J. Mater. Environ. Sci. 7 (7) (2016) 2551-2560
ISSN : 2028-2508
CODEN: JMESC

Energy storage with PCMs: Experimental analysis of paraffin's phase change phenomenon & improvement of its properties

A. Khyad*, H. Samrani, M. N. Bargach, R. Tadili
Department of Physics, Laboratory of Solar Energy and Environment, Faculty of Sciences,
Mohammed V University, B.P. 1014, Rabat, Morocco.

Received 18 Feb 2016, Revised 28 Apr 2016, Accepted 30 Apr 2016

**Corresponding author. E-mail: akhyad@gmail.com; Tel (+212 661 411819)*

Abstract

Using organic materials is one of the most efficient ways of storing thermal energy. The latent heat storage provides much higher storage density with a smaller temperature difference between storing and releasing heat. However, it's noted that slow thermal response is due to low thermal conductivity of PCMs. This paper presents relevant previous methods for improving the thermal conductivity of the used PCM, particularly paraffin, to effectively charge and discharge latent heat energy and looks at the formulation of the phase change problem. Furthermore, experiences to improve the solid-liquid phase change process were conducted to investigate a technique of enhancing the thermal conductivity of paraffin by incorporating in it a 1% mass fraction of two additives (Aluminum and Copper). The energy was stored in paraffin and was discharged to cold water. Charging and discharging processes were performed and experimental results showed that incorporation of the additives improves heat transfer capabilities. Charging time was reduced and useful heat gain increased by adding aluminum powder.

Keywords: Solar energy, Latent heat storage, PCM, paraffin, Thermal conductivity.

1. Introduction

The latent heat storage is considered one of the most efficient means for storing thermal energy and characterized by a higher storage density and low temperature difference between the storage and releasing of heat. The application of PCMs is a potential technique for the storage of solar energy.

However, practical difficulties often occur in the application of the latent heat method, due to the low conductivity, the changing density and the instability of PCMs properties. In this work, the latent heat refers to the melting since other phase changes such as evaporation are not practical due to the related large volume change. The feasibility of using PCMs in the latent heat storage system is based, in addition to economic criteria, on desirable physical, chemical and thermal properties.

Given that the main problem with the use of solar thermal energy is its storage, we have proposed as a solution the use of PCM (paraffin in our project) for storing energy by latent heat. Based on our investigations on previous experiences, it was found that the major disadvantage of organic PCM, particularly paraffin, is super cooling(liquid state of a body when its temperature is less than temperature of crystallization).

In our paper, the problem to be solved is to find out the way to decrease the phase change temperature (T_{pc}). This problem is related to the thermal conductivity of the PCM, which is relatively low(for utilized paraffin: 0.15 $W.m^{-1}K^{-1}$inthe liquid state and0.232$W.m^{-1}K^{-1}$inthe solid state). This fact prevents a good heat transfer, amplified by the thickness of the phase to cross. In this way, we come to find an additive material, to the concerned PCM, which may decrease its T_{pc}.

The expected ultimate objective is the improvement of paraffin's properties. For this purpose, we were led to pursue research and carry out experiments by finding the best pair of materials(paraffin +embedded additives), comparing the phenomenon of phase change between the single paraffin and the mixture (paraffin + additive) and determining which mixture will show a decrease in temperature on both sides of the curve retracing the variations. We also aimed to find the simplest way to explain the phase change effect and measure energy that paraffin captures and/or releases (given that after 1.5h, the utilized paraffin cools).

2. Materials &Methods

In general, the specificity of PCMs is to store energy in latent form, which justifies their ability to store heat and keep cold and /or hot (in fact, the energy storage means the storage of the material containing it).Typically, paraffin has a phase change temperature (T_{cp}) that lies between 40 and 70°C.

During the melting phase, the PCM liquefies by absorbing energy beginning from a temperature T_{cp} (that is the thermal storage step).The larger the melting energy per volume unit, the better the heat storage.

During the solidification phase, PCM restores this energy when $T < T_{cp}$ (this is the thermal discharging step). Furthermore, the determination of the transmitted energy and the quantity of energy recovered would be of great utility. The temperatures of phase change (T_{cp}) of some materials are given in the following table:

Table 1: Phase change temperature of some PCMs

Wax	Melting Point (°C)	Density (g/cm^3)
Sun Flower wax	55	0.94
Flax wax	40	0.93
Corn wax	42	0.90
Olive wax	68	0.91
Soya wax	23	0.91
Sesame wax	45	0.91

According to Table 1, some materials have lower T_{cp} than others, which conducts us to study the effect of incorporating another material on the change of the concerned PCMs T_{cp}. The search of this additive material, which may decrease or increase its T_{cp}, would be very useful. That's the aim of this section in the current work.

2.1. Justification of the PCMs Choice

Considering its wide availability in the market, our choice was made on paraffin to be used as PCM in this experiment: Itis nontoxic and about 99% pure, its melting point is between 40and70 ° C, it is transparent in the liquid state and opaque in the solid state and its latent heat is very high (266 kJ/kg).The characteristic values of the tested paraffin's thermo-physical properties are provided by the manufacturer, as shown by the following table:

Table 2: Thermo-physical properties of the tested paraffin

Characteristics	**Thermal Conductivity (W/m.K)**		**Specific heat (J/kg.K)**		**Density (kg/m^3)**	
Paraffin 52-54	Solid	Liquid	Solid	Liquid	Solid	Liquid
	0,232	0,15	2195	2950	900	814

According to our investigations, the suppliers recommend the paraffin having a latent heat superior or equal to 180kJ/kg. There are no national or international standards for testing PCMs and contradictions in the thermo physical properties of PCMs, providing especially the latent heat of fusion, thermal conductivity and densities in solid and liquid states, are due to the absence of unified certification standards and procedures.

2.2. Benchmark for comparisons of used heat transfer enhancement methods

In order to improve the low thermal conductivity of pure PCM, two approaches are possible: i) the improvement of heat transfer using mass transfer, which is convection (only occurs in the liquid phase), and ii)the improvement of heat transfer through increasing the thermal conductivity (by adding objects with larger thermal conductivity to the pure PCM) [1].The most common materials added to PCM are graphite, aluminum and butadiene and also employing lessing rings, finned tubes and carbon fibers.

2.2.1. PCM/graphite composites

Antoni.G et al. [2] concluded that PCM/graphite composites have a thermal conductivity between 5 and 10 W/mK, while PCMs have thermal conductivities around 0.2–0.8 W/m K. This value depends on the quantity of graphite embedded on the PCM [3, 4].

Vitorino et al. [5] prepared cellular graphite/paraffin composites which show remarkable enhancement of thermal conductivity, in the range of 5–8W/mK.

Satzger et al., Mehling et al., and Cabeza et al.[6–9] and Py et al. [10] proposed a graphite compound material, where the PCM is embedded inside a graphite matrix. The main advantage of such material is the increase in heat conductivity in the PCM without much reduction in energy storage, but other advantages are the decrease in sub cooling of salt hydrates and the decrease of volume change in paraffin.

Fukai et al. [11–12] studied the use of graphite as heat transfer enhancement material and developed brushes made of carbon fibers. The feature of this method is that the volume fraction of the fibers is accurately and easily controlled and that the fibers with low volume fraction are entirely dispersed in the PCM.

2.2.2. Matrix of expanded graphite (MEG) and paraffin

Satzger and Eska [13] proposed a method to store thermal energy in a composite material consisting of a PCM embedded in a matrix of expanded graphite (MEG). Similar composite materials were investigated also by Mehling et al.[14]. They concluded that the effective thermal conductivity was increased from 0.2 W/(mK) for pure PCM to 25–30 W/(mK).

2.2.3. Matrix of compressed, expanded, natural graphite (CENG) and paraffin

Py et al. [10] investigated a new phase change composite material made of paraffin and compressed, expanded and natural graphite (CENG) matrix. The effective conductivity of this composite material, consisting of 65–95% of paraffin by weight was experimentally measured and calculated.

2.2.4. PCM / Aluminum composites

S.M.Shalaby et al.[15] demonstrated that composite of paraffin with 0.5% mass fraction of aluminum powder was used to enhance the conduction heat transfer process. It was concluded that the freezing time of the PCM is inversely proportional to the mass flow rate (it took a longer time approximately (8h) with a flow rate of 0.05kg/s).

2.2.5. Employing paraffin with lessing rings

In terms of performances of heat transfer enhancement techniques and systems used by Choi and Kim [16], Horbaniuc et al. [17], Velraj et al. [18] and Hamada et al. [19], the best enhancement technique was that due to Velraj et al., where the effective thermal conductivity, calculated employing paraffin with lessing rings, was ten times ($2Wm^{-1} K^{-1}$) greater than the thermal conductivity of paraffin ($0.2Wm^{-1} K^{-1}$).

2.2.6. Use of finned tubes

The use of finned tubes with different configurations has been proposed by various researchers such as Sadasuke [20], Costa et al. [21] and Velraj[22].

Ismail et al. [23] studied theoretically and experimentally the solidification process around a vertical tube with longitudinal fins. However, it's noted that the stated properties of paraffin, such as a density of 772.2 kg/m^3, both in the solid and liquid states, and a heat conductivity in the liquid state of 0.089 W/(mK), contradict the data provided by Zalba et al. [24] for saturated paraffin.

Tayeb et al. [25] carried out the first qualitative experiment with the aim of increasing the effective thermal conductivity in such a latent heat storage medium (HSM) as a paraffin wax by embedding metallic slags and chips. Hafner and Schwarzer [26] presented the study results of different metallic structures effect on the heat transfer in paraffin. They reported that the materials investigated provided the highest thermal conductivity of 1W/(mK), which is about six times that of pure paraffin.

2.2.7. Use of Styrene–butadiene–styrene (SBS) and paraffin

Xiao et al. [27] have developed a shape-stabilized thermal storage material on the basis of the mixture of paraffin (melting point of 56–58°C) and a styrene–butadiene–styrene (SBS). A typical curve for the solidification process of this composite is presented in Figure 1 and the time for the completion of the solidification process is two ninths that of pure paraffin.

2.2.8. Use of carbon fibers

The carbon fibers are considered as a prospective material that might be used to enhance the heat conductivity in the heat storage systems with PCMs. There are various carbon fibers, available commercially, with a thermal conductivity close to that of aluminum and copper.

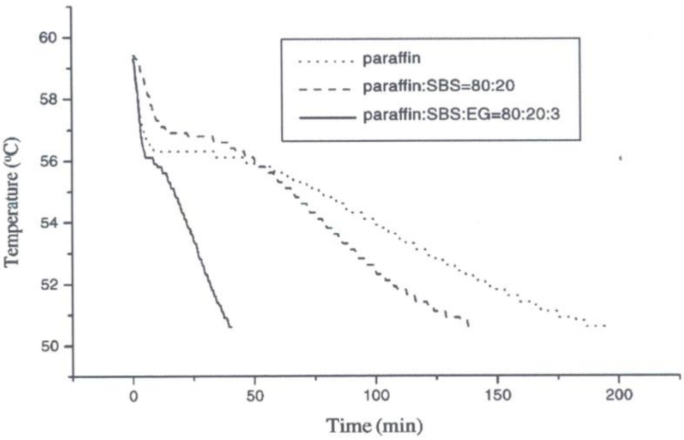


Figure 1: Cooling process of pure paraffin and styrene–butadiene–styrene (SBS) composite [27]

According to Fukai et al. [28], the thermal conductivity of some products is greater than 1000 W/(mK). The authors studied two heat transfer enhancement techniques using carbon fibers. In the first case, the fibers were randomly distributed in a PCM. In the second experiment, carbon fibers were oriented along the direction of the heat flow.

From the previous Benchmark and to indicate where the problems are, we concluded that most of the studied systems have employed paraffin as a storage material. Unfortunately, most kinds of paraffin suffer from low thermal conductivity which delays the discharging process of the storage systems, requiring heat transfer enhancement techniques to improve its rates of charging and discharging of energy.

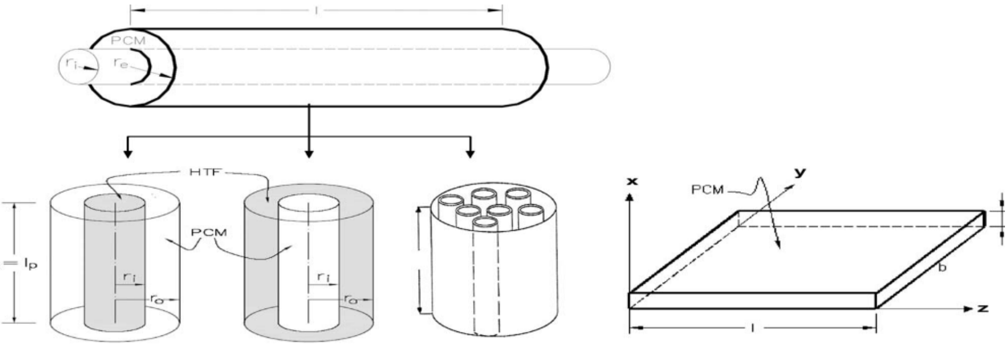
2.3. PCM containers: rectangular and cylindrical

Agyenim.F et al. [29] reported that, once the PCM has been selected based, primarily, on the temperature range of application, the next most important factors to consider are:

(i) the geometry of the PCM container;
(ii)the thermal parameter of the container required for a given amount of PCM.

Each of these factors has a direct influence on the heat transfer characteristics in the PCM and ultimately affects the melt time and the performance of the PCM storage unit.

A survey of previously published papers reveals that two geometries commonly employed are the rectangular and cylindrical containers. Figure 2 classifies the commonly used PCM containers in terms of geometry and configuration.



(a) Pipe model (b) Cylinder model (c) Shell and tube model (d) Rectangular or slab container

Figure2: Schematics of the commonly used PCM containers (rectangular and cylindrical).

2.4. Comparison between PCM and water

Cassedy et al. [30] claim that current PCMs do not offer economic savings for thermal storage, since the paraffin systems cost about double of what hot water systems cost and point out the advantages associated with materials like paraffin, such as low corrosion, and chemical stability. Therefore, water appears to be the best Sensible Heat Storage (SHS) liquid available because it is inexpensive and has a high specific heat.

In the same approach, Sharma.A et al [31] noted that the solar energy, which was stored in paraffin, was discharged to cold water flowing in pipes located inside paraffin.

2.5. Description of experimental setup

2.5.1. Equipment and measurements

In this section, we present the description of the initial experiment using brute paraffin:

Type T thermocouples are used to measure temperature and their usage is adapted to the relatively low temperatures. Temperatures are measured at several levels of the tested paraffin, since the melting process does not occur in a uniform manner inside the material.

In the Laboratory of Solar Energy and Environment (LSEE), where our experiments are performed, all measuring instruments and thermocouples are connected to the acquisition system, which is controlled by a PC using a data acquisition program.

After installing and setting up all the experimental equipment, we start by cutting paraffin into small pieces which are put into a container. Then, the assembly (container +paraffin) is placed on the heating plate after turning it on. Once paraffin pieces begin to melt, firstly those which are in direct contact with the container's bottom and the heating plate, the material becomes transparent and then we place two thermocouples: one at the bottom of the container and the other at the top melted paraffin. At that moment, we turn off the heater plate and leave the assembly to cool while we take temperatures every five minutes using the data system (see Figure3-a).

Figure 3-a : Usage of single brute paraffin

Figure 3-b: Limiting the cooling speed of paraffin

To enable paraffin to melt or solidify for a longer time, we put the vessel containing it in a larger container filled with water, called "host container", and then, we put the whole on heating plate. We observed that cooling occurs faster than before, which is due to the large volume of water in the spacious container.

In order to minimize the cooling speed of the paraffin, we used a host container, smaller than the first, and surrounded by an insulating layer. At that time, we place the receptacle containing paraffin in the isolated host container (see Figure3-b). This method enabled us, on the one hand, to limit the cooling speed of the paraffin, and on the other hand, to visualize the faster variation of the water's temperature.

The experiments investigating the latent heat storage systems, particularly those using paraffin as the organic material, have demonstrated a slow thermal response due to its low thermal conductivity (0.15W/mK in the liquid state and 0.232W/mK in the solid state).In this study, the next steps of these experiments aim to improve the thermal conductivity of the tested paraffin by adding copper and aluminum.

In this paper, the incorporation of two additives with paraffin enables us, firstly, to study the characteristics of heat transfer during the storage process and, secondly, to compare the obtained results by using single pure paraffin and various mixtures (paraffin + additives). The quantities of incorporated additives have been used as shown in Table 3.

Table 3: Quantities of incorporated additives during experiments

Experience	**Aluminum powder**	**Copper powder**
Test 1	36.3g of paraffin + 0.67g of Aluminum	78.61g of paraffin + 0.7g of copper
Test 2	Addition of 0.73g of Aluminum	Addition of 0.69g of copper
Test 3	139.43g of paraffin + 1.4g of Aluminum(=1% mass fraction).	113.32g of paraffin + 1.23g of copper (=1% mass fraction)

2.5.2. Findings from previous experiments

The problem to be solved is related to the thermal conductivity of paraffin which is relatively low(0.15W/mK in the liquid state and0.232W/mK in the solid state), that prevents a good heat transfer, amplified by the thickness of the phase to cross. Regarding the resistance to heat transfer, it was illustrated that the greater the thickness of the Liquid or Solid phase, the larger the generated thermal resistance, and was proposed that the solution is to ensure that the thickness is as small as possible.

Therfore, in the last step of experimental protocol, we used a small amount of paraffin (during heating and cooling) and we incorporated, simultaneously, the same quantities of additives (1% mass fraction of the additive).

3. Results and discussion

With the aim of improving the tested paraffin’s properties, measurements of temperature, during storage and releasing, illustrate the thermal behavior, throughout the heating and cooling, for several repetitive melting/ solidification cycles that the paraffin may endure without degrading.

These measures helped us to find the easiest way to determine the amount of energy that the paraffin will capture and/or release and to quantify the energy restored, given that after1.5 hours, paraffin is cooling and consequently, itis necessary to explain the phase change effect.

After cooling down, that lasted a few hours, we have drawn the curves to visualize the temperature’s variation: The following figure shows the variation of temperatures(top and bottom of the vessel containing the paraffin).

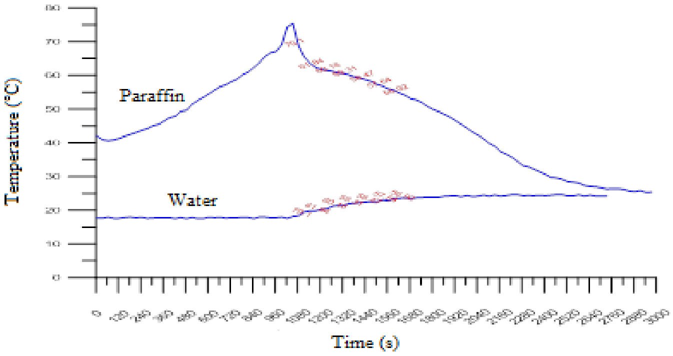


Figure 4 : Evolution of the paraffin’s temperature

From Figure4**,** it is noticed that there is a temperature difference between the top and the bottom of the vessel during the cooling operation. This first stage of the handling has enabled us, particularly, to identify the temperatures and the way to visualize them on the acquisition chain. Equally, the result of this experiment illustrates the variation and distribution of the tested paraffin’s temperature.

The results we have obtained indicate that, during the process of cooling and heating, the temperatures of the vessel’s top and bottom don’t change similarly. Their rapid variation does not allow us to visualize the phase change level.

The result of the 2nd stage of the experiment is presented in the curve Figure 4**.** Based on this graph, it is observed that, during the cooling of paraffin, heat loss was retrieved by the water of the host container. This is manifested, simultaneously, by a decrease in the temperature of the paraffin and increase in the water’s temperature. At the moment of phase change, it is noted that the two temperatures remain constant and that the cooling of paraffin has been restarted, once all the paraffin has solidified.

3.1. *Confrontation of the problem and the results*

According to the results, paraffins seem to be the best PCMs for thermal storage because they possess, through their phase change enthalpies, high thermal densities (that makes them able to store a lot of energy in a small volume) and interesting melt-crystallization characteristics.

The results of the last step of the experience allow us, to compare the phenomenon of phase change between brute paraffin and the mixture (paraffin + additive), and determine with which mixture, it will be found that, the temperature decreases on both sides of the curve retracing the variations. In this step, we studied the linkage between type and characteristics of the additive and the cooling time.

The templates and patterns that we have adopted, for determining the density and heat capacity, are those used in the literature. The simplest model to predict the thermal conductivity of the two-phase mixtures composite is based on the mixing rule that takes the following form:

$$(\lambda_m)^n = \varphi(\lambda_{Additive})^n + (1-\varphi)(\lambda_P)^n \qquad (1)$$

Where λ_m, λ_P et $\lambda_{\text{Additive}}$, respectively, designate the thermal conductivity of the mixture, the paraffin and the additive. The φ parameter designates the volume concentration of the additive: $\left[\varphi = \frac{V_{Additive}}{(V_{Additive}+V_P)}\right]$.

It is noted that the two extreme cases, namely, the parallel and serial combination rules, are obtained when the index n takes the values1 (that we have considered) and–1, respectively. The values of thermal conductivity, corresponding to both cases, serve a supper limits (parallel) and lower (serial).Equation (1) is applicable for special distributions of the additive in the case of high concentrations. For low concentrations, the applicability of the mixing rule is not verified.

Eman-Bellah et al. [32] have demonstrated that physical properties of new compounds will be defined and calculated as follows:

- The thermal conductivity of the mixture (paraffin + additive):$\lambda_m = (\lambda_a V_a + \lambda_p V_p) / V_a + V_p$
- The density of the mixture (paraffin +additive): $\rho_m = (\rho_a V_a + \rho_p V_p) / V_a + V_p$
- The specific heatof the mixture (paraffin +additive): $C_{Pm} = (C_{Pa} Ma + C_{Pp} M_p) / M_a + M_p$

$V_a = v_a/v_m$: the volume fraction of the additive
$V_p = v_p/v_m$: the volume fraction of paraffin
$M_a = m_a/m_m$: the mass fraction of the additive
$M_p = m_p/m_m$: the mass fraction of paraffin

3.2. *Case of incorporating the aluminum powder*

For thermal conductivity of the mixture (paraffin + Alumina (Al_2O_3)), we can adopt the model of Maxwell:

$$\frac{\lambda_m}{\lambda_P} = \frac{\lambda_{Al_2O_3} + 2\lambda_P - 2\varphi(\lambda_P - \lambda_{Al_2O_3})}{\lambda_{Al_2O_3} + 2\lambda_P + \varphi(\lambda_P - \lambda_{Al_2O_3})}$$

This pattern allows giving a good estimation of the mixtures conductivity in the static case. Other models and patterns are available in the literature and help to consider the effect of the additive's size, the Brownian motion and the temperature.

Witha1% mass fractionofAl_2O_3 and after calculation, Table 4shows the physical properties of the paraffin, aluminum powder and mixture:

Table 4: Thermo-physical properties of the mixture (paraffin + aluminum)

Characteristics	**Aluminum**	**Oxyde of Aluminum (Al_2O_3)**	**Paraffin**	**Composite**
Density (kg/m3)	2700	3970	900	844
Melting temperature °C			53.5	53.5
Latent heat of fusion (kJ/kg)			266	266
Specific heat (kJ/kg K)	0.896		2.19	2.476
Thermal conductivity (W/mK)	207	46	0.23	**4.11**

The comparison of some selected points between the result of single paraffin and mixture indicates that the composite's temperature gradually increases with relatively high temperature gradients thanks to the thermal conductivity of the new mixture (4.11W/mK which is about eighteen times that of pure paraffin (see Table 4)).

Thermal energy storage can be stored as a change in internal energy of a material as sensible heat, latent heat and thermochemical or combination of these.

Sensible heat storage: In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material.

The amount of thermal energy, stored in a mass of material, can be expressed as the useful heat gain, which is given by the following classical equation:

$$\mathbf{Q= m\, C_p\, (T_f - T_i) = \rho\, V\, C_p\, \Delta T} \qquad \mathbf{(2)}$$

Where Q is the amount of heat stored [J], ρ is the density of the storage material [kg/L], C_p is the specific heat over the temperature range of operation [J/(kg K)], V is the volume of storage material used (L), T_f and T_i are respectively the final and initial temperature and ΔT is the temperature range of operation [°C].

Latent heat storage: Latent heat storage (LHS) is based on the heat absorption or release when a storage material undergoes a phase change from solid to liquid or liquid to gas or vice versa. The storage capacity of the LHS system with a PCM medium is given by:

$$\mathbf{Q= m\, C_{sp}\, (T_m - T_i) + m\, a_m\, \Delta h_m + m\, C_{lp}\, (T_f - Tm) = m\, [C_{sp}\, (T_m - T_i) + a_m\, \Delta h_m + C_{lp}\, (T_f - Tm)] = m.L_m} \qquad \mathbf{(3)}$$

Where $\mathbf{L_m}$ (J/Kg) is used to quantify the latent heat (L_{fusion} for Liquid-Solid phase change, $L_{vaporisation}$ for Liquid - Vapor phase change), T_m is melting temperature (°C), C_{sp} is the average specific heat between T_i and T_m (kJ/kg K), a_m is a fraction melted, Δh_m is heat of fusion per unit mass (J/kg) and C_{lp} is the average specific heat between T_m and T_f (J/kg K) [31].

It's found that, the useful heat gained is greater for composite than for pure paraffin, which is due to the increase of the heat transfer, because of the higher thermal conductivity of the mixture.

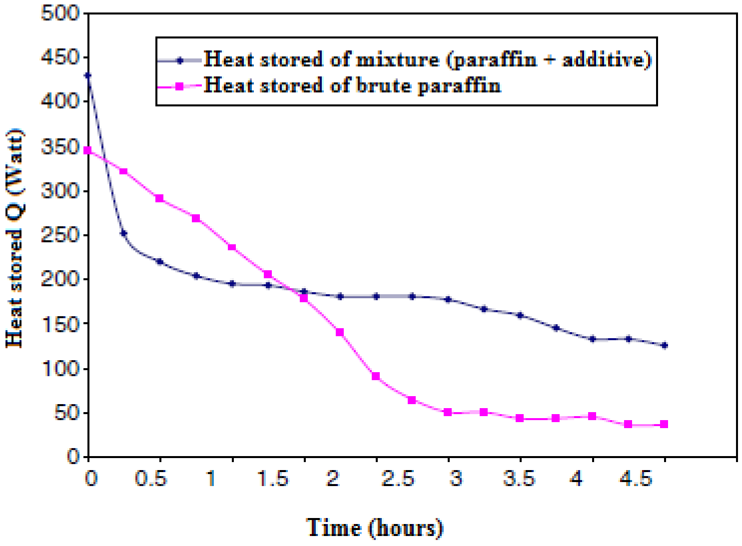


Figure 5 : Comparison of stored heat during the discharging process for paraffin and mixture

According to Figure5,it is observed that the heat transfer rate has increased in comparison with those of the brute paraffin. In fact, this rate increases proportionately with the weight of the added aluminum fraction. This figure also shows, that for the paraffin, the temperature measured by the thermocouples increases gradually in solid state with relatively low temperature gradients: for example, for the thermocouple N°1, the maximum melting time of the mixture is approximately 1 hour while it is almost 1.5h for pure paraffin.

Based on this comparison, the positions of the solid-liquid interface, for both the pure paraffin and for the mixtures, are significantly different and the heating rate of those compounds is more important than the single paraffin.

According to the phase changes visualization during different experiences, the thickness of the solid-liquid interface proportionally increases along with natural convection: the heat is not directly transported through the thickness crossed, but this phenomenon occurred by natural convection of the liquid paraffin to the interface of the solid paraffin.

For each interval of additional heating (in terms of time), the thickness of the upper portion is larger than the lower part. This behavior can be attributed to the geometry of the used containers and its sections.

During the discharge process, the distribution of the paraffin's temperature, indicated by the thermocouples, located in the containers, was measured at equal intervals. The solid-liquid interface can be identified by reading measurements of the thermocouples attached at the level of the container.

At the beginning of this process, the shapes of the mixture and paraffin (undergoing solidification) are not homogeneous due to the effect of natural convection of the container's upper portion. But after sometime, the effect of conduction becomes predominant. Therefore, we noted that the higher the mixture's thermal conductivity, the more homogeneous the shape in comparison with single brute paraffin.

Also, the useful heat gained **increases** by embedding aluminum powder to the paraffin and charging time was reduced.

Conclusion

Paraffin is stable and has a good latent heat. Its use is interesting and attractive in the solar heat storage. The incorporation of additives such as aluminum and copper in paraffin catalyzes its low thermal conductivity. The experimental study, presented in this work, led to the following conclusions:

- This work highlights the interesting heat transfer capabilities of the compounds (paraffin + additive). It is found that carbon fibers, graphite foam and high thermal conductive particles improve the thermal conductivity of paraffin significantly. Therefore, they could be integrated, within solar energy devices, to improve paraffin charging/discharging capabilities;
- According to the phase change evolution, we notice that the paraffin can be used as thermal phase control (visualization of the phase change phenomenon with thermocouples that recreate a thermal cartography);
- The useful heat gained increases by embedding aluminum powder to the paraffin;
- For pure paraffin, liquid-solid profiles, formed through the heating, are almost similar during the charging and discharging process (regardless of the time). However, for the composite, these profiles are similar for the charging process and different for the discharge process;
- Different researchers employed diverse experimental setups, container materials and dissimilar PCMs to investigate the heat transfer enhancement characteristics. Thus, it's necessary to develop a unified international standard to test thermal energy phase change heat storage;
- None of the heat storage products, which are commercially available on the market, have heat transfer enhancement capabilities that would improve performance of low temperature devices. At present, this is mainly an area of interest for academic researchers.

Nomenclature

Q: Useful heat gained [J]
ρ: Density of the storage material [kg/m^3]
C_p : Specific heat over the temperature range of operation [J/(kg K)]
C_{sp} : average specific heat between Ti and Tm (kJ/kg K)
C_{lp} : average specific heat between Tm and Tf (J/kg K)
T_i: initial temperature (°C)
T_m: melting temperature (°C)
T_f : final temperature(°C)
a_m : fraction melted
Δh_m : heat of fusion per unit mass (J/kg)
λ : Thermal conductivity [W/(m K)]
T: Temperature (°C or K)
t : Time (s)
T_{pc} : Phase change temperature
v : Volume (m3)
V: Volume fraction
φ: Volume concentration of the additive
m : Mass (kg)
M : Mass fraction
PCM: Phase change material
HSM: Heat storage medium
TES : Thermal energy storage
SHS: Sensible heat storage
LHS : Latent heat storage
MEG: Matrix of expanded graphite
CENG: Compressed, expanded and natural graphite
SBS: Styrene–butadiene–styrene
LSEE: Laboratory of Solar Energy and Environment

References

1. Lane G.A. Technology. CRC Press, (1986).
2. Antoni G., Marc M., Ingrid M., Ana L.Pablo D., Belén Z., Luisa F. C., *Renewable Sustainable Energy Rev*. 14 (2010) 31–55.
3. Acem Z. thotropes. Ph.D. Thesis, University of Bordeaux, France, (2007).
4. Tamme, R.In DISTOR Dissemination Workshop, Energy Storage for Direct Steam Solar Power Plants, (2007).
5. Nuno V., Joao C.C., Jorge R. F., *Mater. Lett*. 92 (2013) 100–103.
6. Satzger P., Eska B., Ziegler F. Proceedings of Megastock, Sapporo (Japan), (1998).
7. Mehling H., Hiebler S., Ziegler F. Proceedings of the 4th Workshop of IEA ECES IA Annex 10, (1999)
8. Mehling H., Hiebler S., Ziegler F.8th International Conference on Thermal Energy Storage, Stuttgart (Germany), (2000) 375–380.
9. Cabeza L.F., Mehling H., HieblerS., Ziegler F., *Appl. Therm. Eng*. 22 (2002) 1141–1151.
10. Py X., Olives R., Mauran S., *Int. J. Heat Mass Transfer*. 44 (2001) 2727–2737.
11. Fukai J., Kanou M., Kodama Y., Miyatake O., *Energy Convers Manage*. 41 (2000) 1543–1556.
12. Fukai J., Hamada Y., Morozumi Y., Miyatake O., *Int J Heat Mass Transf*. 45 (2002) 4781–4792.
13. Satzger P., EskaB. European patent 914399 B1, (2000).
14. Mehling H. Proceedings of the 6th workshop of IEA ECES IA annex 10, Stockholm, Sweden, (2000).
15. Shalaby S.M., *Renewable and Sustainable Energy Rev*. 33 (2014)110–116.
16. Choi J.C., Kim S.D., *Energy*. 17 (1992) 1153–1164.
17. Horbaniuc B., Dumitrascua G., *Energy Convers. Manage*. 40 (1999) 1765–1774.
18. Velraj R., Seeniraj R.V., Hafner B., Faber C., Swharzer K., *Sol. Energy*. 65 (1999) 171–180.
19. Hamada Y., Ohtsu W., Fukai J., *Sol. Energy*. 75 (2003) 317–328.
20. Sadasuke I., Naokatsu M. Solar Eng, *ASME*, (1991) 223–228.
21. Costa M, Buddhi D., Oliva A., *Energy Convers. Manage*. 39 (3/4) (1998) 319–330.
22. Velraj R., Seeniraj R.V., Hafner B., Faber C., Schwarzer K., *Sol. Energy*. 60 (1997) 281–290.
23. Ismail K.A.R., Alves C.L.F., Modesto M.S., *Appl. Therm. Eng*. 21 (2001) 53–77.
24. Zalba B., Marin J., Cabeza L.F., Mehling H., *Appl. Therm. Eng*. 23 (2003) 251–283.
25. Tayeb A.M., *Energy Convers. Manage*. 37(2) (1996)127–133.
26. Schwarzer K., Hafner B. Proceedings of the 4th workshop of IEA ECES IA annex 10, (1999).
27. Xiao M., Feng B., Gong K., *Sol. Energy Mater. Sol. Cells*, 69 (2001) 293–296.
28. Fukai J., Hamada Y., Morozumi Y., Miyataka O., *Int. J. Heat Mass Transf*. 46 (2003) 4513–4525.
29. Agyenim F., *Renewable Sustainable Energy Rev*. 14 (2010) 615–628.
30. Cassedy E.S. Prospects for Sustainable Energy, Cambridge University Press, (2000).
31. Sharma A., *Renewable Sustainable Energy Rev*. 13 (2009) 318–345.
32. Eman-Bellah S., *Sol. Energy*. 81(2007) 839-845.

(2016) ; http://www.jmaterenvironsci.com/