Performance enhancement of photovoltaic household refrigerator using a phase change material in contact with evaporator

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Abstract— **We present in this paper the design, realization, and experimental tests of a PV domestic refrigerator, which performance is improved by using a phase change material (PCM) as a cold storage device. The PCM, a 25% water/propylene-glycol mixture, is integrated in direct contact with evaporator. The experimentation provides an energy analysis of the refrigerator, with and without PCM for different thermostat setting positions, in order to monitor refrigeration cycle's evolution and to determine refrigerator performances. The effect of PCM on operating regime of compressor and heat transfer inside refrigertor is also presented. The introduction of the PCM induced a 2°C reduction in the freezer's temperature fluctuations, and 11.2% reduction in electric consumption. These improvements lead to a reduction in required sizes of photovoltaic panels and batteries, and to extended liftime for the refrigeration equipment.**

***Keywords*—phase change material, household refrigeration, cold latent thermal storage, photovoltaic energy, performance enhancement**.

I. INTRODUCTION

Many areas in Algeria and elsewhere are lacking conventional electricity. This is due to the remoteness of these regions from power grids. The use of photovoltaic solar energy remains one of the most appropriate solutions for these regions in order to meet their electricity household needs, mostly refrigeration [1]. However, the cost of photovoltaic devices is unfortunately quite expensive and laws to grant such facilities do not exist. The idea of this work is to use the simple solution of integrating phase change materials (PCM) into refrigerators, in order to reduce the energy consumption, and thus reduce the initial cost of the photovoltaic (PV) system.

PCM can store cold as a latent heat of solidification during the refrigerator compressor operation, and release a significant quantity of cold as a latent heat of fusion when the temperature rises in the compartment refrigeration. This permits to shift the compressor start time, and thus to lengthen the period of the compressor stop and save electricity consumption [2]. Its isothermal character during solidification/melting process allows the PCM to perform the role of a temperature regulator in the refrigerator compartment, and also minimizes temperature rise of the freezer, which occurs due to door openings and electrical power failure [3].

Some authors have reviewed different phase change materials used for cold thermal storage according to their thermo-physical properties [4, 5], and have studied various energy systems related to residential refrigeration, power generation and thermal storage [6–8]. Marques et al. [9] investigated a numerical work on a thermal storage refrigerator and concluded the integration of Integration of a PCM into the refrigerator allows for an extended off-cycle period, while Alzuwaid et al. [10] introduced water based PCM in a refrigerated display cabinet, and noticed an improvement in performance by 5%, with a Better control and stable air cabinet temperature.

Gin et al. [11] analyzed the performance of a freezer after introducing phase change panels against the internal walls of a freezer, during defrosting and door opening cycles, and showed that the PCMs helped limiting the rate of temperature increase and reduce the energy consumption during these cycles.

This work focuses on operating regime enhancement of a PV household refrigerator, after being coupled with a phase change material as a cold thermal storage device. The PCM was integrated directly in contact with the refrigerator coffered evaporator. The experiment aims to define energy performance of the refrigerator before and after the integration of PCM, in order to reduce the PV system size, and lengthen refrigerator's lifetime.

The first part of the paper presents the experimental setup, which describes the PV household refrigerator tested, the data acquisition system and the phase change material integrated in the refrigerator. The 2rd part is about the experimental and parametric study, and discusses the PCM influence on the heat transfer and energy performance of the refrigerator.

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II. EXPERIMENTAL SETUP

A. Description of the refrigerator system

The experimental study involved tests on a standard domestic refrigerator with a useful volume of 350 liters, provided with a standard alternating current (AC) compressor using HFC-R134a as a refrigerant, and a coffered evaporator (Fig.1 and 2). The electrical supply of the refrigerator is provided by a PV array of 700 W_p and six (6) chemical batteries ($24V_{DC}$) with a capacity of 105 Ah for each one of them. An electric power converter is used to convert the PV power electricity to alternative current ($220V_{AC}$) in order to supply the refrigerator compressor.

The refrigerator is equipped with a polyurethane isolation with a thickness of 0.025 m, and a thermal conductivity of 0.025 W/m.K. the dimensions of the household refrigerator are: 1.45 *0.52 *0.52 m.

The particular refrigerator used in our experiments falls within a standard of Algerian household refrigerators. The selection of a refrigerator through its useful volume is related to the number of the members in a family. It is usually recommended to have a refrigerator with a volume of 150 liters for one person and to increase this volume by 50 liters for any additional person. An average Algerian family generally includes 5 people, which corresponds to a refrigerator with a 350 liters useful volume. The number of people in an average Algerian family was estimated from the value of the total fertility rate [2012], which is estimated to 2.93 children per woman (This rate represents the average number of children that would be born to a woman over her lifetime).

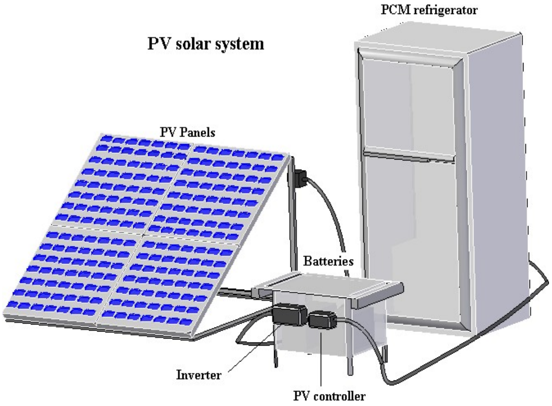

Fig.1 PV household refrigerator used in the experimentation.

B. Data acquisition

For the acquisition of air temperature inside the refrigeration compartment and temperature values of the refrigeration cycle, a fluke hydra Data logger and K-type thermocouples was used. The air temperature is measured at three (3) equidistant levels in the refrigeration compartment and at one (1) level in the freezer. In each level, 4 thermocouples are placed, and an arithmetic mean of the four (4) temperatures is calculated to estimate the average temperature for each level (Fig.2).

Moreover, the temperature values of the refrigeration cycle are measured by placing one (1) thermocouple in contact with each component of the refrigerator. An energy meter was also used to measure the energy consumption in KWh for a period of 24 hours.

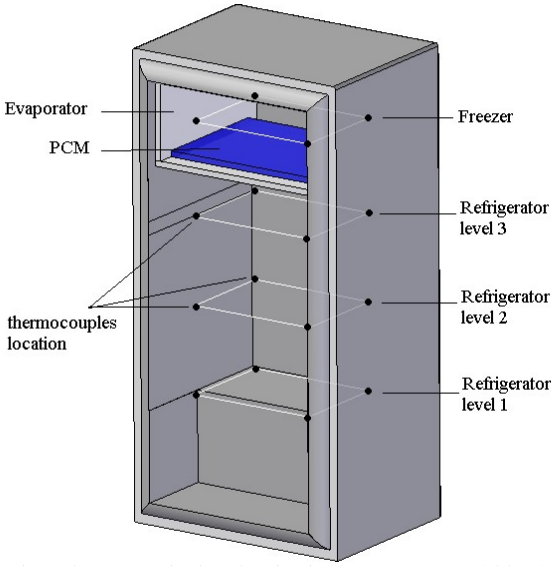

Fig.2 Thermocouples location for the temperature acquisition in the refrigerator compartment

C. Phase change material

The PCM chosen for the experimentation is a mixture of propylene glycol and pure water at 25 %, with an initial melting temperature of -11°C. The PCM is trapped in plastic packs (Fig.3.a); and each pack has dimensions of 0.12 *0.1 *0.015 cm and weighs 0.145 kg. The amount of PCM used for each test is 0.58 kg. The PCM were uniformly disposed in a single layer on the evaporator surface, so that one of the sides of the PCM pack is set into direct contact with the evaporator surface and the other sides with the air of the room (Fig.3).

Fig.3 PCM integrated in contact with evaporator

III. EXPERIMENTAL STUDY AND DISCUSSION OF THE RESULTS

The experimentation aims to define the energy performance of the refrigerator before and after integrating the PCM. The experimentation concerns a comparison in a performance refrigerator without PCM, and refrigerator using propylene glycol/water mixture as a thermal storage device, with the temperature profile and energy consumption as study parameters

A. Temperature profile in the refrigerated compartment

The temperature profiles in the refrigerator compartment and freezer are presented in figure (4):

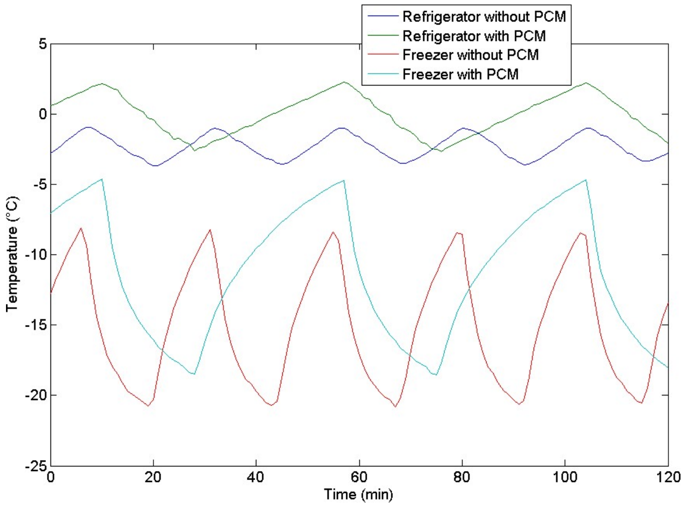

Fig.4 Temperature profile for mean temperature of refrigerator and freezer, Thermostat setting Position 5. With PCM vs without PCM.

From the refrigerator compartment temperature measurement (level 1 to 3) , a slight increase in the value of the mean air temperature of the order of 1 to 2°C and a stabilization of the air temperature fluctuation was noticed during the shutdown/operating cycle, compared to the refrigerator without MCP. We define the temperature fluctuation as the difference between maximum and minimum temperature values reached, for one thermocouple position. From the measurement of air temperature at the freezer compartment (freezer level), which is the area closest to the PCM, a slight improvement was noticed in the air temperature fluctuation measured during the operating cycle of the compressor. However, a drop of the order of 1°C in average temperature was noticed in the refrigerator compartment and no improvement in the temperature fluctuation was observed. The increase in the mean air temperature in refrigerator and freezer compartments is mainly due to the increase in the evaporation temperature.

B. Effect of PCM on heat transfer inside refrigerator

For a flat plate evaporator without ventilation, heat transfer between the evaporator and the air chamber is by natural convection. The introduction of the PCM into the refrigerator in contact only with air leads to a low heat transfer between the air of the chamber and the PCM, and the phase change phenomenon does not occur. We propose to dispose the PCM in direct contact with the surface of the evaporator, wherein heat transfer between evaporator surface and PCM is driven by pure conduction. The phase change temperature of the PCM must be lower than the temperature of the air in the chamber and approaching the evaporation temperature by a few degrees so that it can solidify during the operating phase of the compressor, And to melt again, during the shutdown phase of the compressor. The choice of phase change temperature of the PCM in this case depends on the value of the evaporator temperature and not the air temperature chamber.

The presence of the PCM at the evaporator surface represents an additional resistance to the heat exchange between the evaporator and the air of the chamber, but its effect remains negligible as long as the phase change within PCM takes place. Indeed, phase change solid/liquid generates a heat exchange in convective/conductive mode that is greater than that of the case where one phase exists. A heat balance at the surface of the evaporator with and without PCM is necessary to determine the effect of the MCP on the heat transfer inside the refrigerator. The heat transfer into the chamber air and PCM are driven by natural convection in laminar flow, while the heat transfer inside the evaporator is by forced convection in turbulent flow [13].

Figure.5 illustrates convective heat transfer coefficients involved inside refrigerator compartment. The presence of the MCP affects only slightly the heat exchange between the evaporator and the air in the chamber, which results in a 2.8% reduction in the global heat transfer coefficient compared to the evaporator without PCM. A more efficient heat transfer inside the PCM improves the overall heat exchange coefficient without reaching its threshold value in case of an evaporator without MCP.

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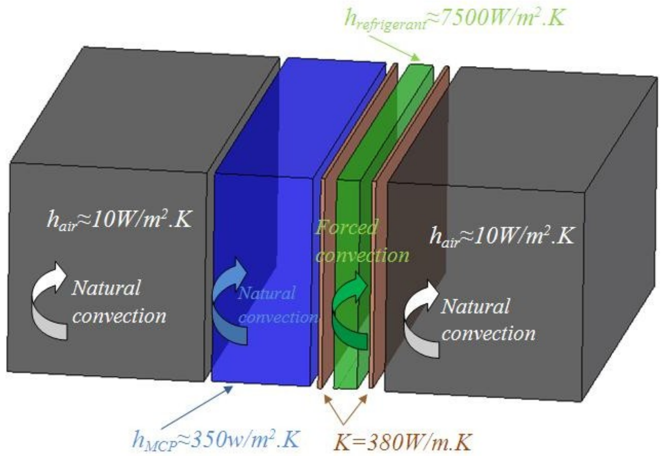

Fig.5 convective heat transfer coefficients inside the refrigerator

C. *Effect of PCM on operating regime of the refrigerator*

For a standard domestic refrigerator, the operating time is mostly conditioned by the refrigerator thermostat, whose role is to control the desired temperature at the refrigeration compartment. When the refrigerator temperature increases and reaches a certain value, the thermostat closes and the refrigerator compressor is switched on and begins its ―on-cycle‖ phase. In the case where the PCM is integrated, instead of having a compressor beginning its operating phase to produce cold, the PCM will react with the increase of refrigerator compartment temperature and will ―release the cold‖ already stored as latent heat from the previous on-cycle of the compressor, which will naturally shift the compressor start time, and thus lengthen the period of the compressor stop. As a consequence, the extension of the resting time of the compressor (Figure.6) will permit the reduction of the on/off cycles number and the daily operating time of the compressor.

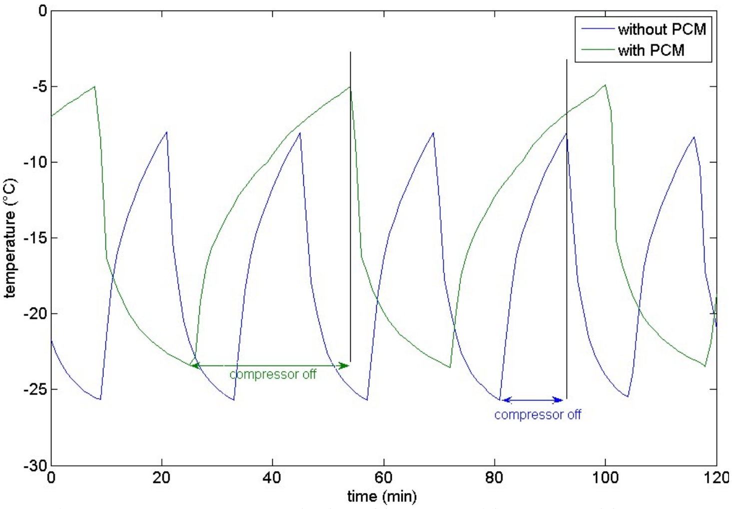

Fig.6 evaporator temperature in the refrigerator. With PCM vs without PCM. Thermostat position 5

The reduction of the compressor start/stop frequency reduces the recurrent compressor starting, and also reduces energy losses resulting from refrigerant charge migration from the condenser to the evaporator during the off cycle. The table I shows the values of the daily power consumption of the refrigerator after integrating the PCM, for positions 3and 5 on the refrigerator thermostat. Reduction is notified for the different operating regime of the refrigerator, and is more significant when the thermostat is hold in position 5.

TABLE I
Daily power consumption for positions 3and 5 of refrigerator thermostat

Electrical consumption KWh/Jour	Case without PCM	Case with PCM	Consumption reduction (%)
Position 3	1.79	1.61	10
Position 5	2.0	1.77	11.2

IV. CONCLUSION

We have investigated the performance of a PV energy-supplied household refrigerator that was improved with using a phase change material as a cold thermal storage device, mounted in contact with the evaporator. The photovoltaic system was designed so to supply the refrigerator with electrical energy. The experimentation provides the energy performance of the refrigerator, with and without the PCM for different thermostat setting positions. The integration of PCM leads to reduction of the compressor start/stop frequency, which reduces the recurrent compressor starting and energy losses resulting from refrigerant charge migration from the condenser to the evaporator during the off cycle. As a consequence, a 11.2% average reduction in power consumption is obtained, as well as a 15.5% decrease in operation time. The presence of the PCM at the evaporator surface represents an additional resistance to the heat exchange between the evaporator and the air of the chamber, but affects slightly the heat exchange between the evaporator and the air in the chamber, which results in a 2.8% reduction in the global heat transfer coefficient compared to the evaporator without PCM. The increase in the mean air temperature in refrigerator by 2°C is mainly due to the increase in the evaporation temperature.

The use of PCMs in refrigeration equipments with substantial electrical power may actually reduce significantly the electric consumption of the compressor, which allows the use of less powerful photovoltaic systems, thus reducing the initial cost and extend the lifetime of the refrigerator system.

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