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Simulation of the Refrigeration Cycle and Calculation of the Heat Balances of a Mobile Solar Fridge (Sustainable Mobility)

[1] Omar Tanane, [2] F. Belmir, [3] A. El Bouari

[1] [3] LCPMC Laboratory Sciences Faculty of Ben Msik / Hassan II University of Casablanca/Morocco.
[2] LMPCE Laboratory - USMBA University of Fez, Morocco.
Corresponding Author Email: [1] o.tanane@gmail.com, [2] fouzi.belmir@usmba.ac.ma, [3] elbouari@gmail.com

Abstract— ***In this article, we present a study of the thermal performance of a new solar mobile refrigeration prototype for the preservation of perishable foods. The simulation of the refrigeration cycle and the calculation of the thermal balances made it possible to estimate its consumption and to evaluate the capacity of each photovoltaic component necessary to produce energy. We provide a description of the refrigerator construction and operation, including an energy balance analysis of the refrigerator performance under typical loads. The photovoltaic system requirements are also detailed.***

Index Terms— ***Composite, Material, Photovoltaic, Refrigeration, Simulation, Thermal.***

I. INTRODUCTION

With existing technologies, solar energy can be converted into electricity and heat. Either can be used to power refrigeration systems. The idea is not new, a solar refrigerator was first recorded in Paris in 1872. A solar boiler was used to provide heat to a crude absorption machine, producing a small amount of ice. Later, solar powered refrigeration systems were installed worldwide in many countries, e.g., Australia, Spain, and the United States. Most are thermally controlled absorption systems designed for air conditioning. Since they have a good power grid all over the world, however, people are more likely to choose a vapor compression air conditioning system. Before the energy crisis of the 1970s, research and development on solar-powered refrigeration systems was greatly reduced. Subsequently, electrical vapor compression systems played an important role in the market. At that time, photovoltaic (PV) technology was expensive, had low efficiency, and was not as widely available as it is today. Due to the shortage of energy in some areas, especially after the energy crisis of the 1970s, solar energy as a renewable energy source has again become a popular energy source. Research and development in the field of solar energy has developed rapidly, as has research into solar cooling. With the invention of the DC motor, photovoltaic technology was first used for pumping water. Later, the pump motor was modified to drive the vapor compression system. Water pumps and PV refrigerators have become a relatively large business. Subsequently, researchers integrated so-called Peltier coolers with PV panels into simple but inefficient solar coolers. These systems are used in the cold chain projects of the World Health Organization (WHO). The WHO initiated the development of solar refrigeration by photovoltaic panels in 1979, following the world conference on the environment in Rio de Janeiro. The first specification of a solar refrigerator for medical use has been published by the "Expanded Program on Immunization" (EPI).

This paper presents the design and evaluation of a new solar mobile refrigeration prototype. The design is primary focused on preservation of food products. We demonstrate by energy balance calculations that our mobile refrigerator has the performance for its use at very varied externals temperatures and loads up to 100 kg for each compartment.

II. CONCEPTION AND DESIGN OF THE MOBILE SOLAR FRIDGE

All the walls of the refrigerator are insulated with the same material and the temperatures at the different sides are homogeneous.

On our solar refrigerator, we have put in place photovoltaic panels that will convert solar energy into electrical energy; this energy is then used to power an electric compressor. The production of cold is provided by a conventional system constituted as shown in Figure 1 of the following main components:

- Electric compressor
- Expansion valve
- Evaporator and condenser.

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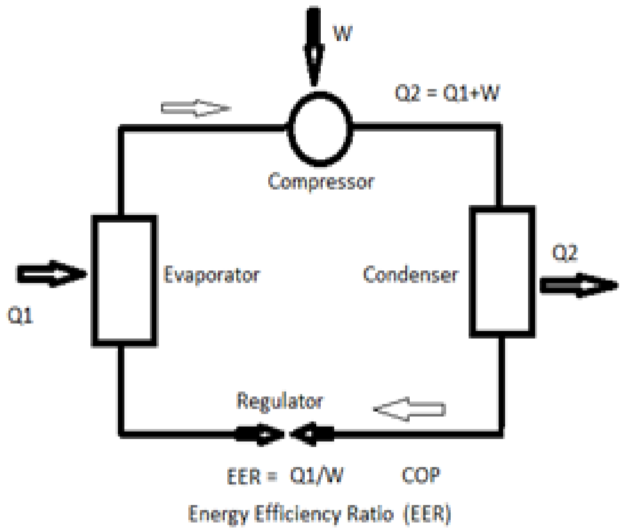

Figure 1: Mechanical compression system

III. CHARACTERISATION OF THE INSULATING MATERIAL

a. Thermal Conductivity

Determination of the thermal conductivity of waste date palm and insulating panel was performed using a

Thermal Conductivity Analyzer (λ-Meter EP500e), its measurement consists in applying variable heat flux in a block comprising a sample taken between two plates.

The conductivity and the diffusivity value of date palm waste are respectively 0,041 K (W/mk) and 90.038 (W.s1/2/m2K). These values are comparable to those found for other insulating materials in the market (Table I). The insulating panel showed an increase in the value of the thermal conductivity of about 0.058 W/mk According to Figure 2, this is due to the attachment of conductive metal sheets on its surface as well as the use of the resin epoxy for strengthening the panel.

Table I: Density and thermal conductivity of some materials

	Density (kg.m^{-3})	Thermal conductivity (W/m.K)
Extruded polystyrene	20-30	0,028*
Polyurethane	30	0,030*
Expanded polystyrene	30-300	0,038*
Date palm waste	200-800	0,041**
insulating panel	-	0.058**
*Values taken from the literature ** our values		

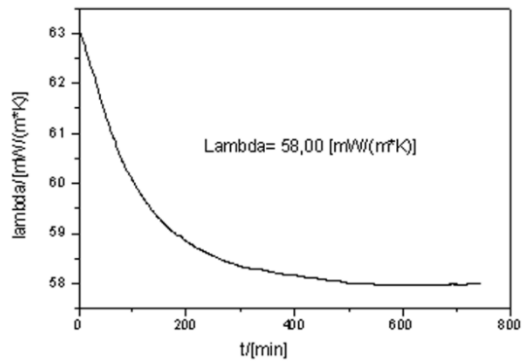

Figure 2: The thermal conductivity of insulation panel

b. Scanning Electron Microscopy

To investigate the origin of the thermal resistivity of date palm wood, the sample of date palm wood and the polyurethane used in the insulation of refrigerators at industrial sector were analyzed by scanning electron microscopy.

The images SEM in figure 3 of the samples (a) and (b) show that the materials are made up of closed cells having a roughly spherical shape each cell is completely enclosed by a membrane or thin-walled plastic. For the polyurethane demonstrates the existence of two types of open and closed cells. In a closed cell, the polymeric membrane forming in the walls of the cells forms a barrier that prevents the passage of gases and liquids, although the gas can pass through the membrane by the slow diffusion process. Therefore, the closed-cell foams have a water absorption and water vapor permeability lower than those of open cell foams. If the gas has a low thermal conductivity, the closed cell foams generally have greater resistivity to heat transfer than those that open cells.

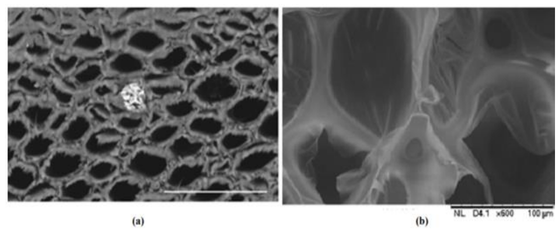

Figure 3: SEM photograph of sample (a) date-palm wood (b) polyurethane scale 100µm

The cell size also has an influence on the heat resistance. The internal structure of the date palm wood reveals the existence of two types of alveolar which explains the low value of thermal conductivity.

The contributions due to the foods to be kept in the refrigerator depend essentially on their thermal properties and were used for the calculation of the losses caused by the food stuffs, these losses are regrouped in Table II

Thermal inputs (sensible and latent energy) from air infiltration due to permeability and the introduction of outdoor fresh air through ventilation must be considered.

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This is the heat coming from the infiltration air inlets and opening the door. The number of 24-hour air changes is difficult to determine. It depends on the device and the frequency of opening the doors.

The use of solar energy in combination with refrigeration systems powered by electricity can represent a solution to reducing the electricity consumption of this sector. Solar refrigeration could therefore be a relevant solution to produce renewable solar cold. The solar cooling system generally consists of three subsystems: the solar energy conversion system, the refrigeration system, and the cooling load. The appropriate cycle in each application depends on the cooling demand, the power and temperature levels of the refrigerated object, as well as the environment. Several possible "paths" from solar energy to "cooling services" are shown in Figure 4. From the solar energy input, there are obviously two important paths to follow: solar thermal collectors for heating or photovoltaic cells with electricity. For solar thermal collectors, different types of collectors produce different temperature levels. This indicates that the temperature level can be adapted to various cycle demands. For example, the Rankine cycle, requires a rather high pipe temperature while the desiccant cycle manages at a lower heat input temperature level.

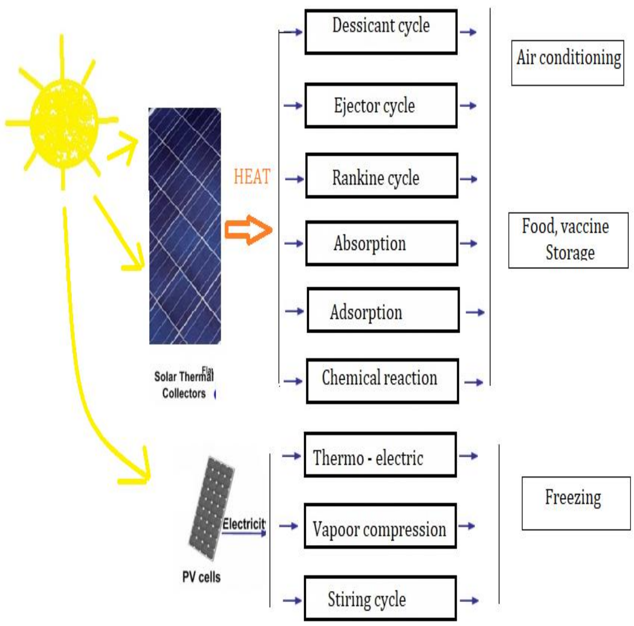

Figure 4: Cold production from solar energy.

The analysis of the advantages and disadvantages of the technologies enabled us to choose the solution of the type photovoltaic conversion of solar energy and mechanical compression, which does not require a large investment and gives both good yields in terms of coefficient of performance, the disadvantages mentioned for this technology will be minimized by the choice of a modulated speed compressor which will lower the consumption of the electricity produced during its operation and also a refrigerant with less effect on the environment will be chosen. The system that is the subject of this study is therefore a passive machine operating only with solar energy. This machine can be confused or compared with a conventional refrigerator made up of functional parts, an evaporator, a condenser, and an insulated compartment, containing the compressor and the expander.

Table II: Thermal loss of products

Before freezing	QD1 = m x C1 x DT1 4700 kJ
Breathing	QD = m x R -1 kJ
During freezing	QD2 = m x L15080 kJ
After freezing	QD3 = m x C2 x DT2 2288 kJ
QD=∑Qdi	QD=∑Qdi22 068 kJ = 0,4 kilowatts

The calculation of the heat balance makes possible to know with precision the quantity of energy which it will be necessary to cool an enclosure, the accuracy of this calculation is essential not only for the cost of the installation, but also for its exploitation. The elements considered in this calculation are numerous, it will be necessary to know the nature, the exposure, the surface of the glass walls, the ceilings, the floors, these elements being multiplied by variable coefficients according to the altitude, the solar radiation, geographical location. Other elements must be considered such as the renewal of natural or mechanical air, the various thermal bridges as well as the contributions which will weigh the calculation, for example the lighting, the quantity of material to be stored, its nature, the conditioning temperature.

The walls generally consist of several layers of materials of different thicknesses and thermal conductivities, the equation used to calculate its transmission coefficient and the following:

$$\frac{1}{k} = \sum \frac{e}{\lambda} + \left(\frac{1}{hi} + \frac{1}{he}\right) \text{ Or } \frac{1}{k} = \sum R + \left(\frac{1}{hi} + \frac{1}{he}\right)$$

- k: Thermal transmittance (W/m² °C)
- e/λ: Represents the sum of the ratios of the different layers,
- e: Thickness of or each material (m)
- λ: Useful thermal conductivities of the building material (W/m. °C)
- 1/hi, 1/he: internal and external surface exchange thermal resistances (m² °C/W)
- R: Thermal resistance of the material (m² °C/W)
- T1: Interior temperature of the heated room (°C)
- T2: Outside temperature (°C)
- Tw1, Tw2= Contact temperature on the wall inside and outside the room (°C).

It is assumed that all the walls of the refrigerator are insulated in the same way and that the temperatures on the different sides are homogeneous, the calculation of the different losses using the Thermo-Excel software are given in the table III

Table III: Leakage from the walls of the refrigerator

vertical walls	Qp1 = Km x Sm x ΔTm x t	7617 kJ	
Ceiling	Qp2 = Kp x Sp x ΔTp x t	2806 kJ	
Floor	Qp3 = Ks x Ss x ΔTs x t	2806 kJ	
	Qp = ∑Q	13230 kJ	0.2296 KW

- Km: thermal transmission coefficient through the walls in W/m². K
- Sm: the surface of the walls in m².
- ΔT: the temperature difference between the external and internal environment in K
- T: the basic time of the installation in second.

The intakes due to food depend essentially on their thermal properties. Table IV illustrates the thermal characteristics of some food products.

Table IV The thermal characteristics of perishable products

Quantity introduced / time base (kg)	100
Quantity stored (kg)	100
Introductory temperature (°C)	12,0
Outlet or storage temperature (°C)	-16
Specific heat before freezing C1 kJ/kg.K	2,350
Heat of Respiration (kJ/kg.K)	-
Latent heat of freezing L (kJ/kg.K)	150,8
Specific heat after freezing C2 (kJ/kg.K)	1,430

The data in Table III were used to calculate the losses caused by food products, these losses are grouped together in Table I

Thermal gains (sensible and latent energy) from air infiltration due to permeability and the introduction of new outside air through ventilation must be considered. This is the heat coming from the air inlets by infiltration and by opening the door. The number of air changes over 24 hours is difficult to determine. It depends on the device and how often the doors are opened. Manufacturers have drawn up tables resulting from statistical analyses. To determine the contributions in question, the operating conditions quoted in the table V have been assumed.

Table V: The conditions of use of the refrigerator

Door opening	
Opening time	10s
Hourly opening frequency	10 times per hour
Daily use of the refrigerator	8 hours per day

The following equation makes it possible to calculate these thermal contributions:

Qr = V x Δh x j x n / 1 000 = 8913 KJ = 0,2 KW

- Qr: Quantity of daily heat per air renewal (kWh).
- V: volume of the cold room (in m3).
- Δh: enthalpy difference between inside and outside the refrigerator (Wh/kg).
- j: air density in kg/m³.
- n: number of air changes over 8 h.

Based on the results of the heat balance, the cooling power required to cool the foodstuffs and the power of the associated motor compressor, which is set at 900 W/m^3, were determined. Based on this calculation, it was also possible to determine the models of the following main components: electric compressor, expansion valve, evaporator and condenser.

Determination of the main elements of the refrigeration cycle

a. Compressor

From the calculation of the heat balance, we chose the rotary compressor, where the speed is modulated by the compressor motor, this process makes it possible to reduce the energy consumed by approximately 20% and to maintain a constant torque at pre-established speeds. With a high air compression capacity, rotary compressors reduce the volume of air to achieve the desired pressure. The cooling capacity to be achieved is an initial selection criterion, but the selection of a compressor requires an overall view of the types available according to the cooling capacity and the capacity regulation mode. The advantages of this choice relate to:

- A reduction in moving mechanical parts (removal of valves) and therefore greater reliability.
- A good volumetric efficiency of a compressor thanks to the absence of dead spaces, as in reciprocating compressors.
- Better power modulation.
- Greater longevity.
- A much more favorable sound level (less vibrations), especially for hermetic devices.
- Less sensitivity to liquid refrigerant ingress (“liquid slugs” destructive to reciprocating compressors).

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- A maintenance cost also lower since the risk of failure is reduced.

Tables VI and VII summarize all the characteristics of the chosen compressor.

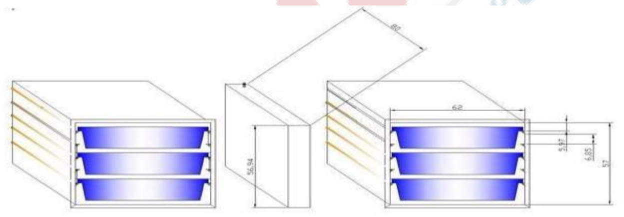
Table VI: records of data required for compressor selection

Cooling capacity	1363 (W)
Input	1.89 (KW)
Current	4.56 (A)
COP	2.89 (W/W)
Displacement	6.63 (m3/h)
Oil Charge	0.95 (dm³)
Dimension	356 (mm)
Weight	23 (kg)

Table VII: Technical characteristics of the compressor

Power required	Operating time	Qm (g/s)	Qva (m3/s)	μv_0	Qvb (m3/h)
Φ_0= 900 W	16h	10,7	1,12x 10^{-3}	0,63	6,42

The evaporator is the enclosure where perishable foods are packaged and stored, it is generally surrounded by a tube in the form of a coil where the refrigerant is transported to carry out the heat exchange with the environment the choice of the tube material and its length are important parameters. Copper is a very conductive material; the use of this material accelerates the exchange between the fluid and the refrigeration enclosure. The evaporator is made up of two compartments separated by a tray containing brine water to keep the quantity of cold and counter losses due to the considerate thermal contributions of the walls, each compartment includes drawers which will be used for storing food perishable.



Evaporator

The inner surface of the refrigerated enclosure is made of 2 mm thick stainless-steel sheet, the choice of this material is dictated by the regulations relating to the safety of materials and objects in contact with food. Stainless steels are among the most widely used materials in contact with food - in the food industry and in kitchens. The choice of grade depends mainly on:

- atmospheric and environmental conditions.
- Architectural design
- The surface finish to be achieved
- Frequency of interviews

In this work, the interior surface of the refrigerator is made of 304 grade stainless steel sheet.

The refrigerator is powered by twelve flexible photovoltaic cells, their unit powers are of the order of 120 W, therefore a maximum power of 1440 W, which will allow both the proper functioning of the solar fridge, the movement of the three-wheeled motorcycle and ensure recharging the batteries thus increasing the duration of autonomy of the whole. We opted for the choice of flexible photovoltaic plates so that they can marry the external design of the fridge. This geometric choice is guided by several factors such as the weight of the system, parasitic air currents and shocks during circulation of the fridge. For this flexible curved panels of figure 58 were chosen and prepared.

IV. ENERGY BALANCE ANALYSIS

The calculation of the heat balance makes it possible to know with precision the quantity of energy which it will be necessary to cool an enclosure, the accuracy of this computation is essential not only for the cost of the installation, but also for its exploitation. The elements considering in this calculation are numerous, it will be necessary to know the nature, the exposure, the surface of the glazed walls, the ceilings, the grounds, these elements being multiplied by variable. coefficients according to the altitude, the solar radiation, the geographical location. Other elements must be considered such as the renewal of natural or mechanical air, the various thermal bridges as well as contributions that will weigh the calculation for example the lighting; the amount of material stored its nature, the temperature of conditioning. Manufacturers have produced tables that result from statistical analyzes. To determine the contributions in question, the operating conditions mentioned in the Table1 have been accepted.

V. COOLING CAPACITY

Based on the results of the heat balance, we determined the cooling capacity needed to cool the foodstuffs and the power of the associated motorcycle compressor which is set at 900 W / m3. Based on this calculation, we have also been able to determine the models of the following main components: electric compressor, expansion valve, evaporator, and condenser.

The measurements made it possible to form an idea about the rate of cooling of the medium as well as the behavior of the medium when the temperature reaches low values. These measurements made it possible to draw the experimental curve of the Figure 5.

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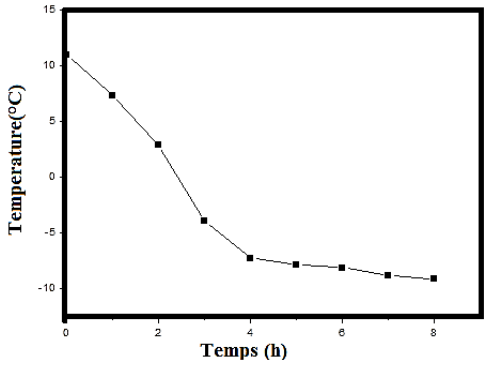

Figure 5: Evolution of the indoor temperature of the empty refrigerator evaluation

The thermal insulation material used in the mobile solar refrigerator was prepared from date palm wood collected and prepared by our own care.

Our measurements confirm that our refrigerated cabinet is intended for low temperature storage. Its performance in refrigeration itself is very modest. The refrigerator reaches the minimum temperature for 8 hours of operation given the large volume it contains; the temperature profile has a bearing after 6 hours of operation, which is explained by the cooling of the glycol water, which is the reserve of cold.

VI. THE TEMPERATURE INSIDE THE REFRIGERATOR

The refrigerated chamber is lined internally with a stainless-steel plate designed to act as a rigid tray and to prevent condensate from migrating into the insulation. The cold reserve is itself a compartment made of stainless steel built into the enclosure

The compartment studied is initially empty and at the average temperature Ti (Figure 6), it brings a certain load, represented by liters of water; at room temperature, it tells us about its capabilities of "refrigeration". Useful information to know what happens when a load is introduced at a higher temperature.

It is noted on the curve shown in the Figure 7 that during a complementary charge intake the temperature of the initial charge increases to go through a maximum. It can be observed that the temperature of the enclosure closely depends on that of the load.

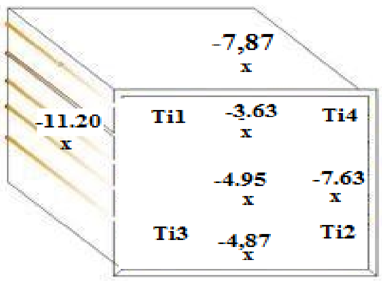

Figure 6: Temperatures of solar Refrigerator walls

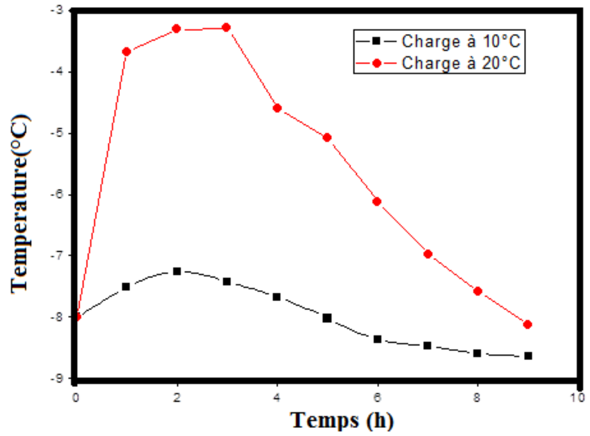

Figure 7: Evolution of the indoor temperature as a function of the temperature of the introduced charge

VII. PERFORMANCE

The Mobile Refrigerator has been instrumented to monitor its thermal behavior at ambient temperatures between 20 ° C and 40 ° C, which covers the temperature range that can be expected in the field. From the different measures, we were able to calculate the system performance. The measurements thus concern essentially the temperatures inside the refrigerated enclosure (on the walls and in the air) and temperatures at the characteristic points of the refrigeration unit. We also measured the current absorbed by the group (at the entrance of the electronic unit) and of course, the instantaneous power delivered by the photocells as well as the charge or discharge current of the batteries. Each result of a temperature measurement was systematically obtained from the average of ten Helpful Hints successive readings taken in time, to eliminate the unavoidable dispersion error when handling microvolts. Figure 6 shows the different places in the compartment where thermocouples have been placed.

(Tpr) are the temperatures of the walls (Ti) are the temperatures of the air inside the compartment.

We have of course experienced only one compartment on the two that make up the enclosure. They behave in the same way.

The temperature in the compartment itself was measured by means of a "cane" of exploration comprising four thermocouples 10 cm distant from each other. We were able to have an idea about the temperature profile in the compartment. We also measured the temperature of the different walls of the compartment in several places.

Our tests were carried out

In case the compartment is empty of any content. Although not of any practical interest, this configuration is very interesting because it corresponds to a rather unfavorable case of use.

In charge: We call charge, the equivalent mass in kg of water from the point of view thermal capacity of the products kept in a compartment. These tests were made for the following three significant temperatures: 20 ° C, 35 ° C and 40 ° C.

We have also followed the evolution of the temperature of the compressor load stopped. This configuration is presented when the reserve of cold being intact, the refrigerating machine breaks down. By letting the system evolve freely we can determine its autonomy see Figure 8.

Examining the curves in Figure 8, we can distinguish an area where the temperature of the load increases very slowly that we call a pseudo-landing zone where temperatures begin a rapid rise similar to a kind of thermal runaway

The phenomenon is observed when the cold reserve is exhausted. The measurements were made for a load equal to 20 kg and at 30 kg. As can be foreseen, the load has an influence on the autonomy, but this influence is negligible, because the quantity of cold stored in the load by sensitive heat is always weak before that stored in the reserve.

A refrigerating machine is often characterized by its Energy Efficiency Ratio (E.E.R) or C.O.P, the ratio between the quantity of cold produced and the work supplied.

Finally, since the operating conditions of the machine change over time, especially the hot source and cold source temperatures, the instant "C.O. P" or (E.E.R) should be distinguished from the average C.O.P (E.E.R) over a given period of use. The coefficients of performance at three temperatures are grouped in Table I. Our results are in perfect agreement with the teachings of thermodynamics.

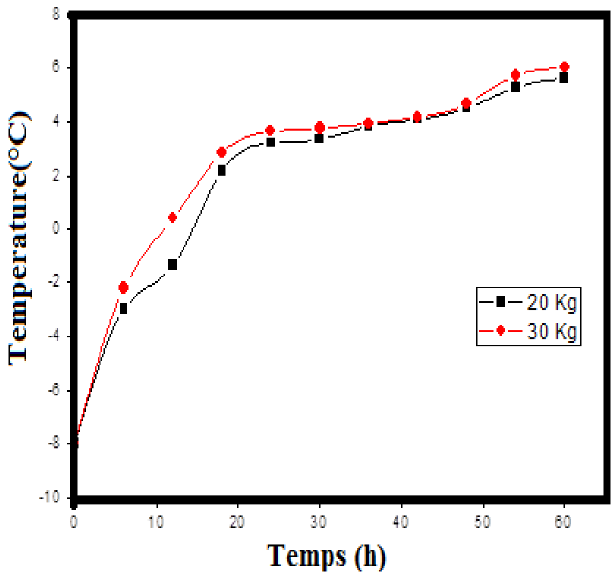

Figure 8: Evolution of the indoor temperature as a function Of the temperature of the load introduced compressor stopped

Table VIII: Energy Efficiency Ratio

Temperature (°C)	**C.O.P** (E.E.R)
0	4
-2.5	5,3
-5	3

VIII. SUMMARY AND CONCLUSIONS

The results presented in this article are part of a set of research that we conducted for the design and manufacture of a mobile solar refrigerator mounted on scooters, after studying each component of our solar refrigerator, and proceeded to different calculations of thermal performance, refrigeration, and energy balance. We have therefore been able to manufacture our solar-powered solar refrigerator prototype, the insulation of which is ensured by a composite material that we have manufactured from date palm wood. This material has been patented and registered under the number: (MA 37225 A1 Publication date October 29, 2016).

The outer walls of our refrigerator consist of 12 photovoltaic panels which cover the solar refrigerator; each panel produces 120 Wh, which gives a total production of 1440 Wh, with an average daily production of 5 to 8kilowattsh. The refrigerated enclosure consists of 2 cabins of 300 liters each, for a total of 600 liters Components: Electric Motor, 1 Chassis, 1 Regulator, 5 Batteries, 1 Accelerator, 1 Current Converter, and Electrical Cables.

For the batteries, we used the deep-cycle batteries that are interesting to be inexpensive. Just make sure that our design is well calculated, and the regulator is up to protect the batteries.

In view of the experimental results that we have presented that the prototype solar cold storage refrigerator that we have designed has the calculated performance, the tests have shown that it can be used at very varied outside temperatures and loads of up to 100 kg for each compartment.

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