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Utilizing Phase Change Materials for Sun-Powered Refrigerators: Experimental Validation in Outdoor Environments

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ABSTRACT

In pursuing sustainable refrigeration solutions, integrating phase change materials (PCMs) within sun-powered refrigerators emerges as a promising avenue to mitigate challenges associated with sun radiation intermittency and reliance on large battery systems. This paper comprehensively examines incorporating PCMs into sun-powered refrigerators to address critical issues hindering the widespread adoption of solar refrigeration technologies, particularly in medicine and perishable goods. The primary objective of this study is to assess the efficacy of PCM integration in achieving grid disconnection and enabling autonomous operation of sun-powered refrigerators. Through experimentation and data analysis, our findings elucidate the transformative impact of PCM utilization on the performance and sustainability of solar refrigeration systems. Key outcomes from the experimental trials demonstrate that incorporating PCMs facilitates prolonged operation of sun-powered refrigerators, even without direct sunlight. By harnessing the thermal storage capabilities of PCMs, the refrigeration unit achieves grid independence, thereby mitigating reliance on conventional power sources and large battery configurations. In conclusion, integrating phase change materials is pivotal to achieving energy autonomy and sustainability in sun-powered refrigeration systems. Through collaborative efforts and continued innovation, PCM-enabled refrigeration technologies hold immense promise in revolutionizing cold chain logistics and enhancing global access to vital medical resources and foodstuffs.

1. INTRODUCTION

The environmental impact of the energy field is a pressing and relevant issue, underscored by the pollution caused by greenhouse gas emissions and the resulting carbon footprint of countries. Electric energy production is not uniquely responsible for global warming because the necessity for thermal energy significantly contributes. Heating and cooling, as highlighted by the International Renewable Energy Agency (IRENA), account for approximately half of the global final energy consumption. Data demonstrate that thermal energy demand surpasses electricity (20%) and transport (30%) and is responsible for over 40% of global energy-related carbon dioxide emissions [1]. Especially for cooling, the refrigeration field accounts for emissions related to the cold chain, which refers to the various stages and technologies used to preserve and transport perishable goods, such as foods and beverages or medicals. The environmental impact of stationary refrigeration and refrigerated transport can be divided into two categories depending on its cause [2]. The first one is the direct impact due to the refrigerant leakages in the atmosphere, which increase global warming due to the capacity of these substances to absorb and reflect solar radiation. Technologies not based on compression vapour cycles have been proposed to reduce this significant issue, such as solid state refrigeration [3, 4]. The second one is the indirect impact of the emissions related to the fuel mix used for producing the electric energy required by refrigerators. The electric grid is the leading source of compression vapour cycle machines, followed by Internal Combustion Engines (ICE), which are used uniquely for tracks and vans equipped with refrigeration units [2, 5]. Especially in refrigerated transport, utilising a Kinetic Energy Recovery System (KERS) is a possible solution to reduce indirect emissions, saving more than 47% of the total electricity demand [6]. For this reason, in recent years, research has focused on developing sun-powered refrigerators using photovoltaic (PV) panels, employing a zero-emissions energy source to reduce the indirect impact of refrigerators. This technique is called PV solar cooling and consists of four essential components: a PV module, a battery, a Maximum Power Point Tracking (MPPT), and a vapour compression system [7]. The battery is necessary to stock electric energy when it is not required to manage the discontinuous production related to the inconstancy of solar radiation during the day. The cooling energy, instead, can be stocked utilising Phase Change Materials (PCM), which can absorb and release it as latent heat and, for pure substances, at constant temperature [8].

This article proposes a novel sun-powered refrigerator using a PV module and PCMs. The system is formed by a foldable PV module, which can generate a maximum of 160 W of electric power, a cockpit hot-wall refrigerator formed by a

Direct Current (DC) 12/24V compressor and a 100 Ah lead acid battery. The innovative idea consists of implementing PCMs in 10 containers positioned along the internal edges of the device to insulate the cell from the external ambient. The research aims to demonstrate how low-cost PCMs, such as water, are a powerful instrument to increase the efficiency of stationary refrigerators and how important the implementation of renewable sources is to decarbonise the refrigeration field.

2. DESCRIPTION OF THE PROTOTYPE

2.1 Cockpit hot-wall refrigerator

The sun-powered refrigerator is a cockpit *hot-wall* cooling device, which means that the condenser is positioned on the front wall of the cell ahead of the evaporator (which is incorporated into the walls of the cell). For a further description of the refrigerator and the components described in the following paragraphs, the article written by Petruzziello et al. [9] is suggested.

The novel sun-powered refrigerator operates through a compression vapour cycle using 60 g of R290 (propane). The fluid is a natural refrigerant widely used for commercial applications with negligible GWP [9, 10]. This quality benefits direct emissions more than other refrigerants [8, 11], such as most HFCs, which will be banned from the market due to several legislations, such as F-gas regulation in Europe [12]. However, specifying that not all HFCs will be forbidden is fundamental because the restriction depends exclusively on the GWP. The regulation accepts several novel HFC refrigerants with GWPs, like R152a, an optimal substitute for R134a used in domestic refrigerators [13, 14].

The DC hermetic compressor is characterised by a nominal power of 89 W. Generally, an inverter is implemented when the refrigerator must be powered by an Alternating Current (AC), but the compressor implemented in the sun-powered refrigerator is a DC device. This feature increases the transmission efficiency through the electric circuit because there is no conversion of DC produced by the PV module to AC. The speed modulation, instead, contributes to improving the coupling between the PV module and the hot-wall refrigerator [15].

2.2 Foldable PV module

Regarding the powering, the prototype employs a 160 W PV module, which permits it to be independent from the electric grid and stock products completely at zero emissions. Moreover, the chosen PV panel is divided into four modules of silicon monocrystalline cells, which can be overlapped to create a foldable device (this characteristic can be seen in Figure 1). It is firmly clasped to a dedicated structure positioned above the refrigerator door, which permits the unfolding of the PV module through mobile arms.

2.3 Lead acid battery

The system has a lead acid battery of 100 Ah (1.2 kWh) to cover the demand for electric energy in the refrigerator when it is not available for irradiation during nights or days when solar production is insufficient. A battery is necessary for correct functioning because it permits the stock of all the electric energy the electric load does not require during the day. Regarding its size, it has been chosen considering an oversizing of the capacity to guarantee reliability for more days without clear weather. A less hulking and capacious battery may be implemented in a future prototype. Another aspect is related to the temperature the battery reaches during continuous charge and discharge cycles during functioning. In some specific cases, such as electric vehicles [16], developing a Thermal Management System (TMS) that requires a certain amount of energy is necessary, reducing autonomy. For the proposed prototype, the battery temperature has not reached dangerous conditions, and no thermal management was required.

2.4 Phase change materials containers

As the prototype has a battery for stocking the electric energy produced by the PV panel, PCM has been implemented to stock thermal energy as latent heat. Ten parallelepiped cases have been positioned along the four internal walls of the cell, as shown in Figure 1. PCM_1, PCM_2, PCM_7, and PCM_8 containers have 650 × 180 × 20 mm dimensions, while PCM_9 and PCM_{10} have 650 × 190 × 20 mm dimensions. Due to the shape of the cell, it has been necessary to implement smaller boxes represented as PCM_3, PCM_4, PCM_5 and PCM_6. PCM_3 and PCM_6 have a dimension of 380 × 220 ×20 mm, while PCM_4 and PCM_5 are less large (380 × 290 × 20 mm). The PCM case sizing has achieved the lowest bulk without affecting the storage capabilities of the substance and the heat exchange phenomena. For this reason, the thickness of the containers has been 0.8 mm, and the material used for their realisation has been aluminium.

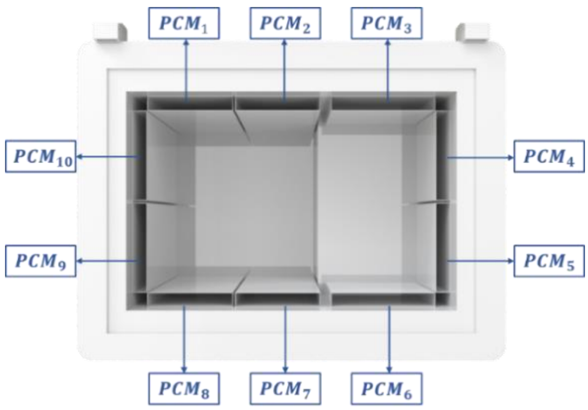

Figure 1. PCM cases in the refrigerator cell

3. EXPERIMENTAL CAMPAIGN

The experimental campaign aimed to test the novel sun-powered refrigerator to preserve goods requiring strict temperature control. The PV module was exposed to the south direction to optimise the incident solar radiation on its surface, minimising any shading that might reduce the electricity produced during the day. The experiments were conducted from the 13th of September 2023 to the 20th of October 2023 at the University of Salerno after a pull-down phase realised by powering the system utilising the electric grid. The PCM was all solidified when the campaign started. Four different tests were made to evaluate the performance of the sun-powered refrigerator in several contexts:

(1) Stocking test without additional thermal mass;

(2) Stocking test with additional thermal mass;
(3) Extended pick and place test;
(4) Narrow pick and place test.

The following paragraphs will report the essential results, such as the internal temperature of the sample solution and the PCM temperature.

3.1 Experimental set-up

A sample has been positioned in the refrigerator, preventing direct contact with the internal sides. This condition was fundamental for nullifying conductive heat exchanges and achieving uniform boundary conditions. The solidification temperature of the substance was -21℃ to ensure the liquid state in every condition of the experimental campaign. The chosen temperature range target has been defined between -1℃ and +1℃. The sample temperature was monitored using a four-wire Pt100 RTD sensor immersed in the solution.

For this experimental campaign, pure water was chosen due to its easy availability and versatility. The choice does not exclude other applications of the sun-powered refrigerator, such as vaccine conservation, in which PCMs characterised by lower or higher melting points can be implemented to maintain the optimal temperature range for preserving specific products. The total volume of pure water implemented in the prototype has been 22 litres, equally distributed among the containers.

The control board of the compressor has been completely modified. A thermostat has been implemented to power it at 12 V DC, controlling the temperature of the cell through a four-wire Pt100 RTD sensor and utilising a new control board that manages the power supply switch. The switch allowed the compressor to be turned on when the cell temperature exceeded an upper limit, and the internal temperature of the sun-powered refrigerator decreased under a lower limit. The hysteresis range of the thermostat was defined between -1℃ and + 1℃ according to the conditions imposed for preserving the sample substance.

Other instruments have been utilised to measure different quantities, such as the PCM temperature, the ambient temperature and the solar irradiance. In particular, the temperatures of PCM and their box surfaces have been estimated utilising two four-wire Pt100 RTDs positioned in strategic points: the first was utterly immersed in the water, while the second one was placed on the external surface of the container at middle height. Double measurement was necessary to analyse the effect of the conductive thermal resistance achieved by the PCM containers. For the experimental campaign, PCM_7 was considered as a sample for all the boxes because it was particularly exposed to solar radiation due to the chosen outdoor position of the refrigerator. Moreover, the shape of the evaporator produced an unfavourable heat exchange because, corresponding to the PCM_7 container, the refrigerant assumed a superheated vapour phase instead of a two-phase condition. For this reason, the measures of PCM_7 ensured that all the water was in a solid or liquid state. Solar irradiance was measured by a pyranometer positioned at the same tilt angle as the PV module. At the same time, another four-wire Pt100 RTD was used to detect the ambient temperature. For all the measurements, the chosen sampling time was 5 seconds to record the possible dynamic functioning of the prototype.

3.2 Stocking test without additional thermal mass

This test was conducted from the 13th to the 21st of September. The test was conducted in stationary conditions, and there was no refrigerator door opening, meaning that the system had to balance only the conductive and convective thermal loads from the environment without considering the air renewal in the cell. Moreover, the system was not subjected to any changes and was in a stand-alone configuration, which means it was not connected to the electric grid. Measuring the external temperature of the environment, the climatic conditions were stable during the days, such as the solar irradiance.

As represented in Figure 2, the sample solution temperature was confined between -1℃ and +1℃ at every test moment, achieving the desired result.

There are particular instances in which the solution temperature plunged around -1℃ because the PCM was entirely solidified, and the heat exchanged by the PCM and the internal air of the cell was exclusively sensible. As represented in Figure 3, the PCM_7 temperature was constant during the test, and there was no particular minimum point like Figure 2.

The complete solidification of PCM is not evident in Figure 4 because, as reported in the previous paragraph, the temperature measurement was done for only one reference box in which water had the most extended times of melting and solidification. For this reason, while the PCM_7 was still in a phase change, the amount of water in the other boxes was solidified and decreased its temperature.

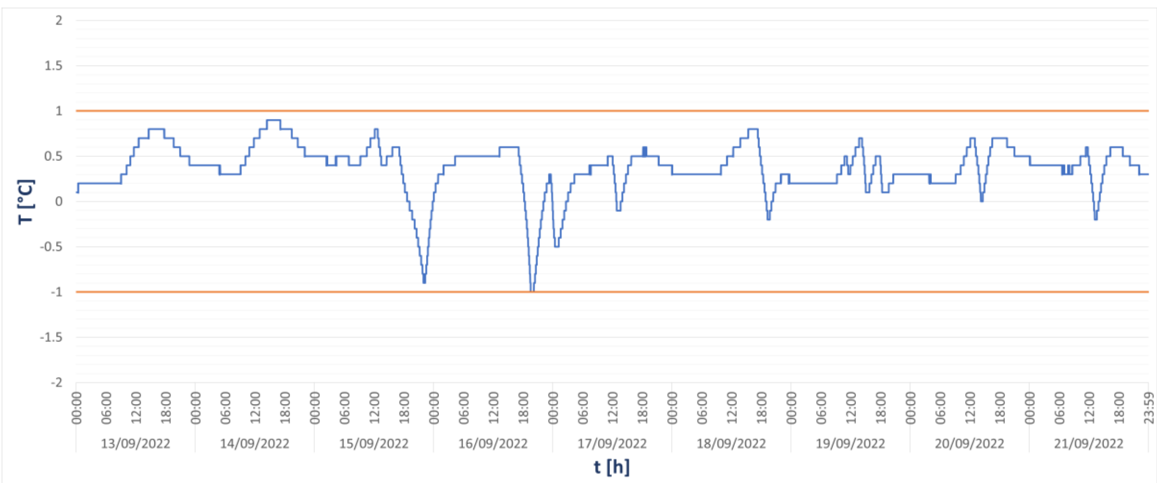

Figure 2. Sample solution temperature during the first stocking test

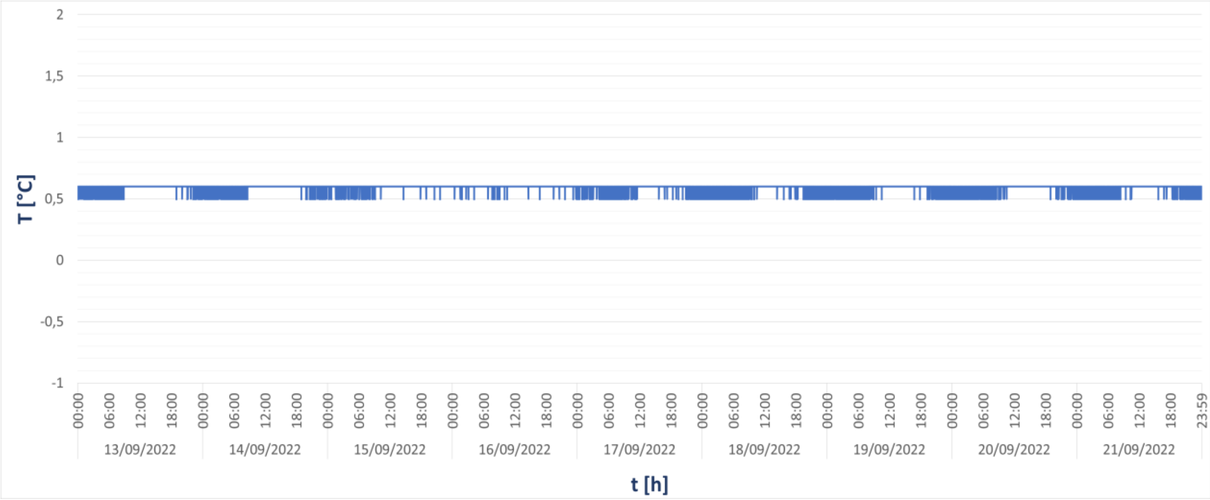

Figure 3. PCM_7 temperature during the first stocking test

3.3 Stocking test with additional thermal mass

Due to the promising performance of the sun-powered refrigerator in preserving the sample temperature in the desired range, it has been decided to test the system in a more challenging condition. This part of the experimental campaign has been conducted from the 22nd of September to the 3rd of October. On the first day, 21 litres of a water and salt solution (20 wt%) was poured into 14 containers and put in contact inside the cell to promote the conductive heat exchange among them. A mixture of water and salt was chosen to decrease the solidification temperature of the thermal load and avoid phase changes. Compared to the previous test, this condition permitted to evaluate the performance of the prototype in dynamic conditions due to the initial higher temperature of the thermal load compared to the sample. The duty cycle required to power the compressor inevitably increased, and the energy demand rose. Still, the system achieved an independent functioning without requiring any amount of electric energy from the grid. Also, according to the measurement, the environmental conditions were stable and did not change in a relevant manner for this test.

In Figure 4, it is possible to examine the sample solution temperature during the test. The product was always maintained in the optimal range except for the first day when the refrigerator door was open for several hours to insert the thermal load.

Comparing the results of the second stocking test with the first one, it is interesting how the average temperature of the solution is higher than before. It depends on the additional thermal mass inserted at ambient temperature in the cell because it increases the thermal load the refrigerator has to balance. A benefit related to the extra thermal mass is the reduction of the fluctuations in the sample solution temperature. Comparing Figure 2 and Figure 4, it is possible to highlight how the sample solution temperature achieved a higher stability in time, improving the conservation conditions. The phenomenon can also be analysed by the superficial temperature of the PCM_7 case, whose average temperature is higher than the previous test. In particular, it reaches values around 0°C, meaning that the water was in two-phase condition most of the time. As represented in Figure 5, the temperature trend of the PCM was characterised by more fluctuations because, as explained previously, the additional thermal load increased the duty cycle. For this reason, the graph has zones in which PCM_7 temperature reaches values under and above 0°C.

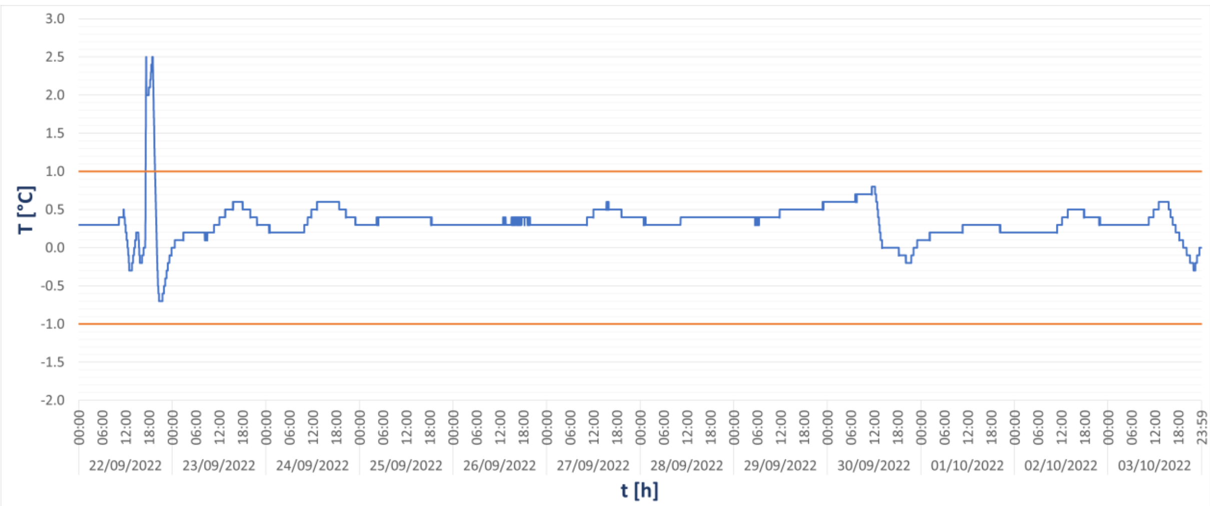

Figure 4. Sample solution temperature during the second stocking test

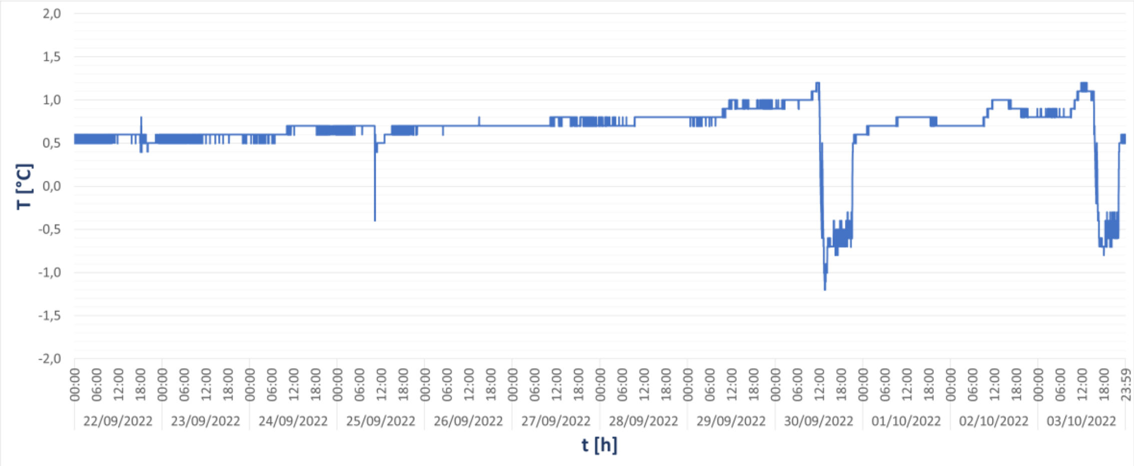

Figure 5. PCM_7 temperature during the second stocking test

3.4 Extended pick and place test

The refrigerator door opening is a crucial phase in the cold chain due to the exchange of air from the cell to the environment and vice versa. Indeed, door opening increases temperature instability and energy consumption and lowers the cooling rate of the refrigeration system [17]. For this reason, the next step of the experimental campaign is the emulation of several door openings to understand if the sun-powered refrigerator can manage to pick and place conditions. The purpose of the test was to analyse the performance of the prototype for medical applications in which products must be conserved for long periods and taken in significant amounts. It regards *extended* pick and place conditions because the additional thermal load was collected and stocked in the cell for a long time. More specifically, the extended pick and place test was repeated every day from the 4th to the 7th of October and was organised in five steps:

(1) At 12:00 pm, half of the thermal load (10.5 litres) was taken from the cell, reproducing a door opening for 3 minutes;
(2) After the first step, the refrigerator door was left closed for half an hour;
(3) Progressively, a second door opening was programmed with the identical procedure as the first step, removing all the additional thermal load;
(4) After the third step, the refrigerator door was left closed for an entire hour;
(5) Finally, another door opening was realised for 5 minutes, and the cell was refilled entirely with 21 litres of water and salt mixture, such as in the beginning.

As in the previous test, the door opening affected the sample solution temperature and rose above the upper limit of +1℃, as represented in Figure 6.

This means the proposed sun-power refrigerator is mainly affected by the door opening, as with other cockpit refrigerators. The fluctuation caused by the door openings was also reflected by the PCM temperature, which reached values over 4℃, as shown in Figure 7. This result indicates that water melted and the condition of solid PCM was lost during the opening due to the exchange of air between and the environment.

However, the prototype managed this situation well because the sample and the PCM temperatures rapidly reached lower values, especially considering a complete stocking of additional thermal load at ambient temperature. An anomaly occurred during the last day when a pronounced minimum point of the PCM container was measured. The environmental conditions may justify this because the ambient temperature and the solar irradiance were lower than the other days, reducing the thermal load the refrigerator had to contrast. Apart from these considerations, the sun-powered refrigerator demonstrated its autonomy from the electric grid because it could guarantee independent functioning from the grid also in this case.

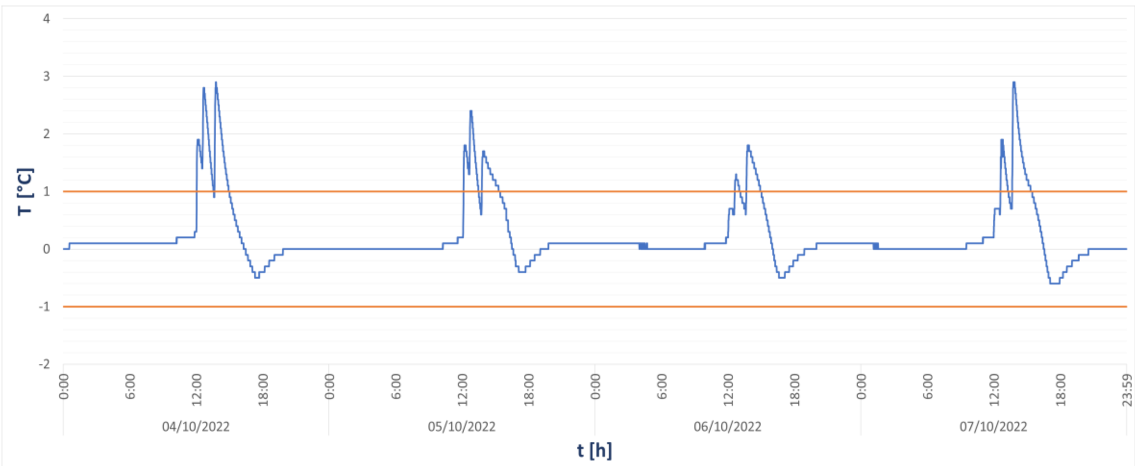

Figure 6. Sample solution temperature during the extended pick and place test

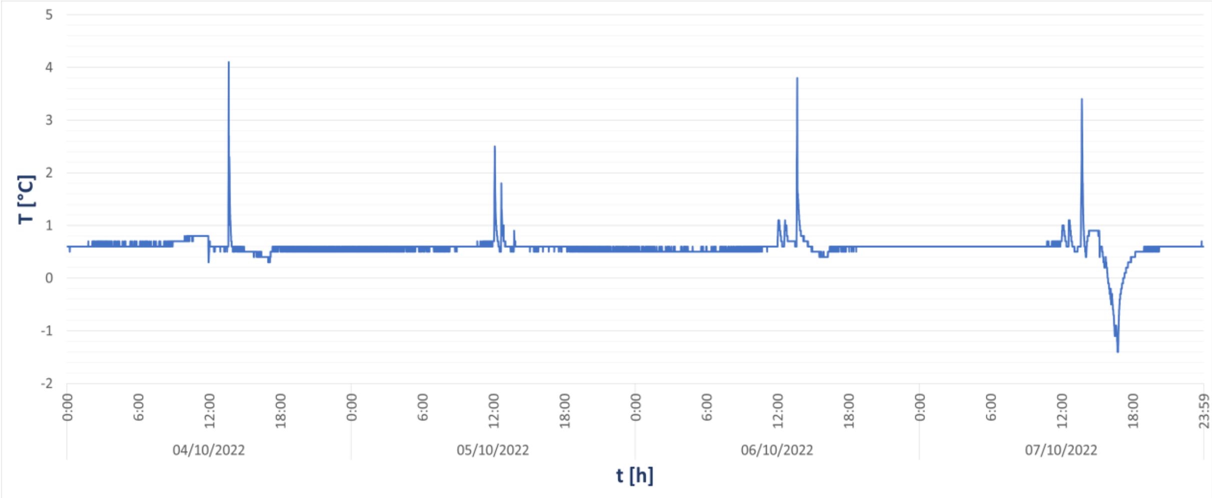

Figure 7. PCM_7 temperature during the extended pick and place test

3.5 Narrow pick and place test

While the previous test was conducted to emulate the stock of medicals, the final test of the experimental campaign reproduced door openings for the food and beverage sector. Due to the necessity of taking small quantities of products incessantly, a *narrow* pick and place test was conducted from the 17th to the 20th of October. As previously, there were defined five steps repeated every day as follows:

(1) At 12:00 pm, 1.5 litres of the thermal load were taken from the cell, reproducing a door opening for 1 minute;
(2) After the first step, the refrigerator door was left closed for 10 minutes;
(3) Progressively, a second door opening was programmed with the identical procedure as the first step, removing all the additional thermal load;
(4) After the third step, the refrigerator door was left closed for an entire hour;
(5) Finally, another door opening was realised for 5 minutes, and the cell was refilled entirely with 21 litres of water and salt mixture, such as in the beginning.

As represented in Figure 8, the sample solution temperature rose above the upper limit of +1℃, following a similar trend to the previous test. For food and beverage products, the condition is not as unfavourable as medicals, which have more strict conservation conditions. Moreover, the prototype restored the temperature to the optimal range between -1℃ and + 1℃ at the end of the pick and place.

In Figure 9, the PCM_7 temperature is represented. The measured value was constant on almost all the days except the last two days when it decreased under 0℃.

This phenomenon can be explained by the environmental conditions reached in the final days of the test. Due to a lower average ambient temperature and solar irradiance, the thermal load decreased and promoted the complete solidification of PCM_7 in the container. It is also demonstrated in Figure 8 because the temperature of the sample solution reached values close to -1℃, indicating that the prototype could remove a higher amount of thermal energy from the products than the first days. Moreover, it is interesting how the PCM temperature has decreased since a minimum point because only sensible heat is exchanged between the refrigerant and the water. At the same time, the OFF phase of the compressor could cause the PCM temperature growth because PCM absorbed heat to keep the air temperature in the cell confined between the hysteresis range limits. Regarding energy consumption, the sun-powered refrigerator was also wholly independent from the electric grid for the narrow pick and place test. As a final result, it is possible to affirm how an economic PCM such as water can increase the performance of refrigerators, assisting other stock devices such as lead-acid batteries.

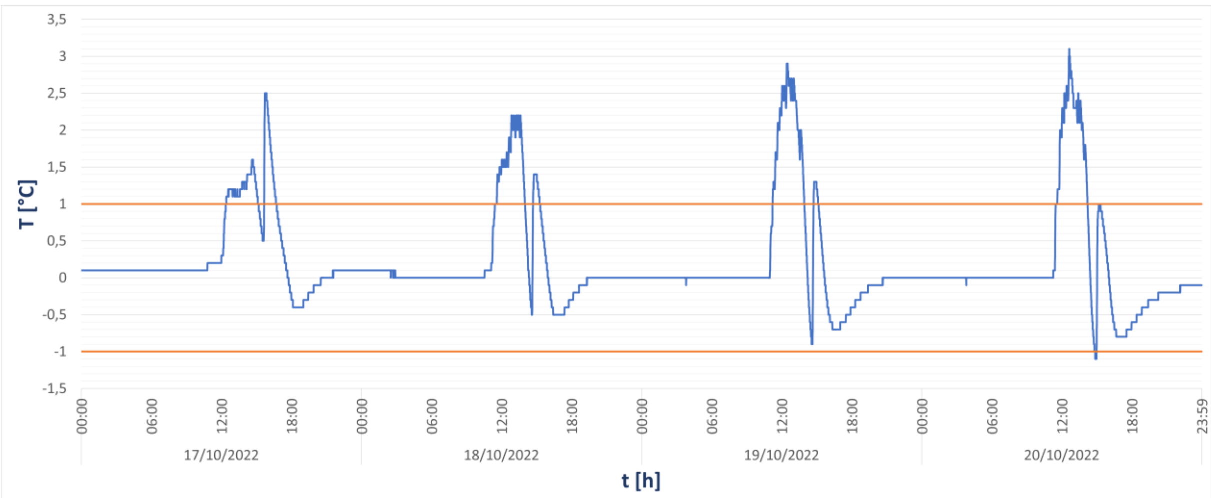

Figure 8. Sample solution temperature during the narrow pick and place test

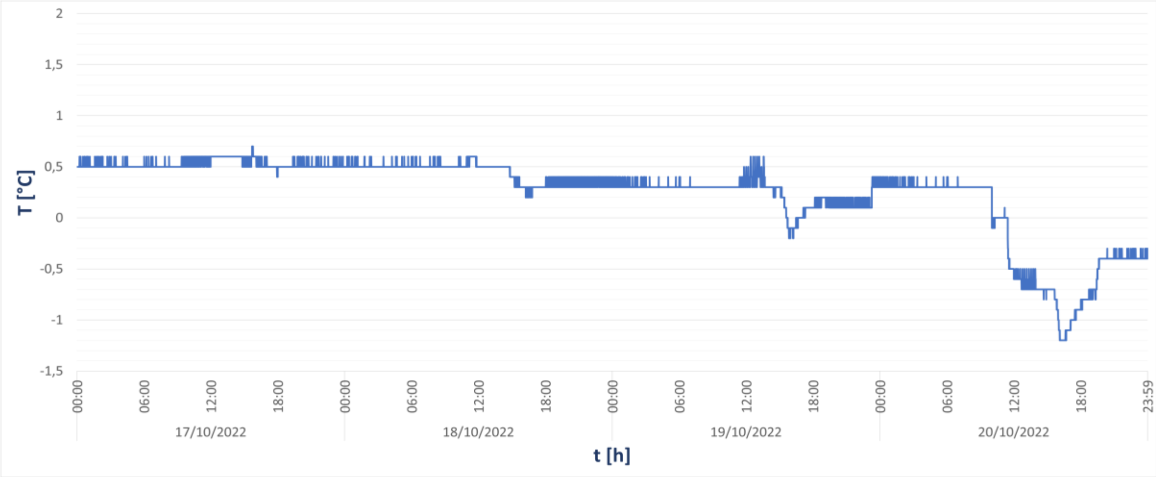

Figure 9. PCM_7 temperature during the narrow pick and place test

4. CONCLUSIONS

The proposed prototype aims to contribute to decarbonising the cold chain by implementing a 160 PV module, a 100 Ah lead-acid battery and PCM containers to a cockpit *hot-wall* refrigerator. The purpose of the sun-powered refrigerator is to propose a zero-impact device on the environment that can preserve perishable goods, such as foods or medicals, which must be conserved in a strict temperature interval and in zones in which there is not a fully advanced electric grid. An experimental campaign has been conducted to evaluate the independence from the electric grid and the ability to maintain the temperature of a sample solution between -1℃ and +1℃. Additional thermal masses and pick and place conditions were considered according to the possible application of the prototype (food and medical industry). The refrigerator could manage the conservation of the products in every situation without requiring any electric energy from the grid. This has been possible due to the PV module and the battery but mainly attributable to the water used as PCM, whose temperature did not exceed 4℃ in the most demanding circumstances. The sample solution temperature was managed in the optimal range during the stocking test while, regarding the pick and place conditions, it rose above +1℃ only when the refrigerator door was open. The results indicate how PCMs increase the performance of PV solar cooling systems through a stock of thermal energy combined with electric energy storage. However, improvements are necessary during the door opening. For this reason, future developments regard better temperature management during the door openings and several tests with other PCMs to test the sun-powered refrigerator's thermal behaviour for other substances requiring lower stocking temperatures, such as vaccines.

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