# Prospects for the Improvement of Energy Performance in Agroindustry Using Phase Change Materials

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**Abstract.** The use of Phase Change Materials (PCMs), able to store latent heat, represents an opportunity to improve energy efficiency in the agroindustry by means of thermal energy storage. PCMs provide higher energy density then sensible heat storage mediums, thus paving the way to multiple applications, like supporting the integration of renewables or allowing for new storage architectures, decentralized and directly installed in the chain production equipment, creating e.g. the opportunity to recover and value low-grade operational heat sub-products. Such new and decentralized architecture, not currently applied in agroindustry, is proposed in this work. A chocolate tempering machine using an organic PCM is conceived and analyzed using ANSYS Fluent software for computational fluid dynamics simulations, comparing the main aspects in the storage capacity and discharging process with a conventional sensitive heat storage solution that uses water. PCMs allows improving the stored energy, keeping the chocolate in the working temperature after being tempered for more than four times longer than using only hot water. If the PCMs are charged by renewables, the self-consumption ratio can be improved while providing energy flexibility to the user.

**Keywords:** Agroindustry, latent heat storage, phase change materials (PCM), thermal energy storage.

# 1 Introduction

Agroindustry is a broad sector, that can be defined as the "post-harvest activities involved in the transformation, preservation, and preparation of agricultural products for intermediate or final consumption" [1]. It involves commercializing and adding value to agricultural products, and the links between enterprises and supply chains for developing, transforming and distributing those products [2]. A broader definition of agroindustry, although not worldwide accepted, involves forestry activities, leather products, and cotton textiles, i.e. non-food sectors [3], beyond fishery activities.

According to the Food and Agriculture Organization (FAO) of the United Nations, agriculture and agroindustry systems are characterized by a high dependency of energy, in particular, fossil fuels, accounting for around 30% of worldwide energy consumption and 22% of greenhouse gases emissions (GHG) [4]. Specifically for the food sector, FAO envisages the transition to energy-smart food systems as a means to make them energy sustainable, with low GHG emissions, more robust to energy price variations, and able to contribute to food safety and sustainable development. This can be achieved by the simultaneous action in distinct but strongly interlinked vectors, namely energy efficiency, renewable energy integration, and circular economy.

Thermal energy storage (TES), and the management of stored energy, is an essential feature for the processing and transformation of food raw materials. It usually relies on sensible heat, where the storage medium increases its temperature while storing heat. Water is often used due to its low cost and availability, but its applicability is limited to temperatures ranging from the freezing to the boiling points i.e. 0 to 100 °C (at 1 atm), although this is still adequate for many agroindustry processes. Water is also inert (non-toxic, non-flammable, and non-corrosive through the addition of corrosion inhibitors), and has the highest volumetric thermal capacity (4.17 $MJ/m^3\cdot K$) when compared to other mediums typically used for sensible heat storage [5]. The volume of water required for an application is calculated straightforward, using the requisites on thermal energy/power, as well as the corresponding temperature change. In addition, water can be directly integrated with solar thermal systems, and its high thermal stratification ability has demonstrated to improve the efficiency of TES systems.

Unlike sensible heat, latent heat storage allows storing thermal energy at a constant temperature, through the phase change of a material. Materials used for this purpose are called Phase Change Materials (PCM) and water is itself a PCM, allowing storing thermal energy at 100 °C when changing to its gaseous phase, or at 0 °C when changing to its solid phase. PCMs with adequate temperature and enthalpy of phase change have the potential of being directly integrated into agroindustry equipment and operations. This is foreseen to allow for higher amounts of stored energy for the same volume and temperature range when comparing to sensible heat storage, while passively maintaining the operating temperature. Simultaneously, new solutions and approaches for energy efficiency are foreseen, like those based on distributed energy storage, directly integrated into the production chain equipment. This has not been applied in the agroindustry sector so far and is proposed in this work to improve the energy performance of that equipment. A chocolate tempering machine is used as a case study for the paradigm of distributed TES, demonstrating to be able to assist the integration of renewables while additionally providing energy flexibility.

This work aims at answering the following research question: *is it possible to improve the energy performance of the agroindustry sector by means of storing thermal energy in PCM materials, with a reduced impact on the production chain equipment?* The following hypothesis is defined: *if it is possible to find a PCM adequate for agroindustry critical stages temperatures, it should be possible to apply and operate it in chain production equipment, in a way that allows maximizing its energy performance.*

In the next section, the relation of the present work to the theme "Technological Innovation to Life Improvement" is described. PCM principles and characteristics are presented in Section 3, while the energy consumption in the agroindustry is characterized in Section 4. The potential applications of PCMs in that sector are summarized in Section 5, and the chocolate tempering machine case study is described in Section 6. Conclusions and future work are drawn in Section 7.

## 2 Relation with Technological Innovation for Life Improvement

The technological innovation proposed in this work, namely a distributed storage concept for the agroindustry production chain equipment, is related to life improvement by several means. It aims at assisting the integration of renewables and providing energy flexibility in that sector, which ultimately contributes to increasing the competitiveness of agroindustry companies by decreasing their energy bill. At the same time, it allows reducing the consumption of fossil fuels and associated GHG, which is a global concern.

## 3 Phase Change Materials

As mentioned, storing thermal energy as latent heat relies on the phase change of a material, often between solid and liquid phases, but also between distinct solid phases or between liquid and vapor phases. Throughout the phase change process, the temperature remains constant, see Fig. 1, while the energy at the molecular level is increased. In sensible heat storage (SHS), the amount of thermal energy stored, $Q$, is given by [6]

$$Q = m \cdot \bar{C}_p \cdot \left(T_f - T_i\right) , \quad \textbf{(1)}$$

where $m$ is the mass of the storage medium, and $\bar{C}_p$ is the average specific heat between the initial and final temperatures of the medium, respectively $T_i$ and $T_f$.

In latent heat storage (LHS) a term corresponding to the heat exchanged during the phase change adds to the stored energy [6],

$$Q = m \cdot \left[\bar{C}_{sp} \cdot \left(T_{pc} - T_i\right) + a_m \cdot \Delta H_m + \bar{C}_{lp} \cdot \left(T_f - T_{pc}\right)\right] , \quad \textbf{(2)}$$

where $T_{pc}$ is the phase change temperature, $\bar{C}_{sp}$ is the average specific heat between $T_i$ and $T_{pc}$ (corresponding to the solid phase, in the solid to liquid transition), $\bar{C}_{lp}$ is the average specific heat between $T_{pc}$ and $T_f$ (corresponding to the liquid phase), $a_m$ is the fraction of the total mass that is melted, and $\Delta H_m$ is the phase change enthalpy. Latent heat storage is thus a more efficient TES method.

There are no relevant sector or regulatory barriers to the application of PCMs, and its exploration is often dictated by their cost, besides technical characteristics that may limit the use of these materials. Some challenges that industry and researchers face are developing materials able to store higher amounts of energy in less mass, at different temperature levels, that are thus able to address multiple energy efficiency solutions, in distinct sectors. Besides agroindustry, PCMs have been used mostly in construction, automotive, storage and transportation of medication and food, telecommunications, solar energy, and space industry, among others [7][6].

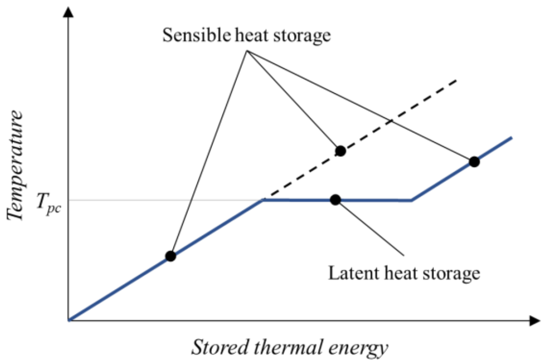


**Fig. 1.** Sensible and latent heat storage, where $T_{pc}$ is the temperature of the phase change (adapted from [8]).

PCMs are classified into three major groups [9]:

*Organic.* These can be divided into paraffin (saturated hydrocarbons) and non-paraffin (fatty acids, alcohols, and glycols) compounds. These materials crystallize with negligible or no supercooling [10], and they show a wide range of phase-change temperatures, which allows them to address a multitude of applications. Yet, they have a relatively low thermal conductivity and they are incompatible with some plastic materials. One major drawback is the fact that they are inflammable.

*Inorganic.* These are essentially salt hydrates and metallic alloys. The latter show a high phase change temperature, in the range of hundreds of Celsius degrees, that limits its exploration often to solar energy applications [11], although several advances with low melting point metals and alloys are undergoing [7]. Hydrated salts are composed of inorganic salts and water. The phase change of these PCMs corresponds, in reality, to the hydration and dehydration of the salt [9]. They are cheaper to produce than organic PCMs and have higher latent heat per mass and volume unit, as well as higher thermal conductivity. Besides, they are not flammable and have a lower variation in the densities of the liquid and solid phase, when compared to the latter. Their main disadvantage is incongruent melting and supercooling [9], being in addition often corrosive to metals.

*Eutectic.* These are composed of two or more substances with similar phase-change temperatures, that melt and solidify congruently, making a mixture of the components crystals throughout crystallization [6]. A wide range of such PCMs is available, including combinations of organic, inorganic and organic-inorganic substances. Their main advantage is the possibility of adjusting their melting point to match the required operating point. Yet, their latent heat and specific heat are lower than the ones of paraffins and salt hydrates [12].

PCMs typically contact with other elements, requiring encapsulation to avoid leaking in their surroundings or corrosion issues [12].

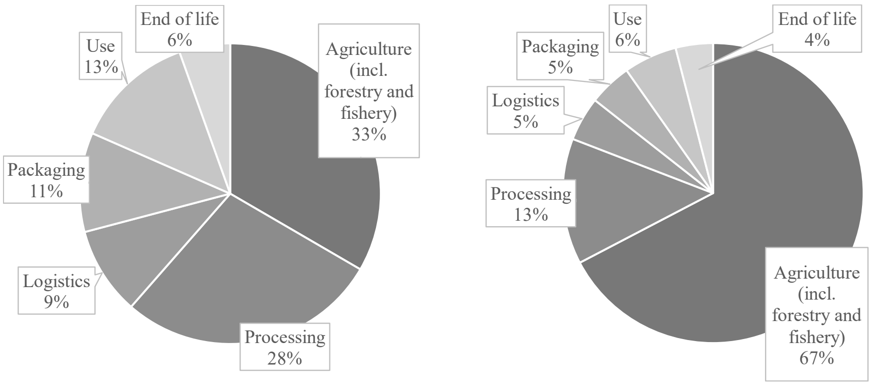
## 4 Energy Consumption in the Agroindustry Sector

Agroindustry, as an aggregator of activities related to the processing of raw materials generated by agriculture (including livestock), fishery and forestry, integrates the value chain between production and consumption, for food and non-food purposes. Agroindustry itself is considered a non-intensive energy industry, yet, due to its size, it is a major global energy consumer [13].

Fig. 2 illustrates the per capita energy consumption and GHG emissions of the EU-27 related to the food sector. Its value chain is divided into agriculture (including forestry and fishery), processing, logistics, packaging, use and end of life. Agroindustry, ranging from agriculture (processing) to packaging, is thus responsible for more than 80% of the energy consumption and for 90% of GHG emissions of the food sector. The industrial processing stage represents almost 30% of energy consumption in the food value chain, which corresponded in 2013 to burning around 655 liters of diesel fuel per EU-27 inhabitant [14].

Agroindustry requires electrical and thermal energy for distinct purposes, besides the raw material production, namely its transportation, processing, preservation, packaging, and storage, as well as non-process uses, related to e.g. lighting or space heating and cooling [15]. Electrical energy may typically be used as the source of any process, namely those requiring thermal energy, while burning fuels to produce the latter has more restricted use.

The share of electrical and thermal (fuels) energy to supply each of the previous processes may change drastically within companies, depending on its positioning on the value chain, its size, its geographical location or the type of products produced, among many others [15]. According to the analysis in [14], cold supply and electric motors are responsible for more than half of the electrical energy consumption in the food sector chain. Nevertheless, while in some agroindustries electrical energy may constitute nearly all the energy sources, as wineries [16], others may depend more on fuels, like olive oil mills [17] (these examples concern representative companies in the EU). It is estimated that 85% of the fuels burnt by agroindustry aims producing steam and hot water for cooking, sterilizing, washing and sanitation [18].



a) Energy, 23.6 GJ average consumption.

b) GHG, 2965 kg of $CO_2$ average emissions.

**Fig. 2.** Per capita statistics of the energy consumption and GHG emissions of the food sector in the EU-27, in 2013 (adapted from [14]).

Despite the previous indicators, energy corresponds to a small fraction of the total cost of production in the food sector, namely 3%, which may often constitute an obstacle to adopting energy efficiency practices in this sector [13]. Nevertheless, considering the scale of the food sector, this 3% factor is relevant.

## 5 PCM Application and Improvement of Energy Performance

TES with PCMs has several potential applications, as previously mentioned. The main prospects for its use in the agroindustry sector are described below.

### 5.1 Industrial Waste Heat Recovery

Agroindustry is a major user of low-temperature process heat, i.e. below 120 °C. Several applications making use of storing and reusing industrial waste heat (IWH) have already been identified, such as for heating fresh water for the different food processes or heating a factory clean-up water. IWH could be collected e.g. from the refrigeration systems commonly used in agroindustrial plants. A review of these topics is described in [18].

### 5.2 Heating and Reduction of Peak Temperatures in Greenhouses

PCMs find applications in the building envelope, to provide extra thermal inertia [19]. In agroindustry, they have been applied to heat greenhouses, often with solar air collectors, keeping its temperature stable and reducing peak temperatures, such as the ones occurring in summer [20, 21].

### 5.3 Food Storage and Transportation

There are commercially available containers with PCMs to store and transport food (and beverage) products, allowing them to keep the latter either hot, either cold, for the time required for delivering after production [8].

### 5.4 Support to the Integration of Renewables

PCMs can assist in the integration of renewables, particularly solar-based technologies, like photovoltaics (PV) and solar thermal. PV produces electrical energy which can be used in resistors to generate heat, and this allows charging PCMs (although this is not technically reasonable, and PV plants in self-consumption are connected to a whole user, not to particular loads [22]). Solar thermal consists of using solar radiation to increase the temperature of a working fluid, like water, and this energy can later be transferred to a PCM through a heat exchanger, also charging it. These schemes are flexible in what concerns the temperature of the targeted PCM. Controlling the heat generated by Joule effect in a resistor is trivial, and distinct solar thermal collectors allow addressing distinct temperature ranges [23]. PCMs are thus foreseen to maximize the self-consumption ratio, i.e. the amount of renewable energy produced locally that is consumed in the premises of the user.

### 5.5 Provision of Energy Flexibility

As illustrated in Section 5, the thermal properties of PCMs can be used to decouple energy consumption from a device's heating needs. This is an instrumental property to provide energy flexibility [24], which can be used for different purposes. As an example, the energy flexibility provided by TES with PCMs can be used to improve the self-consumption of local PV generation or to shift electric energy consumption to periods with cheaper tariffs. The characterization and use of the energy flexibility provided by these devices can be supported by the work already developed under the context of IEA (International Energy Agency) EBC (Energy in Buildings and Communities program) Annex 67, which defined the energy flexibility of a building as *"the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements*" [25]. A comprehensive review of methodologies used to characterize energy flexibility of buildings can be found in [26], while a generic methodology, which can also be applied to TES with PCMs, has been described in [27].

# 6 Application Example

The goal of this research is to assess the opportunity of using PCMs for multiple purposes, namely building a distributed TES paradigm, providing energy flexibility to agroindustry and supporting the integration of renewables. For such, a chocolate tempering process was selected as a case study. Chocolate must undergo a tempering pre-treatment process, which allows a controlled crystallization of the vegetable fat in its composition in one of six possible polymorphic states, named as form V [28]. This form is considered ideal for the manufacturing of chocolate products. Besides good color, texture, hardness, gloss and demolding properties, crystallization in the latter form leads to a melting point of around 28 to 32 °C (depending on the composition), which allows chocolate to be solid at ambient temperature and to melt in the mouth [29], thus making it ideal for consumption.

Simulations will demonstrate that PCMs allow improving the performance of the tempering machine, keeping the chocolate at the working temperature for a longer period.

## 6.1 Chocolate Tempering Process and Equipment

Tempering requires an industrial water bath-based equipment, where chocolate can be processed continuously or in batch. This work refers to the latter, and a tempering kettle is used for the batch process, see Fig. 3. In this equipment, water is heated up to a temperature set-point by an electric resistor located at the bottom of the kettle, where a simple on-off control system maintains the temperature inside an admissible range. The set-points are changed according to a predetermined temperature profile.

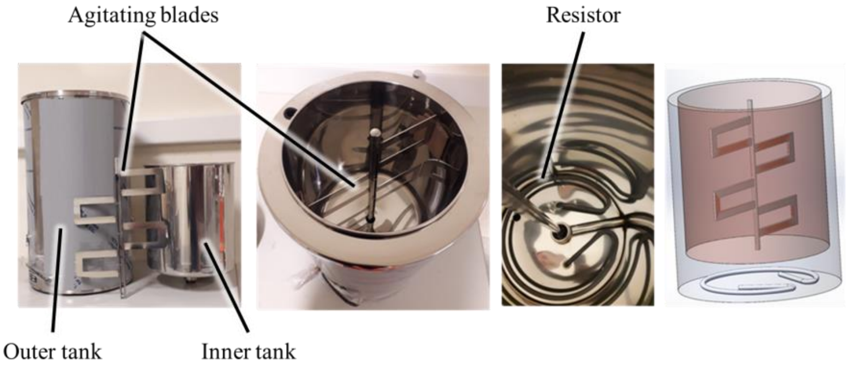


**Fig. 3.** Water bath-based chocolate tempering kettle considered in the work. The rightmost image is the computer representation of the equipment.

The parameters of the tempering kettle are given in Table 1. The equipment is built by two stainless steel (A316) coaxial cylindrical tanks. A water jacket is built between the tanks and, in the inner one, an agitator assures chocolate homogenization.

Water is used to provide a temperature profile required to temper the chocolate, but also for SHS. Water allows keeping an adequate working temperature during the several hours that may be required for the chocolate molding tasks, where it is transformed in products like candies or chocolate bars. Water temperature is controlled by an electric resistor at the base of the kettle. An example of a tempering cycle (and its description) is shown in Fig. 4. After the cycle, chocolate is ready for molding, being kept at a working temperature of 32 to 36 °C.

**Table 1.** Parameters of the tempering kettle used in this work.

| Parameter | Value |
|---|---|
| Water volume | 14 L |
| Maximum chocolate batch volume | 22 L |
| Power of the heating resistor | 3 kW |
| Typical maximum tempering duration (for commercial chocolate) | 40 min |

## 6.2 Simulations

Computational fluid dynamics (CFD) simulations were run to assess and compare the performance of the tempering machine, both with a PCM and water as heat storage mediums. The water jacket will be filled either with water (SHS), either with a PCM (LHS). Simulations concern stage 5 of Fig. 4.

**PCM Selection.** Paraffin was selected as a phase change material, with parameters described in Table 2. This choice, instead of a salt hydrate, is justified by the vertical configuration of the equipment, which may lead to segregation and total reversibility of the phase change cycles of the PCM.

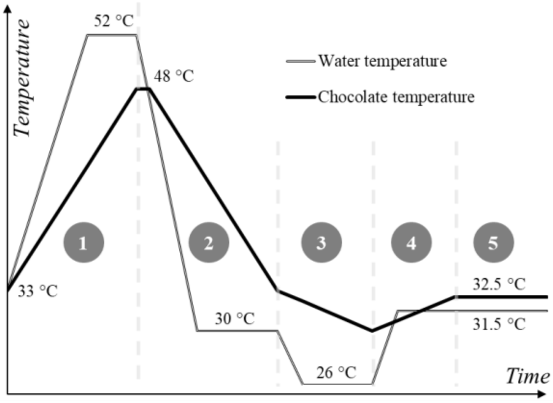


**Fig. 4.** Kreuter interval pre-crystallization procedure (adapted from [30]), which includes the following stages [28, 30]: 1 – chocolate is heated until all fat is melted; 2 – precooling, without crystal formation; 3 – slow cooling, for growth of stable type V crystals, where unstable are also formed; 4 – re-heating, for melting of unstable crystals; 5 – end of cycle, chocolate is kept at a working temperature, allow molding it into the desired form.

**CFD Simulations.** Simulations were performed in ANSYS Fluent software. The geometry and respective mesh are shown in Fig. 5.

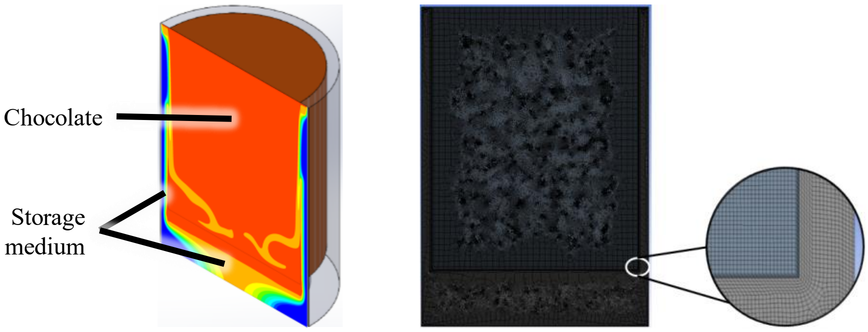
A transient thermal analysis was performed, to study the change in thermal energy stored as sensible heat and as latent heat, using both materials, water and paraffin, as well as the process of cooling and solidification of the chocolate, its relevant thermal gradients and the evolution of its liquid mass fraction. The Boussinesq approach, the $\kappa - \varepsilon$ turbulence model and the Fluent's PCM model. As initial conditions, it was considered both for the chocolate, as well as for the PCM, that they were totally liquid at 36 °C. As boundary conditions, an air temperature of 20 °C was considered. Convection losses were set to 3 W·m$^{-2}$·K$^{-1}$. Fig. 6 shows the results of the water-chocolate scenario and Fig. 7 the PCM-chocolate scenario.

**Table 2.** Properties of the selected PCM.

| Property | Value |
|---|---|
| Phase change temperature | 35 ºC |
| Density, $\rho$ | 776 kg·m$^{-3}$ |
| Specific heat, $c_p$ | 2.37 kJ·kg$^{-1}$·K$^{-1}$ |
| Thermal conductivity, $k$ | 0.18 W·m$^{-1}$·K$^{-1}$ |
| Dynamic viscosity, $\mu$ | 5.9 kg·m$^{-1}$·s$^{-1}$ |
| Phase change enthalpy, $\Delta H_m$ | 130 kJ·kg$^{-1}$ |

The comparison of temperatures' evolution in both scenarios is shown in Fig. 8.a), while the liquid fraction of chocolate also for both cases is represented in Fig. 8.b). From those figures, the following can be concluded:

- The amount of thermal energy stored in the PCM nearly doubles when compared to the water (1 799 kJ vs. 879 kJ).
- Without supplying electrical energy to the resistor, water is able to keep the chocolate in the working temperature for around 2.5 h, while with the PCM this goes beyond 12 h.
- The previous intervals limit the appearance of the chocolate solid phase.



a) Geometry of the simulated domain.

b) Zoom of the mesh used in simulations.

**Fig. 5.** Geometry built in ANSYS Fluent CFD simulation software. A hexahedral hybrid mesh was used, with 150000 elements and 150000 nodes.

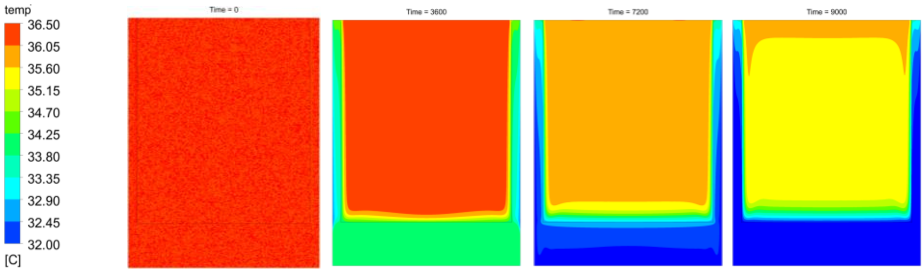


**Fig. 6.** Temperature evolution in the simulation of the scenario with water used for SHS. After 9000 s, water temperature decreased to 32 °C and the chocolate temperature is around 35.5 °C.

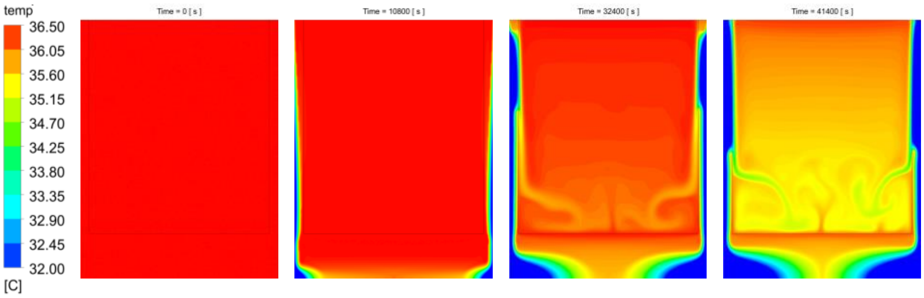
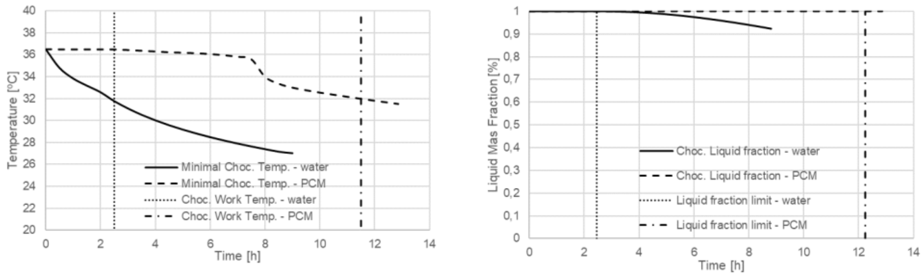


**Fig. 7.** Temperature evolution in the simulation of the scenario with the PCM used for LHS. After 41400 s the PCM is still all solid, and the chocolate is hotter than in the previous case.

To be able to obtain an amount of storage by sensible heat comparable to the one by latent heat (with the PCM at 36 °C), the water temperature would have to be raised above 50 °C, which could represent a risk to the conservation of organoleptic and functional properties for other food products and applications.



a) Evolution of the chocolate temperature.

b) Evolution of the liquid fraction of the chocolate.

**Fig. 8.** Comparison of the performance of the system either with water, either with PCM. The intersection of the vertical lines with the curves gives the moment where both the minimum chocolate temperature is reached, in a), or the minimum liquid fraction, in b).

## 7 Conclusion and Further Work

In this work it was demonstrated that the PCM, used as a storage medium, allowed improving the performance of an industrial tempering machine, keeping chocolate at the working temperature for longer. One key aspect, not mentioned in the case study description, is that to go above the 35 °C phase change temperature of the PCM, as required by the tempering process, additional energy needs to be supplied to the material. This is clear from (1) and Fig. 1, and that additional energy corresponds to the one that is stored in the PCM when its phase changes. Therefore, in this case, to gain the advantages of PCMs, improving the energy performance of the system, that surplus energy needs to be free of charge, i.e. should be provided by renewables. Solar energy is suited for this application, as it can charge the PCM either by photovoltaics or by direct thermal energy exchange. If this occurs, the PCM can also decouple consumption from generation, thus providing energy flexibility to the system and improving the self-consumption ratio.

Future work will consist of developing the encapsulation that will allow optimizing the performance of the PCM and running real experiments to validate simulations.

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