan assembly is illustrated in the down picture. It is directly related as to the design module done in SolidWorks®. This prototype was tested at different conditions.

(a) (b)

Figure 13: (a) Actual constructed model and (b) AA-100-24-22 thermoelectric heat pumping assembly

5. CONCLUSION

The detail design of the thermoelectric cooling holder was discussed in this paper. The design of the solar power supply was also discussed. The calculation for the sizing of the photovoltaic panels, charge controller and batteries were done. It was concluded that five 130 W photovoltaic panels must be used to provide 650 W of power in order to charge the batteries during the day and provide power to the cooling unit. The simulation that was done in OrCAD® on the KEMO M169 temperature switch was discussed. The results of the simulation validate that this temperature switch will be able to control the temperature in the refrigeration space between 2 ˚C and 8 ˚C. The design of the cooling holder is done in SolidWorks®. Thermal simulations of the cooling holder were performed in Flow Simulation. A thermal analysis of the complete cooling holder was done in Flow Simulation at the ambient temperature of 20˚C, for no-operation and full operation of the TECMs in order to test their cooling performance. The results reveal that the cooling holder takes about 17 minutes to reach 5˚C in the refrigeration space when the ambient temperature is at 20 ˚C. A prototype cooling holder was build based on the design done. This design and investigation is very important to show if a cooling holder for the storage of medication can be made from using thermoelectric cooling modules instead of the normal compression cycle as used in normal refrigerators.

6. REFERENCES

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