Experimental Testing of the Thermal Response of Different Food Alveoli Solutions for Packaging Boxes

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***Abstract*—Fruits and vegetables are perishable fresh products that have a short shelf life. Post-harvest treatments intend to slow down the physiological processes in fresh fruits and vegetables such as respiration, senescence, and ripening. In addition, those treatments also reduce the occurrence of pathogen attacks and microbial contamination to increase the shelf life of fresh fruits and vegetables. Refrigeration plays an important role in food preservation, as low temperatures helps in preventing or delaying microbial, physiological, and chemical changes in food The food alveoli are used to protect and prevent products to suffer from external damages while their transportation in a package. This experiment was developed to analyse the thermal response in two different types of alveoli. The experiments were repeated for the 2 different alveoli and after that bags of phase change materials (PCMs) were added in the packages and the thermal behaviour of the packages with and without the PCM's were compared. Expanded polystyrene (EPS) balls are used as fruit simulators in the alveoli. Paraffin wax RT11HC was used as PCM. The aim of this experiment is to evaluate the heat transfer in the different food alveoli made from carton and aluminum foil material with respect to time. The test was performed by lowering the temperature inside the cold chamber for 8 hours Once the 8 hours passed the cooling period finishes and the chamber is opened, exposing the packages and artificial fruits to the environmental temperature in the laboratory for a period of 15 hours. Results shown that in the cooling process, aluminum foil alveoli have quick response in the heat transfer to the fruit simulator and it took longer time in the heating process with PCMs. Hence the PCM which stores cold thermal energy is an effective method for cold storage food products in a packaging.**

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***Index Terms*— Phase change materials, Alveoli, Thermal chamber, Artificial Fruit simulators, Shelf Life.**

I. Introduction

The world population has been increasing over the past decades, overall, undernourished people in the world are estimated to be 1.02 billion [1]. Hunger and malnutrition are the primary causes of more than half of all child deaths, killing nearly 3.1 million children each year [2]. The concept of hunger is defined by a condition in which people require macronutrients (energy and protein) and micronutrients (vitamins and minerals) for fully productive, active, and healthy lives [3]. The main goal of many scientists over the world in the past decades has been trying to find new solutions regarding the improvement in the use of natural resources, and to be produce enough food to fight the worlds hunger.

Healthy soil produces healthful food and nutrition, unsustainable use of land practices and human pressures on resources are reaching critical limits. Poor farming methods are depleting soil nutrients faster than they are able to form. One of the possible solutions for this issue would be reducing the food waste. The growing interest for food waste is not surprising, given its astonishing numbers. Recent estimates suggest that up to one third [4] of all food produced in the world is lost somewhere throughout the chain.

Refrigeration plays an important role in food preservation, as low temperature supports in preventing or delaying microbial, physiological, and chemical changes in food [5]. Therefore, the need to develop some technologies that help the food to be preserved for longer is extraordinary.

Latent heat thermal energy storage system is an attractive technique as it can provide higher energy storage density than conventional heat energy storage systems and has the capability to store heat of fusion at a constant (or a near constant) temperature corresponding to the phase transition temperature of the phase change material (PCM).

Fruit consumption is an ever-increasing trend due to the scientifically acclaimed health benefits of fresh fruit consumption [6]. Globally, over 67% of the volume of fruit production is consumed freshly [7]. There are very problems associated to meet this global goal since fresh fruits suffer from rapid loss of quality due to increased respiration rate, weight loss, loss of firmness, colour changes, and microbial spoilage. The precooling, cold storage, cold transportation processes and the ultimate fruit quality are considerably affected by the packaging practice. Packages must protect fruits from mechanical damage, reduce the moisture loss from the fruit and prevent the proliferation and spread of decay-causing microorganisms. Considering this, the utilization of PCMs appears as a possible solution. In this experiment, PCMs were used to conserve fruits temperature for a longer period, aiming reducing the losses of all the properties that a fresh fruit should have.

II. Materials and Methods

A. Experimental setup

To perform the experiment, a cold chamber was used (Figure 1) where the artificial fruits in the different packages were tested in different boxes. The boxes were placed vertically (3 different boxes).

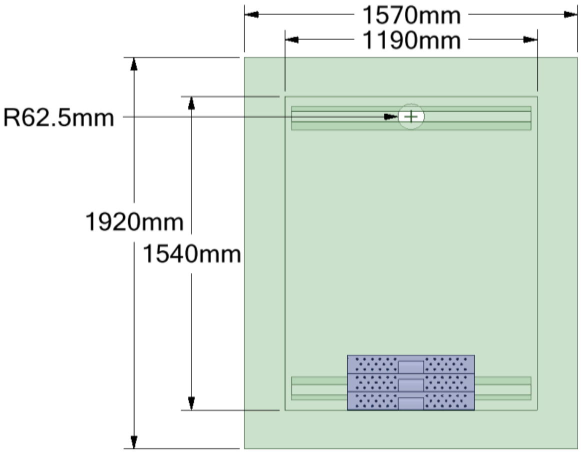

Fig. 1. Dimensions of the cold chamber used in the experiment.

Additionally, Figure 2 shows a schematic of the experimental setup used to perform the experiment. The components to perform the refrigeration required consist in the cold chamber mentioned before, a heat exchanger section with an axial fan, a refrigerant pump, a tank with the cooling liquid and a chiller.

The fan leads the air through the heat exchanger. The fluid used for refrigeration is pre-cooled with the aid of the refrigerator and pumped into the heat exchanger. The air prevenient from the fan cools down and runs through the pipes and enters the cold chamber to cool it down. The chiller is used to cool the refrigerator fluid.

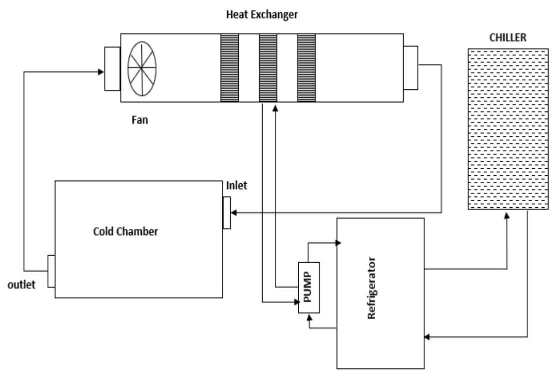

Fig. 2. Schematic diagram of the experimental setup.

B. Fruit simulator

The artificial fruits used in the experiment were made from agar-water solution with a volumetric concentration of 5% in volume. The solution was heated until its boiling point. Acrylic balls were filled with the solution prepared, and to measure the temperature thermocouples were inserted in the center of the final object (figure 3).The same process was repeated until reaching a total of 5 functional prototypes to represent artificial fruits. This chamber and refrigerator system were used in a previous work [8].

Fig. 3. Example of an artificial fruit used in the experiments.

C. Thermocouples placement

The temperature was measured giving use to two different sensors: hygrometer sensors (Figure 4a) that record the temperature of the air and thermocouples type T sensors (Figure 4b) inserted inside of the artificial fruits to measure its temperature. The thermocouples used require a device and a software to read and allow visual analysis of the results, so a thermocouple data logger was used to plug all the thermocouples (Figure 4c)

(a) Thermo-hygrometer sensor. (b) Thermocouple type T. (c) Thermocouple data logger.

Fig. 4. Measurements equipment.

In the first set of experiments, where the agar fruit simulators temperature was tested with and without the use of PCM's, the thermocouples type T were placed in the different boxes in a specific way (Figure 5).

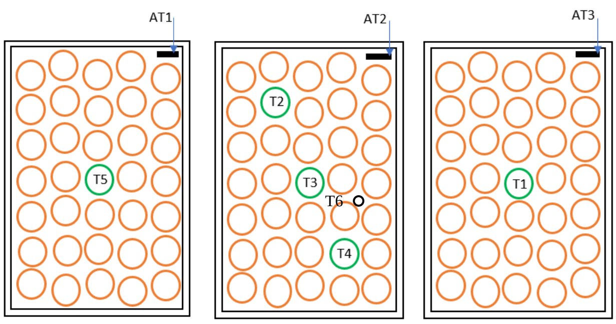

Fig. 5. Location of thermocouples type T and hygrometers.

The hygrometer sensors were positioned in the same places in both set of experiments, and they are represented by AT1, AT2 and AT3 in Figure 5. One more sensor was added in the side of the chamber, denominated by AT4.

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D. PCM characteristics

PCMs have been used in thermal applications for a long period of time [9].

- PCMs have thermo-physical properties such as high latent heat and thermal conductivity, density and volume changes during the phase-change is high, and low to minimize storage volume.
- Kinetic and chemical properties such as super-cooling is limited to a few degrees, and materials have long-term chemical stability, compatibility with materials, no toxicity, and no fire exposure.
- Economic advantages (low cost and large-scale accessibility of the PCMs).

Table I represents a summary of the characteristics of the phase change material used to perform the experiment.

TABLE I
THERMOPHYSICAL PROPERTIES OF PCM RT8HC AND RT11HC.

Description	Units	Typical Values	Typical Values
		RT8HC	RT11HC
Melting Point	˚C	7 to 9 (peak: 8)	10 to 12 (peak: 12)
Congealing area	˚C	8 to 7 (peak: 8)	12 to 10 (peak: 12)
Heat storage capacity (+- 7.5%)	kJ/kg	190	200.
Specific Heat capacity	kJ/kg·K	2	2
Density solid (0 ºC)	kg/l	0.88	0.88
Density liquid (20 ºC)	kg/l	0.77	0.77
Heat conductivity	[W/(m·K)]	0.2	0.2

E. Mathematical formulation

The cooling time was calculated to predict the performance of fast-cooling systems for the research purpose. According to [9], this factor (time) can be defined by the Dimensionless Temperature Rate, *y*, given by Equation (1).

$$y = \frac{T - T_{min}}{T_i - T_{min}} \quad (1)$$

Where T is the temperature inside the fruit simulator, T_{min} represents the minimum temperature, and T_i the initial temperature.

F. Methods

The experiment is performed with the aid of agar balls representing a fruit simulator. To analyze the temperature, thermocouples type T were inserted in the center of the functional prototype with the purpose of measuring its inner temperature.

Three boxes are placed horizontally, with cartoon alveoli inside. The top box alveoli is fully filled with EPS balls with exception at the central position. The central position of the top alveoli is filled with one agar fruit simulator. In the middle box alveoli, three agar fruit simulators are used, and the rest is filled with EPS balls. The agar and EPS balls within the bottom box have the same disposal as the top box alveoli. Each experiment starts with the cooling process that run during 8 hours. Once the 8 hours are completed, the heating process takes place. The cold chamber is opened, and the temperature is recorded for 15 hours. Once the experiment is performed without PCM, it is included a PCM bag inside the middle box, between the base of the box and under the alveoli.

III. ANALYSIS AND DISCUSSION OF RESULTS

The temperature was determined to obtain a better understanding of how the air flow was entering in the boxes and interacting with the boxes and the PCMs. Any difference in the air flow could result in faster or slower heat transfer rates in a certain location of fruit simulators.

As previously mentioned, the T-type temperature probe was used to find the temperatures at all 6 positions indicated before. The experiment consisted of 3 stages with cooling and heating process. The first stage was completed without using PCM. The second stage using Paraffin RT11HC as PCM. Finally, the last experiment involved paraffin RT8HC. The experiment was scheduled for three tests to obtain the results with and without PCM and the experiment time were closely monitored to obtain any deviation. The temperature results from the artificial fruit test points in the boxes are presented in the next sub chapters.

A. . Cooling Process

Past experiences performed, such as in Coca-Ortégon et al [10], where PCMs were used to in refrigerators walls and studied their behavior in the process of cooling and demonstrated that well positioned PCMs represent an increase of latent heat storage. The position where in the refrigerator the product is will affect their cooling behavior, and in the experiment performed in our laboratory, that aspect was demonstrated. The study explains that during the cooling process very less deviation is observed in the artificial fruit location T1, T2, T3, T4 and T5. The T6 probe used to define the air temperature inside the boxes.

For comparison purposes, it was performed a first experiment without any PCM included. The results are shown in Figure 6.

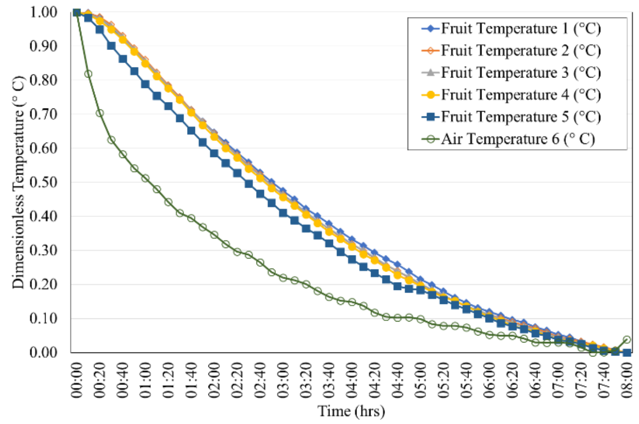

Fig. 6. Behavior of the cooling artificial fruits during the 8 hours of experiment.

This first experiment represents the behaviour of the temperature inside the cold chamber when there is no PCMs involved. On a second approach the PCM RT11HC was tested. A layer of phase change materials was introduced in the top box, between the base of the box and the cartoon alveoli. The behaviour of the fruit's temperature during the 8 hours of cooling is shown in Figure 7.

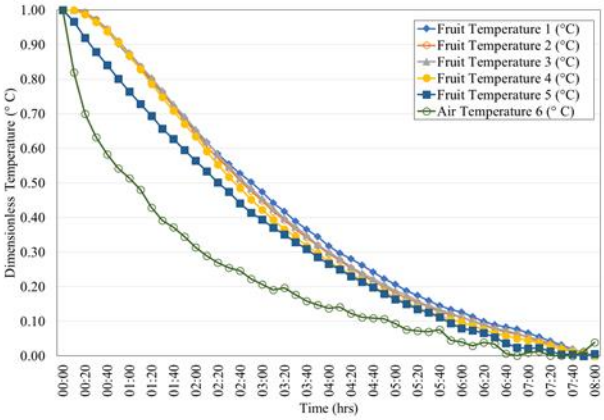

Fig. 7. Behavior of the cooling artificial fruits during the 8 hours of experiment with a layer of PCM RT11HC.

Lastly the approach left to make in the cooling process was to replace the RT11HC PCM for the RT8HC PCM. The results of this experiment are shown in Figure 8.

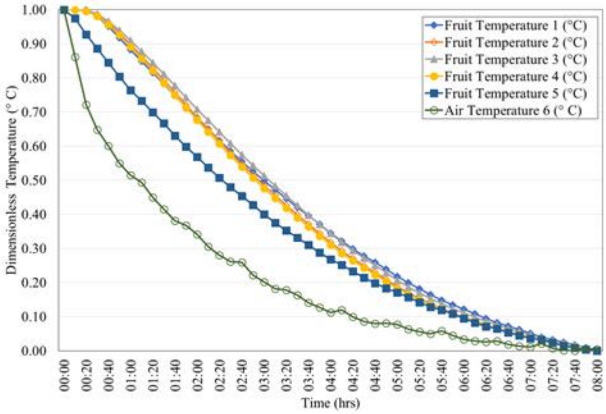

Fig. 8. Behavior of the cooling artificial fruits during the 8 hours of experiment with a layer of PCM RT8HC.

To clarify once again the graphical disposal, three approaches were tested in this experiment. Several identical prototypes of artificial fruits were placed in pre-defined positions in three pilled boxes. In each artificial fruit was inserted a thermocouple to be able to analyze the temperature. That temperature is disposed in the graphs with the designation of "Fruit Temperature 1,..,5" as explained in the figures above. The objective of the experiment is to observe the temperature variations when there is no PCM's involved, and when PCMs are implemented (both RT11HC and RT8HC). The line with "Air Temperature 6" is referred to the thermocouple that is exposed to the air temperature inside the box 2. That air temperature control is mostly to verify how the temperature inside the boxes behave along the time. Comparing the results of the different experiments, it can verify several differences. It must be noted that the behaviour of the temperature along time and the temperatures recorded at the end of the experiments were compared. Table II shows the comparison of the final temperature in the different sensors for each experiment.

TABLE II
COMPARISON OF THE TEMPERATURES IN THE DIFFERENT SENSORS.

Fruit Sensors	Location	Temperature cooling process (°C)		
		Without PCM	RT8HC	RT11HC
T5	Top box, center position.	5.60	5.38	5.59
T2, T3, T4	Placed diagonally in the middle box.	6.34, 6.31, 6.00	7.28, 7.41, 6.99	7.74, 8.06, 7.86
T1	Bottom box, center position.	7.60	7.63	8.10

Taking into account how a phase material works, and realizing that stores energy and releases it to change its phase, this condition is verified during the cooling process, where it has a higher value for temperature, even if that difference is not significant, being almost constant through the 3 different processes. The largest variations depend by the position of the sensors in the cold chamber. The cooled air that enters the cold chamber, and interacts with the boxes, provides an easier heat exchange with the top box. The top box is directly exposed to the chamber air temperature and the heat exchanges occur directly between the cooled air and the fruit simulator. The more down in the chain the more difficult it get to those heat exchange happen. It can be verified by comparing the results from the sensor T1 and T5. The difference of values between them is around 2°C.

B. *Heating process*

The heating process is important to study the performance of PCMs. The cooled fruits are exposed to the labs temperature and analyzing their temperature rising behavior will inform us about the advantage or not of the use of those materials. When this kind of experiments are performed, the expected results are that PCMs help to maintain the temperature of the fresh products for a longer period, helping to delay the impacts that the non-ideal temperature has on fresh products. This study shows the temperature variation along time. The final temperature of each case was compared. Figure 9 shows the heating process of the non PCM included case.

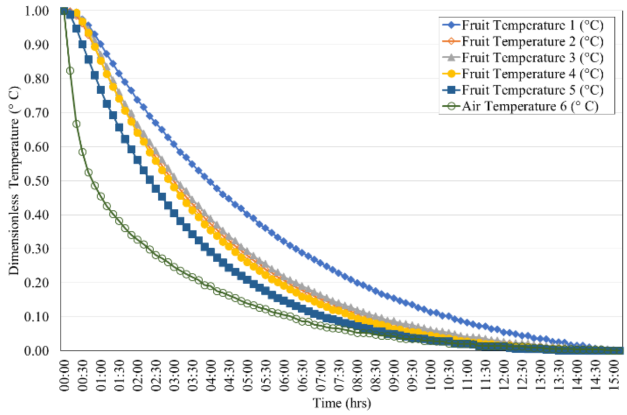

Fig. 9. Behavior of the artificial fruit's sensors during the heating process without PCM included.

Following the same order as in the cooling experiments, a layer of PCM was placed in the top box. The results for the RT11HC PCM are shown in Figure 10.

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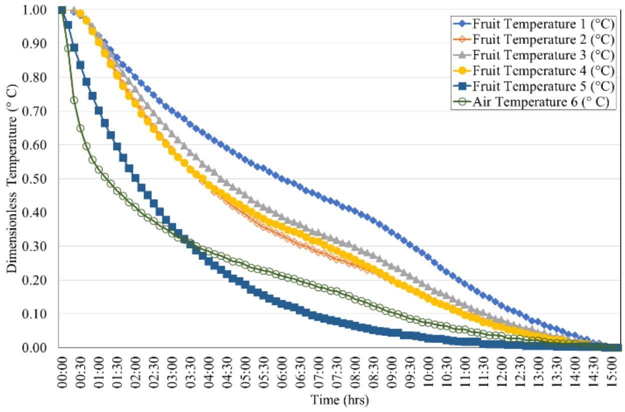

Fig. 10. Behavior of the artificial fruit's sensors during the heating process with PCM RT11HC included.

Lastly the layer of PCM RT11HC was replaced with the PCM RT8HC and the procedure was the same. The results are shown in Figure 11.

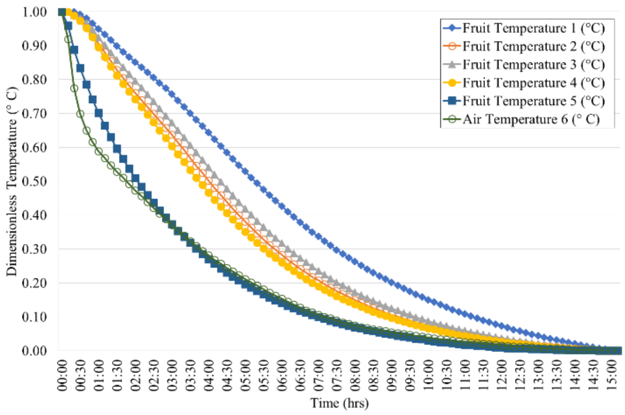

Fig. 11. Behavior of the artificial fruit's sensors during the heating process with PCM RT8HC included.

Observing Figures 9 to 11 and their curves slope, it is easy to verify that the top box reaches higher temperatures faster. The sensor positioned in the top box is directly exposed to the lab's temperature, that being very superior, fast heat exchanges happen to reach a thermal balance. It also happens in the sensors of the boxes above, however the heat exchanges doesn't happen so fast. Studying the slope of the curves it can be verified that the PCM, in both cases works as a thermal support. The slope in the curves where the PCM was included change more drastically at some point. That point represents that the PCM released all its energy and is no longer functioning becoming obsolete. So, at some point of the experiment and due to its longevity, the outcome is the same for both with and without PCM. The bigger changes are in the early minutes of the experiment. The energy released by the PCM layer helps to maintain the temperature of the fruits. In this study it was only studied the final temperature and in the end of the experiment the temperatures are quite similar in all the cases studied. The important aspect about PCM's is the delayed slope analysing Figure 10 and Figure 11 for the time 00:00 to the approximately 01:30. The slope in the Figure 8, that represents the experiment where no PCM was include the temperature starts to increase right away, while in the two cases with PCM there is a delayed of that temperature increase allowing to maintain the temperature for a longer period of time.

When comparing the two PCMs it can be identified that for an early stage the RT8HC has a better behaviour, because it releases energy on an early stage. While the other releases later, so the results are shown later.

IV. Conclusions

This study aims to contribute to the reduction of fresh food waste. With non-ideal conservation time and temperatures, the fresh food suffers from a quality and nutritional value decline causing potential problems of food health as well as food waste. The food waste also implies a waste of resources used to produce that food with serious impacts in the planet. As an attempt to mitigate that problem, the inclusion of phase change materials (PCM) to the packages where the fresh food is handled is studied. During the transportation chain from producers to the final consumer, the food goes by many stages with several temperature variations. The PCM technology will function as a thermal capacitor, releasing energy to help maintaining the food temperature. With the experimental tests performed it can be concluded that by the end of the 15 hours, the PCM is not releasing latent heat, allowing the temperature to be similar on all the experiments. PCM helps maintaining the ideal conservation temperature at an early stage. However, the PCM must be adjusted for each application. The positive aspect of the PCMs is their wide variety of temperature applications, so studying at what temperature food should be stored is important to choose the appropriate PCM.

The PCM technology can have a large impact in the world's fresh food chain. Nowadays, people are paying more attention to their alimentation habits, giving priority to fresh food with healthy properties. Thus, this study aims to contribute in thar sense, maintaining fresh foods quality for longer time and reducing the food waste. Several other studies have to be performed, such as adjusting the minimum quantity of PCM required and time that will be able to release energy.

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