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Design and Performance Evaluation of a Mobile Solar Vending Cold Cabinet

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Abstract: *This study focused the design and evaluation of a mobile solar vending cold cabinet used for storing and distribution of temperature-sensitive items. The system consisted of aphotovoltaic (PV) panel, charge controller, deep-cycle battery, and the cold cabinet that has a drier-cum-filter with other basic refrigerating components. The solar power generation system was designed to produce a battery backup life of 18 hours. Tests were conducted with and without loads inside the cold cabinet, and the daily coefficient of performance (COP) of the system was determined. The results obtained indicate that the average daily actual COP was 4.5 and the minimum temperature attained in the cabinet was -3.8Celcius (269.2 K). The study showed that the solar powered cooling cabinet designed can serve as an alternative means of storing and distribution of temperature sensitive items.*
Keywords*: Photovoltaic Panel, Coefficient of performance, Cold Cabinet, DC Compressor*

I. Introduction

Amount of energy consumption by refrigeration and air-conditioning systems constitutes a significant amount in global energy utilization. The International Institute of Refrigeration (IIR) has estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning processes of various kinds (Wimolsiri, 2006). A reduction in overall energy consumption cannot be achieved solely by efficient design of the air cooler but by powering the refrigerating system using renewable energy source.The use of renewable energy in cooling technology does not only provide additional energy source but also enhance clean energy utilization that mitigate environmental pollution. Solar energy can be used to power refrigerator in form of work-driven or thermal-driven systems depending on the particular refrigeration system required. Work-driven systems which are the focus of this study are classified as vapor compression system while thermal driven systems are mostly vapor absorption system.Solar-powered refrigerators are capable of keeping perishable goods cool during hot weather conditions and serve as means of storing vaccines at their appropriate temperature to avoid spoilage. This technology will go a long way to alleviate poverty in the developing countries such as Nigeria which has great potential for marketing dairy, fruits, meat and vegetables.The idea of solar refrigerator started in Paris 1872 by AlbelPifrewho designed a solar boiler to supply heat to a crude absorption machine, producing a small amount of ice (Wimolsiri, 2006).This technology needs to be developed due to irregular power supply in most developing countries.

A state of art review that presented different technologies that deliver refrigeration from solar energy was conducted by (Kim and Ferreria, 2008).A comparison was made between different solutions both from the point of view of energy efficiency and economic feasibility. Thermal absorption is given preference over thermo-mechanical systems. However, in the developing country like Nigeria where chemicals are not readily available in the rural areas, more attention is focused on work-driven refrigerators.An extensive work was conducted by Randip (2010) on solar adsorption refrigeration cycle. The research focused adsorption refrigerator due to its low noise and non-corrosiveness. However, the fact still remain that vapor compression system is more efficient and capable of high tonne of refrigeration.A study of solar powered cooling systems with the absorption pair of Ammonia-Water was carried out by Rupesh et al. (2012). Various attempts to improve the performance of the system were compared. It was noted that the most important parameter in the design of a solar powered absorption refrigerator is the generator inlet temperature of the chiller. However, the design of a vapor compression system eliminates the difficulties of chiller design and the available solar power can be used directly to power the compressor. El-Shaarawa et al.(2013) studied the performance and economic analysis of a simple photovoltaic powered vapor compression refrigeration system in winter at the Eastern Province of the Kingdom of Saudi Arabia. A refrigeration efficiency of 60% was calculated after the formation of ice that took about 6hours 40minutes.Recently, solar powered fridges were introduced in Nigeria due to irregular supply of electricity. This has been of help in the storage of vaccines and medicines in hospitals and pharmacy shops. There are many challenges facing the retailing system of manytemperature sensitive merchandise. These include; Poor temperature regulation of merchandise, lack of appropriate mobility and poor delivery system at the required temperature.Most of the available solar fridges are thermally driven absorptionsystems, designed purposely for air-conditioning purposes. However, the system is used as refrigerator due to the cost of operating a compressor using solar inverter.The possibility of operating a compressor driven, manually powered refrigerator was investigated by Oke et al., (2015).The study shows that small direct current compressor can be used for small size refrigerator. The compressor was mounted at the back of the bicycle that powered the refrigerator.The present study was aimed at the design and implementation of a mobile solar vending cold cabinet. In achieving this, the following objectives were met; design of a cabinet that houses temperature sensitive merchandise, mobile unit for conveyance of the refrigeration system, and solar powered direct current generating system that incorporates a direct current compressor.The project is relevant in Nigeria because of high solar insolation which is evident by high ambient temperatures throughout the year in most parts of the country.Maiduguri has solar power availability of about 6.5kWh/m^2/day (Osueke et al., 2013). This implies that we have more energy at our disposal topower refrigerators that will be able to fulfill the huge potential demand for refrigeration in the rural areas. It will also cater for mobile refrigeration for hawking of temperature sensitive materials.

II. Materials and Method

Description of the System

The system was designed, fabricated and tested in the Department of Mechanical Engineering, ObafemiAwolowo University, Ile-Ife, which lies at latitude 7^{o}31.06^{1}N and longitude 4°31.22^{1}E.A 130W Photovoltaic(PV) panel (1480 x 673 x 35mm^3, manufactured by Salphon Solar Modules Ltd., India) was used to obtain the desired voltage and current, respectively. A 12V deep-cyclestorage battery was charged by solar PV module during daytime and used to supply power to theloads as needed.The primary function of a storage battery in a PV system was to enhance energy storage capacity and autonomy, voltage and current stabilization. A 15A charge controllerwas used to regulate the flow of electricity from power generation system (PV panel) into the load (DC compressor) and storage system (deep-cycle battery).In photovoltaic systems the charge controller is used between solar module and battery bank. The mainwork of the charge controller is to protect the battery from deep discharging and overcharging.All electrical wires used with the system are of size 50 mm^2 to keep the voltage loss of the PV panel and battery less than 1% at designed range.The cold cabinet consists of a drier-cum-filter besides the main components: a DC compressor, acondenser, an expansion device and an evaporator. R-134A was used to serve as refrigerant for low, medium and high temperatures. It condenses at moderate pressure under normal atmospheric conditions and boils at 246.7 K.

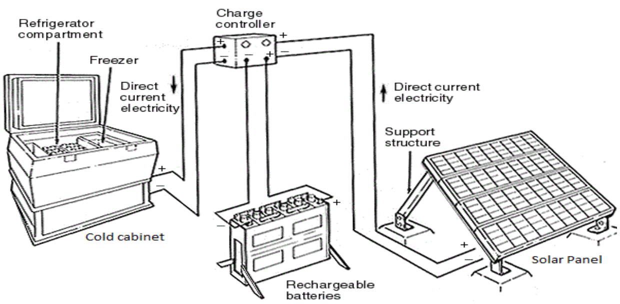


Figure 1: Schematic Diagram of the Refrigerating system

The design was done using Autodesk Inventor 2013 due to the availability of integrated motion simulation and assembly stress analysis environment. It has the ability to input driving loads, friction characteristics and dynamic components, and run dynamic simulation tests to see how a product will work under real-world conditions. The schematic diagram of the cold cabinet and solar power source is shown in Figure 1. This is combined with the trolley and was translated to real time assembly in the Autodesk Inventor as shown in Figure 2.

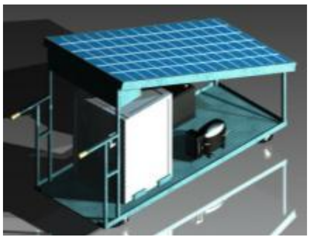


Figure 2: The Assembled Isometric Drawing of the System

The cold cabinet was positioned on the trolley in front of which are the deep-cycle battery, charge controller and the DC compressor. On the frame above the cold cabinet lies the solar panel inclined at an angle of about 30^0 for proper trapping of the solar radiation. The schematics in Figure 1 show how the flow of Direct current electricity gotten from the solar panel is used to charge the Deep cycle battery which in turn drives the dc compressor which is the heart of the refrigeration system.The working principle of a refrigeration system isshown in Figure 3. The refrigerant in the evaporator absorbs heat from the refrigerated space; the heat absorbed heat up the refrigerant which goes into the compressor. The compressor works on the refrigerant from low temperature and pressure states to high temperature and pressure states. The vaporised refrigerant then enters the condenser where the heat absorbed from the refrigerated space is expelled to the surrounding. The refrigerant further flows into the expansion valve where the temperature and pressure drops making the refrigerant liquid enough to enter the evaporator. Once this cycle is completed and heat being absorbed from the refrigerated space is released into the atmosphere through condenser, cooling is experienced in the cold cabinet.

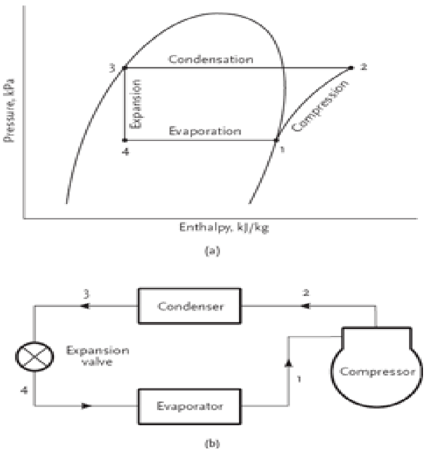


Figure 3: A typical refrigerator cycle

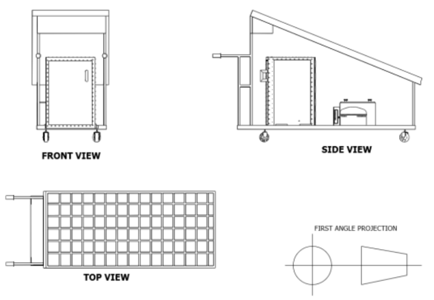
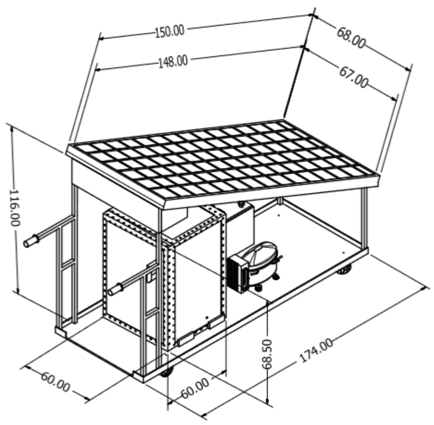


Figure 4: The first angle view of the refrigerating system

Figure 4 is the first angle view that shows the front, plan and the side elevation of the refrigerating system. The orthographic view which shows the systematic assembly of various components is shown in Figure 5.



Figures 5: The orthographic view of the system.

The dimension of the cold cabinet is 60mm x 60mm x 68.5mm and the solar panel has dimensions 148mm x 68mm x 35mm which covers the top of the entire refrigeration system thereby protect it from being exposed to direct sunlight.

2.1Project Fabrication

The cold cabinet was fabricated with Aluminum sheet because of its low density and ability to resist corrosion. Aluminum is a relatively soft, durable, lightweight, ductile and malleable metal which made it the choice of material for the design of the cold cabinet. The ends were riveted to one another and welded where necessary.

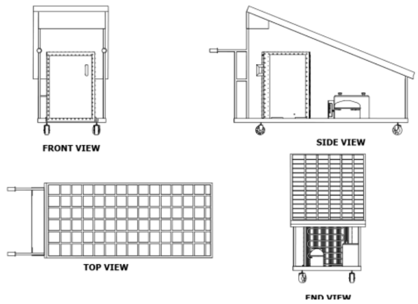


Figure 6: Various views of the project

The trolley was fabricated using steel angle bars for the frame work and rough surfaced steel plate for the platform. The safe was fabricated with steel plate and the handles with rectangular pipe. The castor wheels were welded to the trolley.The choice of electrode for welding of the whole project was mild steel electrode (gauge 12) as it is the best for welding steel plates.

III. Results and Discussion

3.1 Testing Conditions

Various tests were carried out outside the Spider Building (Department of Mechanical Engineering, ObafemiAwolowoUniversity, Ile-Ife, Nigeria) under normal atmospheric conditions. Ambient and cabinet temperatures were recorded using mercury in glass thermometer. The actual temperatures (of the condenser and evaporator) were also recorded using a thermocouple. Most measurements were made between the hours of 8.00 and 11.00 in the morning. Further measurements (as needed) were made between 12.00 noon and 3 P.M on those days as significant change in atmospheric conditions occur within these periods.

3.2 Experimental Results

On the test days (in June 2014), initial ambient and cabinet temperatures were recorded in 10 minute intervals. Tests were carried out on sunny, cloudy and rainy days to study effects of atmospheric conditions on the performance of the system.On the first day, the initial ambient temperature recorded in the morning was 23.9^{o}C while the cabinet temperature was 26.5^{o}C. The cabinet temperature was observed to drop to 3^{o}C in 30 minutes and -2.2^{o}C in 60 minutes. The cabinet temperature dropped to -3.6^{o}C after 90 minutes from the beginning of the test as shown in Fig. 7. On the second day, the initial ambient temperature recorded was 25.6^{o}C while the cabinet temperature was measured to be 26.6^{o}C. The cabinet temperature dropped to 10^{o}C in 10 minutes, -0.2^{o}C after 30 minutes and a temperature of -2.5^{o}C was recorded after 60 minutes. The minimum cabinet temperature of -3.6^{o}C was attained in 1 hour 40 minutes as shown in Figure 8.

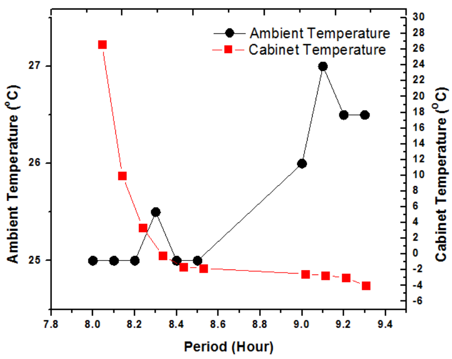


Figure 7: Temperature recorded in the morning of the first day.

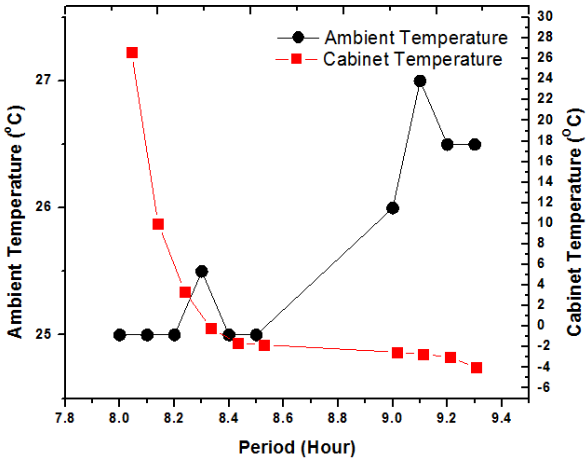


Figure 8: Temperature recorded in the morning of the second day

The afternoon tests were conducted within the noon hours as shown in Figure 9. The ambient temperature measured was 33.5°C and the cabinet temperature was steady at 30.4°C. The cabinet temperature dropped to 12.2°C in 10 minutes and 4°C after 30 minutes. The cabinet minimum temperature of 3°C was attained after 50 minutes as shown in Fig. 9.

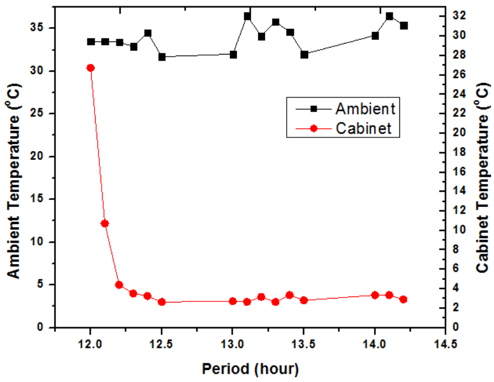


Figure 9: Temperature recorded in the afternoon of the third day

The tests conducted on the third dayinvolved about 1 Litre of water filled into a satchet. The initial ambient temperature was 25.5°C while the cabinet temperature was 26.5°C. The cabinet temperature dropped to 11.2°C in 10 minutes, 1.5°C in 30 minutes and -1.9°C in 60 minutes. A minimum cabinet temperature of -3.8°C was obtained in 110 minutes from the beginning, and the water in the satchetwas found to have frozen (Fig. 10).

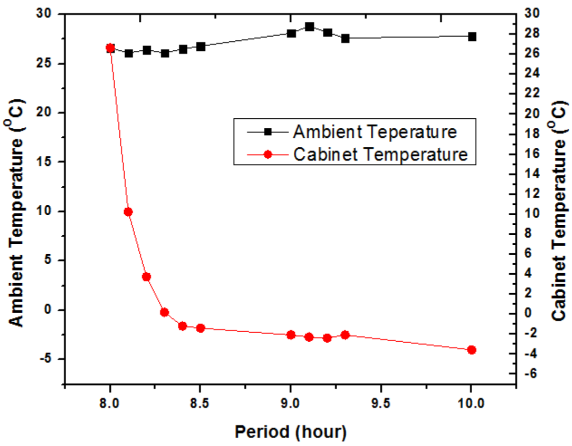


Figure 10: Temperature recorded in the morning of the third day

Coefficient of Performance of Cabinet

The maximum possible coefficient of performance, COP, is that of a Carnot cycle, and is given as follows (Arora, 2000):

$$COP_{carnot} = \frac{T_{evap.}}{T_{cond.} - T_{evap.}}$$

Since it is practically impossible to obtain the Carnot C.O.P due to losses, it was assumed that the obtainable C.O.P should be multiply by a factor.

$C.O.P_{ref} = 0.8 \times C.O.P$

Where $T_{evaporator.}$is the minimum temperature of the evaporator in Kelvin and$T_{condenser.}$ is the maximum temperature of the condenser in Kelvin and $C.O.P_{ref}$is the coefficient of performance of the cooling cabinet.

The COP represents the overall efficiency of the system. Based on the actual data, the maximum COP_{ref} was calculated using values recorded very early on the first morning with light rainfall between 8:00AM and 12:00PM. While the minimum was calculated at noon. This is attributed to higher temperature difference between condenser and evaporator at noon hours. The results show that the COP of cooling system decreases as we go to lower refrigeration temperatures. It was observed that the COP from the afternoon values were always constant. The average daily actual COP of the refrigeration system between the hours of 8:00am and 12:00noon is 4.5 while between the hours of 12:00noon to 3:00pm it was found to be 4.4.From the calculated COPs, it is observed that the COP of the first morning is higher than all the rest. This is as a result of a light rainfall during the testing period. This resulted in a drop in ambient temperature which led to an increase in the temperature difference between condenser and evaporator. The low ambient temperature (with respect to the condenser) caused a more efficient heat transfer from the condenser to the condensing medium (environment).

IV. Conclusion

The capability of the design, fabrication and implementation of a mobile solar vending cold cabinet has been demonstrated. Furthermore, the operating conditions were found to be almost exactly in accordance with the design specifications. The theory of the system is therefore well understood.The energy supply from the solar panel (130W) charges the battery which when fully charged powers the refrigeration system for 18 hours. The average temperature maintained in the cabinet between the hours of 8:00am and 12:00noon is -4^0C (269 ^{0}K) while between the hours of 12:00noon and 3:00pm was 3^0C (276 ^{0}K).The average daily actual COP of the refrigeration system between the hours of 8:00am and 12:00noon is 4.5 while between the hours of 12:00noon to 3:00pm was found to be 4.4.In summing up the overall discussion, it can be concluded that the conditions obtained by the designed system can maintain items in their most edible and marketable conditions. The cold cabinet can be sized to suit different load requirements. It can be used outdoors for business activities and also indoors with the panel placed outside. The lightness of the system makes it portable and can therefore be moved around easily.It is recommended that further research be carried out to improve the COP during high temperature periods (afternoons). The system should also be optimized for commercialization.

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