# Phase change material product design. Market and business development assessment in the food industry

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## Abstract

Tea and coffee are very popular beverages but are often served too hot and do not stay warm for long periods of time. A phase change material (PCM) can be used effectively as a passive heat storage method since it can absorb large quantities of latent heat. Preheating is not required since it absorbs heat at temperatures at which the liquid cannot be drunk. The use of such materials in combination with liquid containers (a thermos and a cup) is investigated. Two PCM materials, a paraffin wax ($T_{\text{fus}}$=55,84 °C) and sodium acetate trihydrate ($T_{\text{fus}}$=58 °C) are experimented. Results show that using these materials in a thermos, a liquid can be cooled to Optimum Temperature ($t^{\text{opt}}$=60 °C) up to 95 % faster and the optimum drinking temperature range, defined between 60 and 50 °C, can be kept around 50 % longer. For a cup, results are dependent on the intended use, but are generally discordant since the absence of proper thermal isolation hinders the heat absorption process of the PCM. A business model and a macro and micro environment analysis are also performed and show a market with an high interest towards these kind of products. Finally, a possible design for the thermos and PCM containers is also proposed and is determined financially viable.

***Index Terms*—Phase change material, PCM, coffee, tea, thermos, vacuum flask, cup, mug, food industry.**

## I. INTRODUCTION

As restaurants all over the world strive to offer customers their best tasting experience, the temperature at which food is served is often overlooked. As outlined by several studies [1], [2] temperature is a key factor in determining how humans taste food. As with food, also the temperature of the drinks affects our tasting experiences. Depending on the culture, a meal is usually accompanied by cold water, ambient temperature water or tea in North America, Europe and Asia respectively [3]. A correlation between drinking water temperature and the perceived intensity and creaminess of sweets was proven, resulting in a preference for North American people to highly sweetened foods [3]. In addition, temperature is often a discriminant for determining how good a drink is. Many beverages widely enjoyed across many different cultures, such as coffee and tea, are best savored when very hot. Others, especially during summer, are required to be always drank cold.

A conventional thermos uses a vacuum gap between two metal walls to accomplish this task. If an optimum drinking temperature is defined and, for example, fresh brewed coffee is poured in, it is then possible to identify three phases. The first one is identified by the fact that since the water was boiling, the liquid is too hot to drink. As the drink slowly cools down, it is possible to define the second phase as the time where the drink keeps the optimum drinking temperature. The last phase starts at the moment when the drink is regarded lukewarm until it progressively cools towards ambient temperature. The result is a very limited time frame in which it is possible to enjoy any beverage at optimum temperature. The final user experience is not as enjoyable as it should be: the user initially can get burnt, and after that, he or she has to rush in order to finish the drink before reaching lukewarm temperature.

### A. Objectives

As concern arises around global warming and the impact that each energy source has in creating electrical and thermal energy, it is important to tackle this issues by increasing energy efficiency without providing or using additional energy. The purpose of this work is to propose a solution through means of passive energy storage methods by using phase change materials (PCMs). If this concept is applied to the earlier example of the thermos filled with coffee, it translates in an attempt of increasing the second phase time frame – the one associated to the optimal drinking temperature – while decreasing the time the liquid stays in the other two phases.

## II. STATE OF THE ART

To tackle these objectives, a PCM was employed. They are materials that are able to store large quantities of heat in a relatively small mass and with small temperature changes. In this chapter an overview of their working principles and characteristics is given.

### A. Latent heat storage materials

Thermal energy can be stored using different physical or chemical processes, and each method has quite different characteristics. The heat stored to change the temperature of any substance is called sensible heat [4]. A change in stored energy corresponds to a direct temperature change. In addition, heat can also be stored as latent heat, i.e. the amount of heat absorbed or released during a phase change. In solid-liquid transformation, the phase change is an isothermal process. High amounts of heat can be stored during the phase change while the temperature remains mostly constant. This is a very important characteristic since each PCM presents a different melting temperature. Once the melting is completed, further supply of heat creates only an increase in sensible heat. This particular behavior allows to choose a PCM depending on the application, by simply choosing the desired melting temperature. Additionally, it allows to have an accurate control of the temperature.

PCMs present very different thermal and chemical properties. It is thus necessary to understand their main differences and to categorize them in order to select the most performing and proper material for any given application. In Figure 1 a classification method is proposed and the main properties, advantages, disadvantages and examples, are reported for each category of materials. Important properties that define the characteristic of any PCM are the latent heat of fusion ($\Delta H_{\text{fus}}$) and the melting temperature ($T_{\text{fus}}$). Other properties such as density ($\rho$), melting behavior and supercooling also need to be taken into consideration.

Three different melting behaviors exist: *congruent melting* where, given a specific melting temperature, the salt in its anhydrous form is completely soluble in water and there is no phase separation. *Incongruent melting*: is given when the salt in its anhydrous form is not completely soluble in water resulting in extensive phase separation. *Semi-congruent melting* presents an intermediate behavior between congruent and incongruent melting [5].

Supercooling is a particular state of a material that is found in its liquid form at a temperature below its freezing point [6].

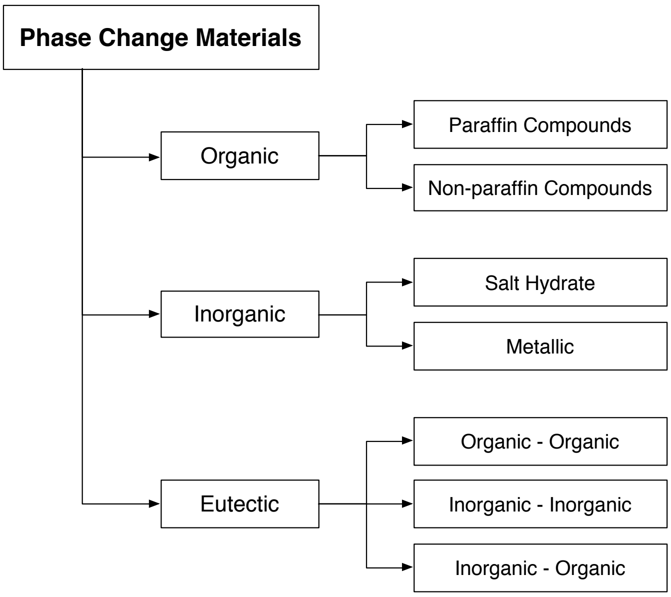


Figure 1. Classification of latent heat storage materials.

## III. METHODOLOGY

The use of a PCM material is investigated with the purpose of creating a system that is able to retain the thermal energy of water for a long period of time. The goal is to create a system that improves the current thermos technology and provides hot liquids (or cold beverages) in a faster way. In addition, it makes the liquids available at an optimum drinking temperature for longer periods of time, in confront of a standard thermos resulting in energy savings.

### A. PCMs and optimal drinking temperature

The optimal drinking temperature was selected by researching and analyzing other works. A company, already selling a similar system, uses a PCM temperature of 60 °C [7]. Additional studies identified the optimal drinking temperature to around 57,8 °C [8].

*1) Paraffin Wax:* A commercial paraffin wax was chosen as the main PCM, since, as highlighted in the previous chapter, they provide a wide range of melting temperatures, relatively high latent heat of fusions, constant performance through cycling and are relatively inexpensive, as well as non toxic [6]. A paraffin wax with a nominal melting point between 53 °C to 57 °C and produced by Sigma-Aldrich was chosen.

*2) Sodium Acetate Trihydrate:* Most of the experiments conducted during this work were developed using the paraffin wax. To test possible performance improvements given by a more dense and higher melting point PCM, a test with sodium acetate trihydrate $\mathrm{Na(CH_3COO)\cdot 3\,H_2O}$ was performed. Table I reports the main properties of this material.

Table I
PHYSICAL AND THERMAL PROPERTIES OF SODIUM ACETATE TRIHYDRATE [9], [10].

| $T_{\text{fus}}$ [°C] | $\Delta H_{\text{fus}}$ [kJ kg$^{-1}$] | $\rho^*$ [kg m$^{-3}$] |  | $c_p{}^*$ [kJ kg$^{-1}$ K$^{-1}$] |  | $k^*$ [W m$^{-1}$ K$^{-1}$] |  |
|---|---|---|---|---|---|---|---|
|  |  | Solid | Liquid | Solid | Liquid | Solid | Liquid |
| 57–58,5 | 260 ±11 | 1450 | 1280 | 2,79 | 3,0 | 0,7 | 0,4 |

$*$: at 58 °C

To suppress the supercooling behavior a nucleating agent was used (disodium hydrogen phosphate dodecahydrate (DSP) $\mathrm{Na_2HPO_4\cdot 12\,H_2O}$) [11]. A solution packed in a single double wall plastic bag was experimented using 124,1 g of sodium acetate trihydrate and 7,6 g of DSP.

### B. Analysis and characterization

*1) Differential scanning calorimetry:* The machine used is a TA DSC 2920 produced by TA Instruments. The mass of the sample used in the text was measured in a controlled environment with a Mettler Toledo UMT2 ultra-micro balance. A paraffin wax sample mass was measured and sealed inside an aluminum pan and placed inside the furnace with a reference empty one. The sample first brought to a temperature of $-10$ °C, then successively a heating cycle up to 80 °C was performed with a rate of 10 °C min$^{-1}$. After the first heating cycle, a cooling cycle brought the samples back to $-10$ °C and a second heating cycle was repeated. This last cooling and heating cycles where used to determine the properties of the paraffin wax.

### C. Density

Density measurements were done using the following methodology. The paraffin wax was liquefied using a thermal bath filled with a low viscosity silicon oil. A predetermined volume (500 µL) of paraffin wax was taken using a Rainin Pipet-lite LTS 100-1000uL (error: ±4µL). Once solidified, the mass was then measured using a Mettler Toledo Newclassic MF - MS205DU balance (error of ±10µg). The error on the temperature measurement of the thermal bath is of ±1 °C.

*1) Viscosity:* To measure the viscosity a DV-II+ Pro viscosimeter, produced by Brookfield Engineering Laboratories, was used. The accuracy associated to the viscosimeter is of the 1 %. Using a thermal bath, a predetermined mass of paraffin was inserted in the apparatus at 80 °C. The viscosimeter, was able to regulate the temperature of the sample with a precision of ±1 °C. The kinetic viscosity was then calculated.

*2) Laser flash analysis:* Through the laser flash analysis (LFA) method it was possible to measure the thermal diffusivity ($\alpha$). The apparatus used is a Flashline 5000 from Anter. The accuracy of the machine is of ±3%. Several samples of different thicknesses and 0,5 inch (12,7 mm) diameter were prepared beforehand since depending on the expected diffusivity a certain thickness is required. The final thickness of the sample was of 2 mm. Five shots with the laser were used for each temperature. The average value between these shots is the value considered valid.

### *D. Datalogger and thermocouples*

An Omega OM-DAQPRO-5300 datalogger was used to record the temperatures. The accuracy provided is of ±0,5% for temperatures above 50 °C and of ±0,5°C for temperatures between −50 °C to 50 °C. In addition, there is an error of ±0,3% on all measurements due to the thermocouples cold junction.

Two different types of K type thermocouples produced by Omega were used for all the experiments. A thin type ("KMQXL-IM050U-450") and a thicker type ("KMQXL-IM150U-450"). The first type was used only for T5 with respect to Figure 2. All the other temperatures were measured with the thicker type.

### *E. Thermos*

A vacuum insulated thermos with nominal capacity of 0,5 L was used. To insert the thermocouples inside the thermos, with the aim of monitoring and recording the water temperature and with the intention of creating the smallest heat loss possible, a small hole in the top of the cap was made.Additionally, all the internal thermoucouples were inserted in a silicon tube in order to increase adherence to the thermos hole and further reduce heat losses.

### *F. Experimental setup and procedures*

The various experimental setups used throughout this work are reported with diagrams outlining the thermocouples positions and type. In all the experiments in which hot water was used, a thermal bath of distilled water at 90 °C was employed.

The maximum useful quantity of PCM was calculated. Taking into account only the sealed thermos and admitting an ideal scenario where there are no losses to the environment, the water to PCM ratio can be defined considering that all the energy contained by the water (inserted at 90 °C) is absorbed by the paraffin wax. The water specific heat capacity is considered constant and equal to $c_{\text{p-w}}$=4184 J kg$^{-1}$ K$^{-1}$ [4]. All the heat contained by the water is absorbed by the paraffin wax (that is found at ambient temperature) as specific and latent heat. After a certain time, the water and the paraffin will be both at the PCM melting point temperature and all the paraffin wax will be completely melted.

$$m_{\text{w}} \cdot c_{\text{p-w}} \cdot (90 - T_{\text{fus}}) + c_{\text{p-PCM}} \cdot (T_{\text{fus}} - 20) = m_{\text{PCM}} \cdot \Delta H_{\text{fus}} \quad (1)$$

Applying equation 1 to the paraffin wax and to the sodium acetate it was possible to obtain equation 2 and 3 respectively. For the paraffin wax the results obtained from the differential scanning calorimeter (DSC) and reported in Figure 4 were used, whereas for the sodium acetate trihydrate the values reported in Table I were employed. A general value for the specific heat capacity was used [4].

$$\frac{m_{\text{w}}}{m_{\text{PCM}}} = \frac{182,4 + 2,89 \cdot (55,84 - 20)}{4,184 \cdot (90 - 55,84)} = 2,0 \quad (2)$$

$$\frac{m_{\text{w}}}{m_{\text{PCM}}} = \frac{260 + 2,79 \cdot (58 - 20)}{4,184 \cdot (90 - 58)} = 2,73 \quad (3)$$

With this data it is possible to know the minimum water to PCM mass ratio that is useful. Mass ratios below these values, and keeping all the other parameters constant, means inserting more PCM which results in a decrease in the amount of available water without fully exploiting the additional PCM inserted.

*1) The reference experiment:* The thermocouple position for a typical run of the reference experiment is shown in Figure 2 (only T1,T2,T3,T4,T5 and T6 were used).

The procedures for a typical run would be the following: first distilled water was heated at 90 °C using a thermal bath; then the Omega datalogger was setup in order to measure the temperature from each thermocouple every 10 s. Water was inserted into the thermos up to the previously defined maximum water level and the thermos would then be closed. The temperatures would then be recorded until the temperature of the water inside would reach ambient temperature.

*2) External PCM layer:* As a first approach, it was decided to drill 3 holes inside the first thermos layer and fill the cavity with PCM. This option would maintain the same amount of water inside the thermos without increasing the volume. The total volume available in the cavity was of 0,180 L (179,6 g of water at 20 °C). By melting the paraffin wax and inserting it in the cavity it was possible to fill the cavity with 127,5 g of PCM.

For the first experiments, also thermocouples were inserted in correspondence of the three holes (TA, TB and TC in Figure 2), but due to pressure build up inside the cavity these thermocouples where removed and the container was sealed.

Additionally, since the isolating vacuum layer was now used to contain the PCM, experiments were run by wrapping the thermos with layers of granulated cork ($k$=0,045 W m$^{-1}$ K$^{-1}$ [4]) to provide insulation and decrease the amount of heat released by the thermos. Two different cork layers were experimented. One layer was 1,2 mm thick, and the other 6 mm thick. Figure 2 provides a schematic of this system, reporting the position of the thermocouples used (all but TA, TB and TC).

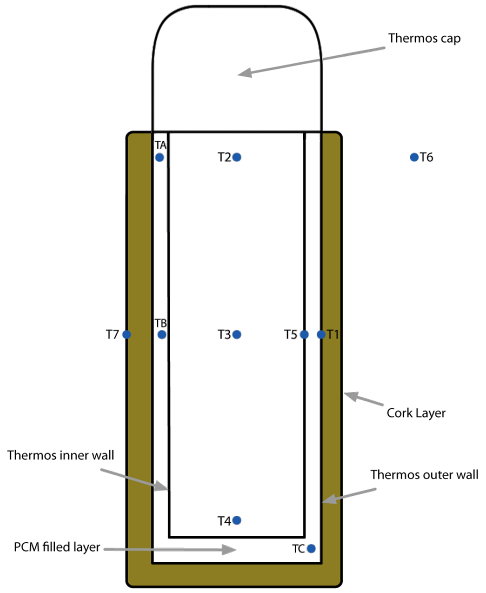


Figure 2. Thermocouple position for the external PCM layer experiment. Each thermocouple is designated with the letter 'T' followed by an identification number or letter. T1: middle of outer thermos wall. T2: 1 cm from the top surface of the water. T3: in the middle of the thermos. T4: 1 cm from the bottom of the thermos. T5: middle of teh inner wall. T6: environment. T7: in the middle of the outer cork layer. TA, TB, TC: in contact with the PCM. Drawing not in scale.

*3) Internal PCM container:* A different approach was also tested. For this experiments, an unmodified thermos was used, and the PCM was inserted in the main compartment. As a downside, this created a significant decrease in the maximum amount of water that is possible to load in the thermos.

To insert the paraffin wax in the thermos different methods were used. Two measures of stainless steel cylinders were used: a low one (Cylinder 1) and a tall one (Cylinder 2). The small one was 9,48 cm high with an external diameter of 2,8 cm and a wall thickness of 1 mm. The tall one had the same diameter and wall thickness but it was 16,25 cm high. The amount of PCM in each tube is reported in Table IV. Additionally, to test surface contact area influence, Cylinder 3, identical to Cylinder 2 but with the addition of stainless steel wool inside was experimented in order to increase the heat exchange area inside. The weight of the inserted wool was of 22,4 g With the same purpose, Cylinder 4 16,5 cm high and with a diameter of 0,8 m was created. To use the same internal volume of Cylinder 2, fourteen of these cylinders were used. With this solution instead of aggregating all the PCM in one container, it was divided into multiple cylinders with approximately a four times increase in surface area. The amount of PCM inserted resulted to be less than Cylinder 2 because of the numerous technical issues encountered while sealing each cylinder.

As a second approach, a flexible latex container was used in order to easily modify the water mass to paraffin wax ratio. The latex containers allowed to put the PCM in practical compact, long and flexible containers with few grams of paraffin per container (around 10 g each, allowing for a more flexible system and providing an easier way to modify the mass to PCM ratio.

*4) Cups:* A simpler system than the thermos was also tested. Normal household cups were tested using the latex containers. The maximum amount of water that was possible to insert in the cup was of 300 g, and it was marked on the cup. With this setup it was possible to easily measure the effects of different water to PCM mass ratios. Figure 3 reports the position of the various thermocouples. The same latex containers described in the previous section were used.

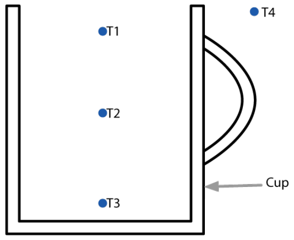


Figure 3. Thermocouple position for the cup experiments. T1: 0,5 cm from the top surface of the water. T2: in the middle of the cup. T3: 0,5 cm from the bottom of the cup. T4: environment. Drawing not in scale.

## IV. EXPERIMENTAL RESULTS

### A. Paraffin characterization results

The data obtained in this section allow the comparison of the various thermo-physical properties between the two chosen PCM. In addition, by knowing all of these data it is possible to create an accurate optimization model of the system in a future work and compare the properties of the paraffin wax with the sodium acetate trihydrate.

*1) DSC results:* Figure 4 reports the DSC results, corresponding to the second heating cycle of the paraffin wax at a scanning rate of $10\,^{\circ}\mathrm{C\,min^{-1}}$. The reported data are the onset melting temperature $T_{\mathrm{fus}}$=55,84 °C and the latent heat of fusion $\Delta H_{\mathrm{fus}}$=$182{,}4\,\mathrm{J\,g^{-1}}$. As it is possible to observe, two peaks are present. Although the higher one is the main one, the second peak reports the presence of another paraffin with a lower melting temperature in a relatively substantial amount. The peak solidifying temperature is found at $T_{\mathrm{fus}}$=51,29 °C with a similar enthalphy of solidification.

*2) Density results:* The calculated density results and their associated errors are reported in Figure 5 on the following page.

*3) Viscosity:* Figure 6 on the next page reports the calculated kinetic viscosity results and their associated error.

*4) Thermal diffusivity:* Table II reports the value of thermal diffusivity for each shot and the average.

### B. Thermos results

*1) The reference experiment results:* Figure 7 reports the temperature over time graph for a normal unmodified thermos of 0,5 L. From the graph, it is possible to note that the external wall maximum temperature (T1) is around 25 °C with an

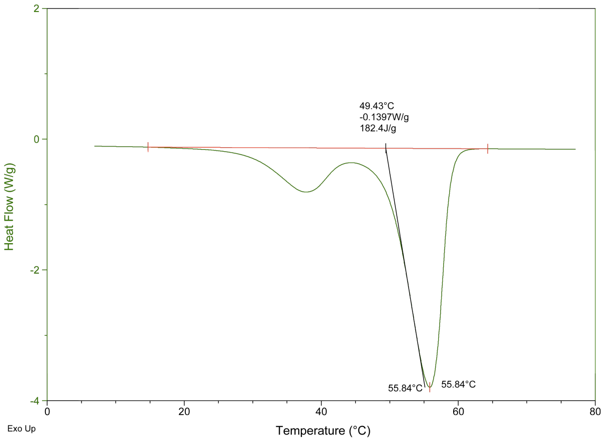


Figure 4. DSC second heating cycle result.

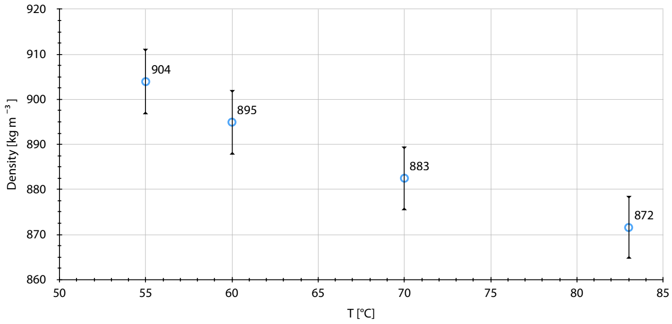


Figure 5. Liquid paraffin wax: density results and associated error.

internal water temperature that is around 85 °C. This result highlights the very good isolation of the thermos vacuum layer.

The results show that the thermos, with an external ambient temperature of around 20 °C need more than 17 h to reach 40 °C from the initial pouring temperature of approximately 90 °C.

If the timeframe in which the water is between 60 °C to 50 °C is taken in consideration as the range in which the liquid contained in the thermos is at optimum drinking temperature defined as "Optimum Timeframe", than the smaller capacity thermos reaches 60 °C ("Time to Optimum") after 25 000 s and keeps the water in the optimum range for around 16 000 s.

*2) External PCM layer results:* Figure 8 shows the comparison of the results for three different experiments: "T3 - No isolation" refers to the the modified thermos with the PCM inserted in the vacuum gap, whereas "T3 - Cork 1,2[mm" and "T3 - Cork 6[mm" refer to the same modified thermos with 1,2 mm and 6 mm of isolation respectively (for which granulated cork was used).

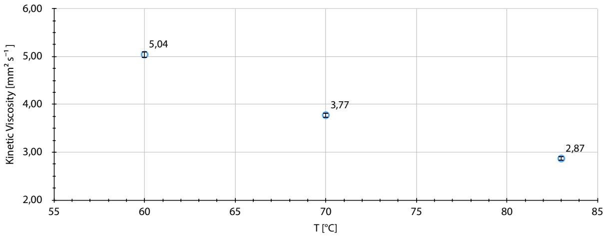


Figure 6. Liquid paraffin wax: kinetic viscosity calculated results and associated error.

Table II
THERMAL DIFFUSIVITY RESULTS.

| Temperature [°C] | Thermal diffusivity [cm$^2$ s$^{-1}$]<br>Average | Shot 1 | Shot 2 | Shot 3 | Shot 4 | Shot 5 |
|---|---|---|---|---|---|---|
| 98 | 0,7574 | - | - | 0,7682 | 0,7207 | 0,7833 |
| 147 | 0,7294 | 0,7105 | 0,7637 | 0,7634 | 0,6978 | 0,7116 |
| 198 | 0,7085 | 0,6995 | 0,7057 | 0,7191 | 0,7046 | 0,7137 |
| 297 | 0,6564 | 0,6556 | 0,6622 | 0,6523 | 0,6383 | 0,6735 |
| 398 | 0,6342 | 0,6554 | 0,6741 | 0,6472 | 0,5818 | 0,6124 |

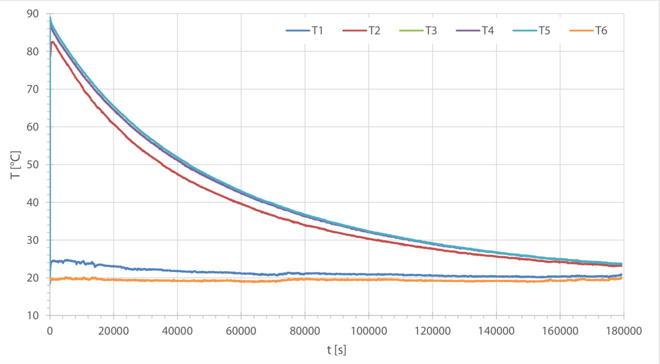


Figure 7. Temperature over time graph for the reference experiment using the thermos.

Table III summarizes the water to PCM mass ratio for each experiment, the time needed to reach 60 °C and the amount of time that the water is kept at optimum conditions (60 °C to 50 °C).

Table III
SUMMARY OF EXPERIMENTAL CONDITIONS AND RESULTS FOR THE EXTERNAL PCM LAYER TRIALS.

| Experiment | $m_{\mathrm{w}}$ [g] | $m_{\mathrm{PCM}}$ [g] | Ratio | $t^{\mathrm{opt}}$ [min] | $\Delta t^{\mathrm{opt}}$ [min] |
|---|---|---|---|---|---|
| T3 - No isolation | 468,0 | 127,5 | 3,67 | 27,5 | 47,5 |
| T3 - Cork 1,2[mm] | 468,0 | 127,5 | 3,67 | 35,0 | 47,5 |
| T3 - Cork 6[mm] | 468,0 | 127,5 | 3,67 | 45,8 | 77,3 |

The best result is obtained by the most insulated thermos. It is possible to observe that the decay of the temperature around the melting point of the PCM is smoothed out by the release of its latent heat energy. As the optimum timeframe is increased, also the Time to Optimum grows with the addition of insulation. This is an unwanted behavior, since it is preferable for the drink to be readily available. The thinner layer of cork has almost no effect on the optimum timeframe, but it increases of around 27 % the Time to Optimum. Although these initial results are promising, they are in no way comparable to the reference experiments reported in the previous section. All of the obtained results (Time to Optimum and optimum timeframe) are an order of magnitude lower than the previous result. The main reason for this is the extreme losses that the thermos has.

Figure 8 compares the results for the three different situations. By performing an analysis and comparison of the external wall temperature (T1 and T7) with the same temperature of the reference experiment of the 0,5 L thermos it is possible to observe a significant increase in maximum temperature. In this case, the external wall reaches almost 60 °C. Although this effect is highly mitigated in the experiment with the better insulated thermos, which reports an external insulation temperature (T7) lower than 40 °C, the losses are still too high to create a comparable result with the reference experiment.

In addition, due to the extreme temperature losses, not all PCM melts. TC and TA in fact, report peak temperatures lower than 50 °C.

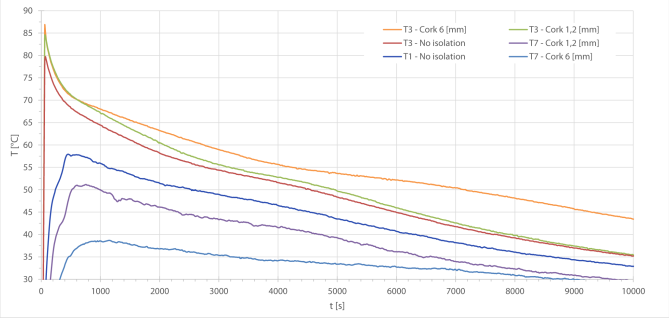


Figure 8. Temperature over time comparison graph for the external PCM layer experiment.

The losses with this type of solution create a system that does not improve a normal unmodified thermos. The vacuum layer creates a very effective isolation that is not possible to replicate unless using expensive isolating materials and/or increasing excessively the insulating radius.

It is possible to observe some initial signs of the PCM latent heat storage effect, which are promising, but a solution in which the PCM is in contact only with the water is probably preferable. Another possible solution that can be explored is the use of a double wall thermos, with the first internal wall filled with PCM and the external one that provides an isolating vacuum gap.

*3) Internal PCM container results:* Table IV reports a summary of the various results obtained using the thermos for each cylinder type. Figure 9 reports a graph that compares all the various solutions.

Table IV
SUMMARY OF EXPERIMENTAL RESULTS FOR THE INTERNAL PCM CONTAINERS. "THERMOS" REFERS TO THE REFERENCE EXPERIMENT DATA.

| Experiment | $m_\text{w}$ [g] | $m_\text{PCM}$ [g] | Ratio | $t^\text{opt}$ [h] | $\Delta t^\text{opt}$ [h] |
|---|---|---|---|---|---|
| Thermos 0,5 L | 468,0 | 0 | - | 6,94 | 4,44 |
| Cylinder 1 | 411,2 | 37,14 | 11,07 | 6,18 | 6,04 |
| Cylinder 2 | 376 | 65,43 | 5,75 | 4,31 | 6,11 |
| Cylinder 3 | 376 | 64,33 | 5,85 | 4,38 | 5,63 |
| $14 \cdot$ Cylinder 4 | 346,7 | 56 | 6,2 | 4,03 | 6,38 |
| Latex | 285,2 | 113,8 | 2,51 | 0,35 | 6,74 |
| SAT | 314,7 | 124,1 | 2,54 | 0,49 | 6,46 |

An increase in the water to PCM mass ratio also increases the amount of time during which water stays in the Optimum Timeframe. Although Cylinder 3 is very similar to Cylinder 2, it performs slightly worse. The insertion of stainless steel wool did not bring any benefit, it only marginally lowered the amount of PCM introduced in the cylinder. Especially for Cylinder 4, the moment in which the cooling temperature changes trend for the release of heat from the PCM is more pronounced. This is primarily due to the increased surface area used in this experiment, which allows all the PCM contained in each tube to receive heat from the hot water more evenly. In addition, although Cylinder 4 has a lower mass ratio, it performs marginally better than all the other cylinders types, possibly for the same reason.

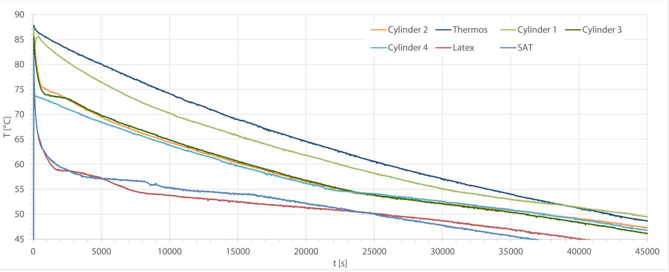


Figure 9. Temperature over time comparison graph for all the internal PCM container experiments; referred to the water thermocouple in the middle of the thermos (T3). Table IV reports each Cylinder type difference. For "Thermos", the reference thermos experiment data was used.

All the different solutions employing a PCM perform better than the reference experiment; it is therefore necessary to use a mass ratio that is closer to the minimum limit calculated in the previous chapter in order to maximize the performance. The "Latex" and "SAT" experiments reported in Figure 9 focus exactly on this point. "Latex" refers to the use of the latex containers. Since these containers were modular and of smaller sizes compared with Cylinder 1, it was possible to insert more PCM inside the thermos. "SAT" refers to the solution of sodium acetate trihydrate, packed in a double wall plastic bag with the correct proportion of nucleating agent as reported in the previous chapter. The water to PCM ratio used is lower than the minimum ratio calculated in the previous chapter, in order to use a ratio similar to the "Latex" experiment. Both of these solutions outperform any other attempt previously made. The amount of water introduced is higher for the "SAT" experiment, since sodium acetate trihydrate has an higher density. For both experiments the Time to Optimum performance is notably low, around 25 min instead of almost 7 h that the thermos without PCM needs. In addition, both increase the Optimum Timeframe to approximately 6,5 h instead of the 4,4 h of the reference thermos. As a drawback, the amount of water that is possible to insert is significantly decreased of 64 % for the "Latex" container and of 49 % for the "SAT" container. This result translates in the need of a bigger volume to transport the same amount of water.

Considering the parameters reported in Table IV, the "Latex" container performs slightly better than the "SAT" one, since it uses a PCM disposition similar to Cylinder 4, i.e. it has an overall higher surface area. Analyzing the curve of the "SAT" it is possible to observe how the use of an higher melting point PCM keeps the water warmer in confront with the "Latex" container that uses the paraffin wax with a lower solidifying point.

*4) Cup results:* Table V reports the mass ratio, the Time to Optimum drinking temperature and the Optimum Timeframe for different mass ratios, with a reference cup filled only with water.

Table V
SUMMARY OF EXPERIMENTAL RESULTS FOR THE CUP EXPERIMENTS.

| Experiment | $m_{\mathrm{w}}$ [g] | $m_{\mathrm{PCM}}$ [g] | Ratio | $t^{\mathrm{opt}}$ [min] | $\Delta t^{\mathrm{opt}}$ [min] |
|---|---|---|---|---|---|
| T1 - Water | 300,0 | 0 | - | 14,5 | 13,2 |
| T2 - Low Ratio | 200,1 | 68,0 | 2,94 | 2,7 | 16,5 |
| T2 - Middle Ratio | 210,5 | 56,5 | 3,73 | 1,0 | 12,0 |
| T2 - High Ratio | 229,7 | 46,4 | 4,95 | 8,2 | 14,8 |

Although all the experiments overall performed better then the reference one containing only water, in this case there is no clear mass ratio that performs better than the others. The Middle Ratio contains an amount of PCM that is probably the closest amount to the optimum ratio, which allows it to cool the temperature of the water to an optimum value in around 1 min, faster than any other option. The downside is that it keeps the water at optimum conditions for the least amount of time. As a result of this situation, the Low Ratio seems to have the overall best performance, since it can cool the liquid at optimum temperature in less than 3 min and it can keep it for the longest amount of time.

If instead what is looked for is the overall longer period above 50 °C, than the unmodified cup has a clear advantage. It can be possible to introduce a small quantity of PCM, such as in the High Ratio experiment, to almost halve the time needed to reach optimum temperature and increase the Optimum Timeframe for around 2 min, but the downside is a 23,4 % lower amount of water in the cup.

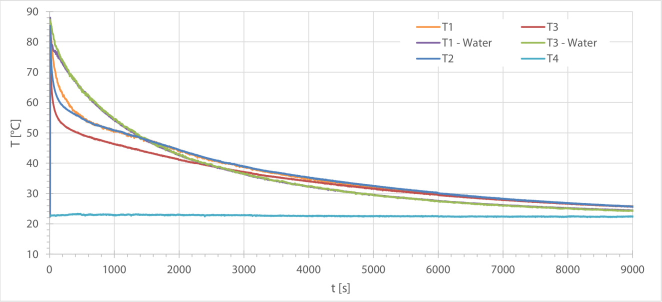


Figure 10. Temperature over time complete graph for the Low Ratio experiment

There are very high water temperature stratifications between the top (T1) and the bottom (T3) water thermocouple (>20 °C). On the contrary, in the experiment with the cup only filled with water, this behavior is not encountered; in fact, there is no significant stratification. This behavior is probably due to the PCM, which creates high convection currents as soon as it gets in contact with hot water and starts absorbing heat. As heat is lost to the environment, this effect becomes weaker and the phenomena decreases in magnitude.1

## V. PLANNING THE BUSINESS

A business analysis is needed to determine the market for a potential product and to prove that it is also financially feasible.

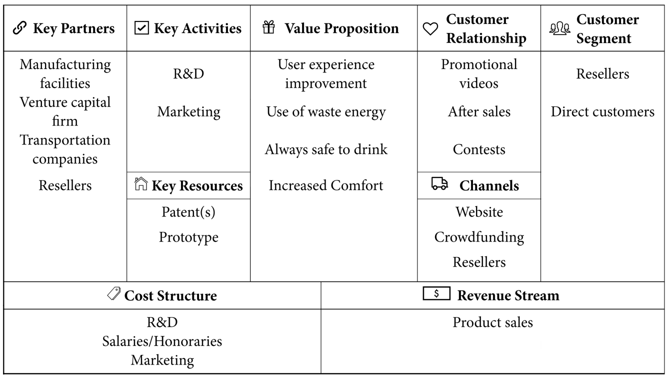
### A. *The need and customer*

The need for food and beverages is one of the constant variables in our lives. Since the introduction of the vacuum container at the the beginning of the 20th century [12] there has been little to no evolution from the initial design. As a result of this lack of innovations, users are now widely accustomed not to be able to control the temperature of their hot beverage and take it as it is, so that now it is widely accepted for a drink to be either too hot or too cold. Two start ups which have already been trying to solve this problem by using a PCM were met with high enthusiasm on the popular crowdfunding website Kickstarter [7], [13].

There has also been an increased awareness of the general public towards sustainability and sustainable solutions. In this direction it is important to underline that the system presented with this work does not need any additional external energy input. The introduction of PCM containers in this market segment would simply use heat that is currently wasted to the environment in a better and more efficient way.

### B. *Business Model*

By developing a functional design it is possible to build a prototype that shows how the system works, providing a basis to showcase the potential of the project to prospective investors. The search for partner manufacturing facilities needs to go along with the search for capital seed money, in order to optimize production process together with the design finalization. In case of lack of capital seed investments, crowdfounding the project can be considered as a viable option. To pursue the described business strategy, a possible Business Model, shown in figurename 11 that an Técnico Lisboa (IST) spin-off company could use is reported.



| **Key Partners** | **Key Activities** | **Value Proposition** | **Customer Relationship** | **Customer Segment** |
|---|---|---|---|---|
| Manufacturing facilities<br>Venture capital firm<br>Transportation companies<br>Resellers | R&D<br>Marketing | User experience improvement<br>Use of waste energy<br>Always safe to drink<br>Increased Comfort | Promotional videos<br>After sales<br>Contests | Resellers<br>Direct customers |
| | **Key Resources** | | **Channels** | |
| | Patent(s)<br>Prototype | | Website<br>Crowdfunding<br>Resellers | |

| **Cost Structure** | **Revenue Stream** |
|---|---|
| R&D<br>Salaries/Honoraries<br>Marketing | Product sales |

Figure 11. Proposed Business Model.

### C. *Analysis of the macro environment*

A political, economic, social and technological (PEST) analysis is necessary to properly evaluate the influence of the all the conditions and of the environment that surrounds the company.

### *1) Political factors:*

*a) Food Safety:* The main document of the European Union (EU) regarding materials that can come in contact with food intended for human consumption is contained in ‘Guidelines on metals and alloys used as food contact materials’ [14]. Although each country has slightly different legislation (with France and Italy having the more stringent laws), any kind of stainless steel is generally accepted. The EU also strictly regulates physical hazards, which must be prevented, eliminated or reduced to an acceptable level [15]. In order to achieve this, all parties involved should use the hazard analysis critical control point (HACCP) methodology, in addition to quality control and management systems such as ISO 9000 [15].

*2) Economic factors:* Since 2008, the EU along with the greater part of the rest of the world entered an heavy recession, as data from Eurostat [16] about gross domestic product (GDP) growth rates confirms. Despite this fact, drinking liquids is a necessity, and this events did not influence beverages. In fact, worldwide tea and coffee production increased during this period [17]. As a consequence, it is possible to affirm that the market is not in a shrinking phase.

*3) Social factors:* People are creatures of habit. Once they have developed a pattern in behavior that proved to be effective they stick to it, preferring what they know to the uncertainty of the unknown [18]. In particular, a product may be better accepted if its use does not require a significantly bigger effort than the one they are used to do.

*4) Technical factors:* Innovations that may affect the operations of the industry and the market are analyzed. Nowadays as it is possible to observe, by examining the product lineup of the main producers, that differentiation is created mainly with product design.

## *D. Analysis of the micro environment*

*1) Thermos L.L.C.:* Undiscussed leader of the market and holder of the first patent regarding the vacuum container technology; it is also the company that invented the Pyrex glass vacuum container and the stainless steel one. Although currently they do not offer PCM enhanced vacuum containers, they have the size, funds and experience to quickly break into it.

*2) Coffee Joulies:* They are a relatively new and small player in the market, but they constitute an unique case because at the moment they are the only ones offering a PCM enhanced container. Their homonymous product was first launched on Kickstarter in 2011. The system is comprised of a stainless steel vacuum flask and 5 coffee bean shaped stainless steel PCM containers. The product works at his best when the PCM container beans are preheated and placed in the vacuum container along with tea or coffee. Although the project received a huge success, collecting 306 944 $ from 4818 founders, costumers reviews once the product was shipped are highly discordant.

*3) Joeveo:* The product, called Temperfect Mug, is still in the final development stages. The new product is made of a vacuum insulated mug with an internal layer filled with PCM. The Kickstarter page also proposes several temperature over time graphs, which show that with the Temperfect mug coffee is cooled to 60 °C from 78 °C in around 225 s, and keeps the liquid at Optimum Temperature for approximately 9500 s. The project financing finished in January 2014, reaching a total of 269 271 $ and 4903 people that backed the project. The amount of water the mug can hold is almost 0,5 L, exactly as the thermos used in this work, but the Temperfect Mug does not provide a leak tight seal.

## *E. Case Study: Thermos design*

By performing an analysis of all the results achieved during this work and by what competitors have been producing and selling, a reference design was created, aiming to tackle all the negative aspects of each different solution while maximizing performance. The designed thermos and PCM vessel applies principles that can also be exported to a smaller travel or desk coffee mug (200 mL to 330 mL).

*a) Esternal container:* The design comprises a liquid container made of stainless steel isolated by a vacuum gap. The bottom part of the liquid container has the size to fit a normal car cup-holder. The container diameter then increases as it reaches the top. This feature allows for an easier access to the internal compartment of the thermos, especially for cleaning.

*b) Lid:* The vacuum thermos is closed by a spill proof lid. This feature provides the flexibility necessary to safely transport the thermos without worrying about spills. The lid is kept in place by a locking mechanism, e.g. a screw thread, and it is possible to completely remove the lid to allow access to the internal compartment of the liquid container.

*c) PCM:* Confronting the two PCM chosen for this work, sodium acetate trihydrate is expected to perform better than the paraffin wax tested. Despite this, futher studies should be conduced and other PCM should also be analyzed and kept into consideration for future reference.

*d) PCM container:* The container is the most innovative and important part of the system. It is made of an hollow cylindrical tube filled with slightly pressurized PCM. The pressure is needed to ensure that all the container is filled with the PCM and all the volume is used. The cylinders need to be correctly sized by an optimization study, with water to PCM mass ratio and contact surface area as main parameters. Naturally, results are dependent from the chosen PCM.

These cylinders can be rendered magnetic with the addition of magnets in the hollow cavity. By doing this they can be stacked and kept together inside the thermos. By magnetically attaching them also to the lid or internal bottom part of the liquid container they would not move when transported, while at the same time granting a better optimized contact with water since the cylinder(s) are surrounded by it. The use of more than one cylinder offers flexibility, i.e. the possibility for the system to work with containers of smaller dimensions, such as travel mugs. The magnets also allow for easier transportation and cleaning. A detachable system gives the possibility to choose between a system that keeps drinks cold or hot by simply swapping the PCM cylinders. In all cases, the lid or the bottom of the liquid container need to be magnetic for the cylinder to be attached to the container.

*1) Preliminary financial analysis:* By analyzing the price points of Joeveo and Coffee Joulies it is proven that people are willing to pay between the 40 \$ of the Joeveo system and the 100 \$ of the Coffee Joulies ones. A bill of materials can be made for the construction of one prototype (1 vacuum flask and 5 PCM containers) as shown in Table VI. The prices reported are intended for private users, i.e. they are common retail prices. The number and price of each PCM container is difficult to calculate because of a lack of manufacturing costs data. A worst case scenario in which one empty PCM container has a cost similar to a single Coffee Joulies bean is considered.

Table VI
ESTIMATED PROTOTYPE COST.

| Material | Price | Unit | Amount | Reference |
|---|---|---|---|---|
| Thermos | 10–25 | \$/piece | 1 | [19] |
| PCM | 27 | \$/kg | 183 g | [20] |
| Magnets | 0,01–0,2 | \$/piece | 11 | [21] |
| PCM container | 7 | \$/piece | 5 | [7] |
| **Total** | 50,1–67,1 | \$/system | | |

To estimate a production run of, for example, 5000 units, similar to the number of customers for Joeveo during their crowdfunding campaign, economy of scale prices can be applied. Table VII reports the cost of the various materials if bulk quantities are bought. As in the previous case it is difficult to estimate the cost of producing the PCM container. For this reason, the previously used price is taken in consideration and reduced of taxes and gross profit margin. Portuguese value added tax (VAT=23 %) was considered and a gross profit margin of 32 % is assumed based on the data rof Butler Consultants [22] for an equipment manufacturer.

Table VII
ESTIMATED COST FOR A 5000 UNITS PRODUCTION RUN.

| Material | Price | Unit | Amount | Reference |
|---|---|---|---|---|
| Thermos | 2–3,5 | \$/piece | 5000 | [23] |
| PCM | 600–650 | \$/Mg | 915 kg | [24] |
| Magnets | 0,001–0,5 | \$/piece | 55 000 | [25] |
| PCM container | 3,66 | \$/piece | 25 000 | [7] |
| **Total** | 102 104–137 095 | \$/5000 system | | |
| **Unit Total** | 20,4–27,4 | \$/system | | |

With bigger production runs it is possible to produce each thermos for a lower price. As in the previous case, the biggest uncertainty is the cost of the PCM container. Similar considerations can also be applied: manufacturing and development costs, taxes and profit margins are still missing. If the same VAT and gross profit margin values are applied to the worst case scenarios, than a possible final retail cost for the product would be of 109 \$ for the prototype and of 45 \$ for large scale production run. Comparing these results with the Coffee Joulies and Joeveo systems prices, the prototype cost is only 9 \$ higher than the final Coffee Joulies price, and the scale production run price per unit is just 5 \$ more than the Joeveo system. Taking into account that these are estimated worst case scenario prices, the product can be considered financially feasible. To obtain a more accurate production costs, a future financial analysis will need to be performed once it is possible to have more precise data about the costs of producing the PCM container and about the real cost structure of the company.

## VI. CONCLUSIONS

The following summarized conclusions can be drawn:

- The patent research about PCM enhanced thermos, mugs and dishes shows that there is a concrete interest about this sector.
- DSC was used to determine the paraffin wax melting (55,84 °C) and solidifying point (51,29 °C), as well as the latent heat of fusion ($182{,}4\,\mathrm{J\,g^{-1}}$).
- For water and ambient temperature conditions similar to the experimental ones, the minimum water to PCM mass ratio was identified in an ideal scenario, taking into account the specific and latent heat of each PCM. The mass ratio calculated with this method amounts to 2,0 for the paraffin wax and to 2,7 for the sodium acetate trihydrate.
- Results showed that higher surface areas (4 to 5 times bigger) perform slightly better than lower ones (4 to 5 % increase of $\Delta t^{\mathrm{opt}}$ respectively).
- In comparison with a standard vacuum thermos, using a PCM can decrease $t^{\mathrm{opt}}$ up to 95 % faster and keep $\Delta t^{\mathrm{opt}}$ up to 50 % longer.
- The denser and with higher latent heat of fusion sodium acetate trihydrate performs better than the paraffin wax. The material, which has a melting temperature closer to 60 °C, overall keeps the liquid warmer during the Optimum Timeframe.
- The use of PCM materials in normal kitchen cups is discordant. Unless for specific situations, normal cups perform better. The lack of insulation and associated thermal losses are too high to allow the PCM to bring significant benefits.
- The main competitors were identified, namely in Thermos L.L.C. [19], Cofee Joulies [7] and Joeveo [13]. The latter two have already proposed PCM enhanced thermos solutions.
- A bill of materials analysis for the proposed design, which is intended to improve the current ones, was made. A comparison with current marketed systems costs proves the proposed design financially feasible.

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## REFERENCES

[1] A. Cruz and B. G. Green, ‘Thermal stimulation of taste’, *Nature*, vol. 403, 24th Feb. 2000.

[2] K. Talavera, K. Yasumatsu, T. Voets, G. Droogmans, N. Shigemura, Y. Ninomiya, R. F. Margolskee and B. Nilius, ‘Heat activation of trpm5 underlies thermal sensitivity of sweet taste’, *Nature*, vol. 438, 15th Dec. 2005.

[3] P. Mony, T. Tokar, P. Pang, A. Fiegel, J.-F. Meullenet and H.-S. Seo, ‘Temperature of served water can modulate sensory perception and acceptance of food’, *Food Quality and Preference*, vol. 28, no. 2, pp. 449–455, 2013.

[4] F. P. Incropera, *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons, 2006.

[5] H. Mehling and L. Cabeza, *Heat and cold storage with PCM: An up to date introduction into basics and applications*, ser. Heat and Mass Transfer. Springer, 2008.

[6] A. Sharma, V. Tyagi, C. Chen and D. Buddhi, ‘Review on thermal energy storage with phase change materials and applications’, *Renewable and Sustainable Energy Reviews*, vol. 13, no. 2, pp. 318–345, 2009.

[7] Cofee Joulies. (). Coffee joulies, Your coffe, just right, [Online]. Available: www.joulies.com (visited on 26/06/2013).

[8] F. Brown and K. R. Diller, ‘Calculating the optimum temperature for serving hot beverages’, *Burns*, vol. 34, no. 5, pp. 648–654, 2008.

[9] G. A. Lane, *Latent heat materials*. Boca Raton, Florida: CRC Press, 1983, vol. 1.

[10] M. Keinänen, ‘Latent heat recovery from supercooled sodium acetate trihydrate using a brush heat exchanger’, Master’s thesis, Helsinki university of technology, 2007.

[11] J. Mao, J. Li, G. Peng and J. Li, ‘A selection and optimization experimental study of additives to thermal energy storage material sodium acetate trihydrate’, in *Energy and Environment Technology, 2009. ICEET ’09. International Conference on*, vol. 1, Oct. 2009, pp. 14–17.

[12] American Thermos Bottle Co, ‘Double-walled vessel with a space for a vacuum between the walls’, Patent US872795 A, 3rd Dec. 1907.

[13] Joeveo. (2014). Temperfect mug, [Online]. Available: http://joeveo.com (visited on 11/06/2014).

[14] Council of Europe, ‘Guidelines on metals and alloys used as food contact materials, Technical document’, Strasbourg, Tech. Rep., 13th Feb. 2002.

[15] European Parliament and Council of the European Union, *Regulation (ec) no 852/2004 on the hygiene of foodstuffs*, Netherlands, 2004.

[16] Eurostat. (2014). Real gdp growth rate - volume, Percentage change on previous year, [Online]. Available: http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tec00115 (visited on 01/07/2014).

[17] Food and Agriculture Organization of the United Nations. (2014). Production growth rates by region, 2001 - 2012, [Online]. Available: faostat.fao.org (visited on 10/06/2014).

[18] M. C. Gonzalez, C. A. Hidalgo and A.-L. Barabasi, ‘Understanding individual human mobility patterns’, *Nature*, vol. 453, pp. 779–782, 2008.

[19] Thermos L.L.C. (2014). Products, Beverage bottles, [Online]. Available: www.thermos.com/product_catalog.aspx?CatCode=BEVG (visited on 11/06/2014).

[20] P212121. (2014). Sodium acetate trihydrate 1 kg, [Online]. Available: http://store.p212121.com/Sodium-acetate-trihydrate/ (visited on 01/07/2014).

[21] Emovendo. (2014). 30 neodymium magnets, [Online]. Available: www.amazon.com/Neodymium-Magnets-inch-Disc-N48/dp/B001KUWM3C/ (visited on 05/07/2014).

[22] Butler Consultants. (2014). Free industry statistics - sorted by highest gross margin, [Online]. Available: http://research.financial-projections.com/IndustryStats-GrossMargin (visited on 05/07/2014).

[23] Zhejiang Rongxuan Industrial Co., Ltd. (2014). Acciaio inox novità riciclato moderno caffè tazza thermos fiasco, [Online]. Available: http://italian.alibaba.com/product-gs/stainless-steel-novelty-recycled-modern-coffee-mug-thermos-flask-1805146222.html?s=p (visited on 05/07/2014).

[24] Foodchem International Corporation. (2014). Acetato di sodio triidrato, [Online]. Available: http://italian.alibaba.com/product-gs/sodium-acetate-trihydrate-1631448628.html?s=p (visited on 05/07/2014).

[25] Sky Magnetech (Ningbo) Co., Ltd. (2014). Neodimio calamita, [Online]. Available: http://italian.alibaba.com/product-gs/neodynium-magnet-1769327501.html?s=p (visited on 05/07/2014).

## NOMENCLATURE

| | |
|---|---|
| $\rho$ | Density |
| $\Delta H_{\text{fus}}$ | Latent heat of fusion |
| $m_{\text{PCM}}$ | Mass of PCM |
| $m_{\text{w}}$ | Mass of water |
| $\Delta t^{\text{opt}}$ | Optimum Time Frame: time that a liquid stays in optimum conditions (60 to 50 °C) |
| $c_p$ | Specific heat capacity at constant pressure |
| $c_{\text{p-PCM}}$ | PCM specific heat capacity at constant pressure |
| $c_{\text{p-w}}$ | Water specific heat capacity at constant pressure |
| $T_{\text{fus}}$ | Temperature of solid-liquid transition |
| $k$ | Thermal conductivity |
| $\alpha$ | Thermal diffusivity |
| $t^{\text{opt}}$ | Time to Optimum: time that a liquid needs to reach 60 °C |

## ACRONYMS

| | |
|---|---|
| **DSC** | Differential Scanning Calorimeter |
| **DSP** | Disodium Hydrogen Phosphate Dodecahydrate |
| **EU** | European Union |
| **GDP** | Gross Domestic Product |
| **HACCP** | Hazard Analysis Critical Control Point |
| **IST** | Técnico Lisboa |
| **LFA** | Laser Flash Analysis |
| **PCM** | Phase Change Material |
| **PEST** | Political, Economic, Social And Technological |