

An Overview of Phase Change Materials and their Implication on Power Demand

Daniel. R. Rousse, Nizar Ben Salah, and Stéphane Lassue

Abstract—Latent heat storage systems involving phase change materials (PCMs) are becoming more and more attractive for space heating and cooling in buildings, solar applications, off-peak energy storage, and heat exchanger improvements. This paper presents an introduction to previous works on thermal energy storage with respect to these applications. It focuses mostly on applications involving a reduction of electric power consumption. It is therefore more likely to be appreciated by those who would like an introduction to the topic rather than pinpoint information on novel aspect of the subject.

Index Terms— Thermal energy storage, Phase change materials, Latent heat, Power system economics, Power demand.

I. INTRODUCTION

The ever increasing level of greenhouse gas emissions combined with the overall climbing in fuel prices (although fluctuations occur) are the main reasons behind efforts devoted to improve the use of various sources of energy. Economists, scientists, and engineers throughout the world are in search of: 1) strategies to reduce the demand; 2) methods to ensure the security of the supplies; 3) technologies to increase the energy efficiency of power systems; and 4) new and renewable sources of energy to replace the limited and harmful fossil fuels.

One of the options to improve energy efficiency is to develop energy storage devices and systems in order to reduce the mismatch between supply and demand. Such devices and systems also improve the performance and reliability of their traditional counterparts and thus play a preponderant role in conserving the energy. The different forms of energy that can be stored are mechanical, electrical, and thermal. Here, mechanical (gravitational, compressed air, flywheels) and electrical (batteries) storages are not considered while thermal energy storage is mostly discussed in the context of latent heat (sensible heat storage is introduced to compare the theoretical performances of latent heat storage systems while thermochemical heat is not considered).

This paper will first provide a short overview of sensible

heat storage materials and a synthesis of the desired characteristics of phase change materials. Moreover, it suggests a classification of such materials. Then, it overviews the storage systems that could lead the power demand reduction.

For the interested reader, excellent global reviews that pertain to phase change materials and their various applications were proposed by Farid et al. [1], Verma et al. [2] Zhang et al. [3], Regin et al. [4], Tyagi and Buddhi [5], Mondal [6], and Sethi and Sharma [7]. In 2009, Sharma et al. [8] proposed an updated review that should be consulted after the above-mentioned global ones.

II. SENSIBLE HEAT STORAGE MATERIALS

In sensible heat storage systems, the thermal energy is stored by raising the temperature of a solid or liquid used as an accumulator to be charged or discharged according to the optimization of the energy demand/availability and energy cost. Such systems are based on the ability of a material to store energy without phase change (their heat capacity) which in turn depends upon their specific heat (the amount of energy stored by unit mass per degree). Another parameter of interest is the density of the materials as the volume of the systems may be an issue (physical, technical, economical). A third parameter of interest is the stability of the material. Fourth is the change in temperature that has to be adjusted to the process, and finally, their relative abundance at low cost.

Table I shows a list of selected solid and liquid materials used for sensible heat storage (adapted from [8]).

TABLE I
SELECTED SOLID AND LIQUID MATERIALS FOR SENSIBLE HEAT STORAGE

Medium	Temp Range [K]	Density [kg/m ³]	Specific Heat [kJ/kg K]
Water	280-370	1000	4190
Rock (avg)	280-300	2500	880
Brick (avg)	290-310	1600	840
Concrete (avg)	280-300	2100	880
Sand (dry, avg)	280-300	1550	800
Soil (dry, avg)	280-300	2040	1840
Caloria HT43	285-533	867	2200
Engine oil	Up to 430	888	1880
Ethanol	Up to 350	790	2400
Proponal	Up to 390	800	2500
Other organic liquids (avg)	Up to 420	800	2300

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Water immediately appears as the most suitable material for it is inexpensive, abundant, and allowing the storage of 4 190 000 J per liter for an increase of temperature of just 1 °C. However, its maximum operating temperature at atmospheric pressure is limited to 100 °C. Rock, sand, and soil are interesting energy reservoirs mostly in the context of geexchange applications. In this context, a fluid is used to carry the energy to/from the storage to the application and the thermal diffusivity, and hence thermal conductivity, becomes an issue.

However, in many applications, the temperature range over which transfer should occur or the average operating temperature of the system, and/or the amount of space available to install the system may find the above listed materials unsuitable for storage applications.

In these cases, latent heat storage materials could be considered as an alternative to their standard sensible counterparts.

III. LATENT HEAT STORAGE MATERIALS

Latent heat storage is based on the absorption/desorption of energy when a storage material undergoes a phase change from solid to liquid, liquid to gas, or vice versa. Latent heat storage is particularly attractive since it provides a high-energy storage density and has the capacity to store energy at a constant temperature – or over a limited range of temperature variation – which is the temperature that corresponds to the phase transition temperature of the material. For instance, it takes 80 times as much energy to melt a given mass of water (ice) than to raise the same amount of water by 1°C.

Table II provides a typical comparison of different thermal storage materials.

TABLE II
COMPARISON BETWEEN COMMON HEAT STORAGE MATERIALS [2]

Property	Rock bed	Water	Organic PCM	Inorganic PCM
Density [kg/m ³]	2240	1000	800	1600
Specific Heat [kJ/kg K]	1,0	4,2	2,0	2,0
Latent heat [kJ/kg]	-	-	190	230
Latent heat [kJ/m ³]	-	-	152	368
Relative storage mass*	15	4	1,25	1,0
Relative storage volume*	11	6	2,5	1,0

*with respect to inorganic PCMs.

Latent heat storage materials also called phase change materials (PCMs) should involve the following desirable thermophysical, kinetics, and chemical properties [1], [3], and [9]:

- Appropriate phase change temperature
- High latent heat of fusion
- High thermal conductivity
- Low viscosity of the fluid phase
- Favorable phase equilibrium
- High density
- Low thermal expansion
- Low vapor pressure (to reduce containment problem)
- Ideally no supercooling

- High crystallization rate
- Long-term stability
- Compatibility with container materials
- No toxicity
- No fire hazard

The rationale behind this list is abundantly justified in the above-mentioned references and is not discussed herein. However, when it comes to applications, the most important characteristics pertain to the economics of each project. Hence, the material should be available in abundant quantity and cheap to buy, transport, install, and, eventually to maintain or replace. The overall cost effectiveness is always the preponderant parameter in any project.

IV. CLASSIFICATION OF LATENT HEAT STORAGE MATERIALS

Comprehensive lists of most possible materials that may be used for latent heat storage are available in papers by Abhat [9], Lorch et al. [10], Lane et al. [11], and Humpries and Griggs [12]. To summarize these papers, PCMs can be categorized into two main families: organic and inorganic materials.

A. Organic PCMs

Organic PCMs are further described as paraffins and non paraffins. The main interest with organic materials is that they involve long term cyclic chemical and thermal stability without phase segregation and consequent degradation of the performance of the system into which they are embedded. Their self nucleation also means they crystallize with little or even no supercooling. Finally, they are non corrosive which is an important feature as listed previously.

Subgroups of organic materials include paraffin and non-paraffin organics. Paraffin consists of a mixture of *n*-alkanes CH₃-(CH₂)-CH₃ into which the crystallization of the (CH₂)-chain is responsible for a large amount of energy absorption. The latent heat of fusion of paraffin vary from nearly 170 kJ/kg to 270 kJ/kg between 5°C to 80°C which makes them suitable for building and solar applications.

Non-paraffin organic materials are the most common of the PCMs and they involved varying properties. Buddhi and Swaney [13] have conducted an extensive survey of esters, fatty-acids, alcohols and glycols suitable for energy storage. These materials generally have a high heat of fusion but low thermal conductivity, inflammability, toxicity, and instability at high temperatures. Although fatty acids are somewhat better than other non paraffin organics, they are even more expensive than paraffins [9].

B. Inorganic PCMs

Inorganic compounds include salts hydrate, salts, metals, and alloys. The first were investigated because of their low cost which is determinant in most projects. Moreover, inorganic PCMs permit high density storage because they have high volumetric latent heat storage capacity and their conductivity may be twice as high as that of organic materials.

The authors [14] used salt hydrates but experienced

supercooling, phase segregation, and a lack of thermal stability. Moreover, it is reported that some are corrosive. Supercooling and phase segregation could be prevented [15] in some cases but then the economics may suffer.

Metallic PCMs are low melting point metals such as Galium and metal eutectics. These have not yet been investigated thoroughly because of their weight. However, when volume is a major issue, they could be considered as they have high latent heat of fusion and very high conductivities compared to other PCMs.

C. Eutectic PCMs

An eutectic is a minimum-melting composition of two or more components, each of which melts and freezes congruently forming a mixture of the component crystals during solidification [16]. A large number of eutectics of

inorganic and organic compounds have been reported [17]-[18]. Eutectics are generally better than straight inorganic PCMs with respect to segregation [9].

D. Choice of an appropriate PCM

There is no simple answer to this question. Cost, space, weight, and the design of the system all play a major role when it comes to select the appropriate material. In general a system analysis is required to determine which material will be used according to the specific application.

This allows dividing PCMs research into two main categories: material oriented research and system oriented research. Fig.1 schematically proposes a synthesis of the different stages involved in the development of a latent heat storage system.

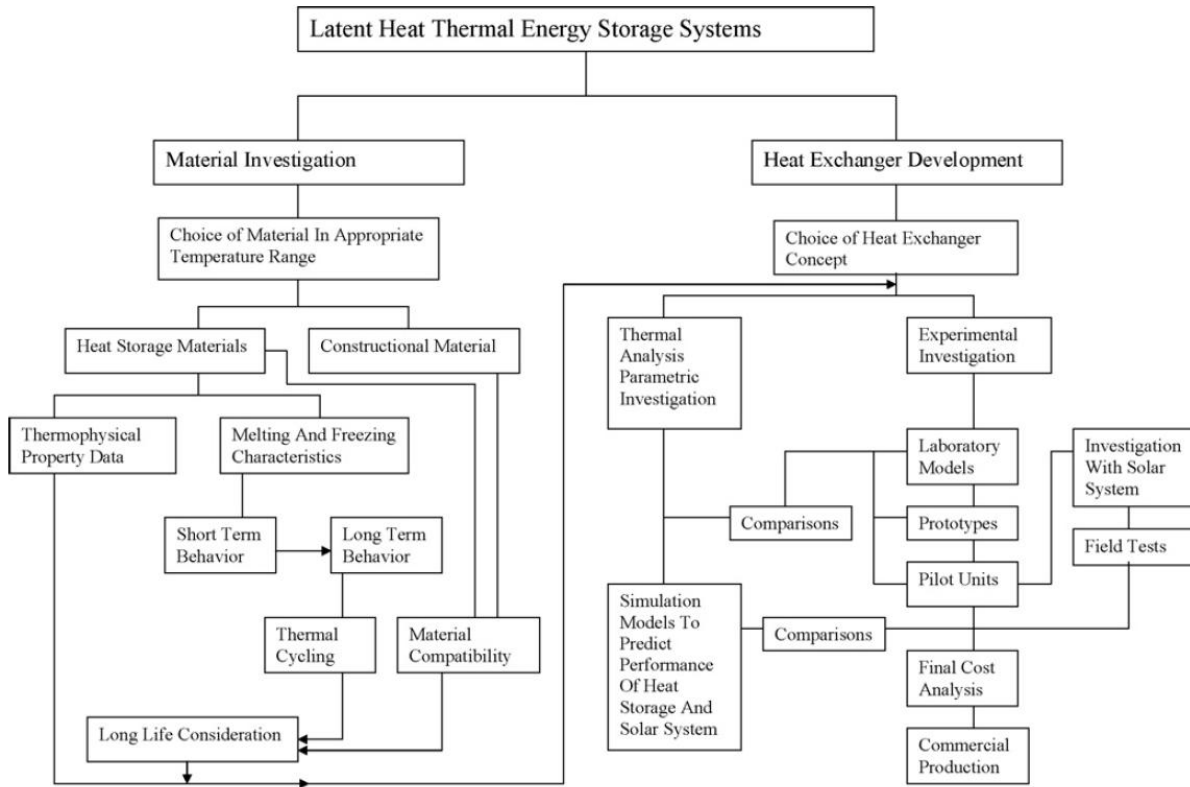


Fig. 1. Flow chart summarizing the different stages involved in the development of a latent heat storage system: Left – Material oriented research; Right – System oriented research [9].

V. THERMAL LATENT HEAT STORAGE SYSTEMS

In this section, applications that may have a significant impact on power demand are overviewed. Other applications exist but are not covered here. The first four subsections present applications to reduce the power demand in buildings.

A. Passive solar collecting walls

A Trombe – named after Michel Trombe – wall consists of a thick masonry wall covered with a single or double layer of glass or plastic glazing mounted about 10 cm in front of the wall surface which is oriented to face the south side of a

building. Basically, when the room temperature inside becomes lower than that of the wall, it begins to redistribute its heat into the building thus reducing the heat demand.

The heat loss to the inside is generally controlled by an insulating curtain. On the other hand, an idea for performance improvement is to have shutters installed on the south-facing wall which will be opened during the day and closed during the night to minimize heat losses to the environment when there is no solar gain.

Because of their greater potential for heat storage, PCMs are preferred over sensible heat storage. For instance, Bourdeau [19] noticed the a 8,1 cm wall using calcium chloride hexahydrate was better than a 40-cm thick masonry

wall. Others found similar results with different materials during the 80's and 90's but the PCM trombe wall is still awaiting a successful commercial implementation.

Asan and Sancaktar [20] investigated the effects of a common wall's thermophysical properties on "time lag" ϕ and "decrement factor" f . Their schematic representation is presented in Fig. 2 for sensible heat storage and Fig.3 for latent heat storage.

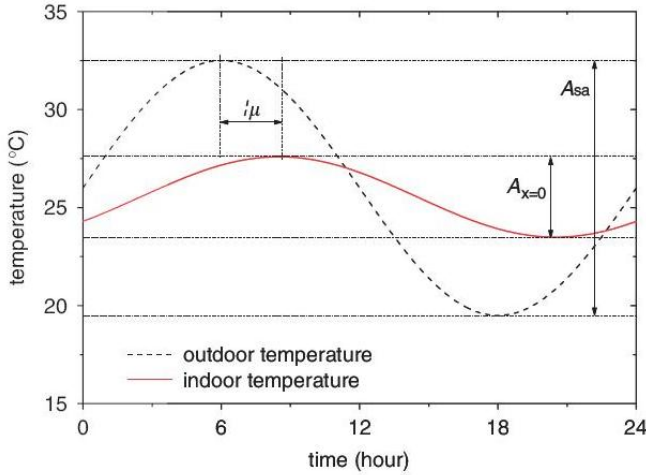


Fig. 2. The schematic representation of the time lag ϕ and decrement factor f ($f = A_{x=0}/A_{sa}$) [20].

ϕ and f describe the change of wavelength and amplitude for heat waves propagating from outside to the inner surface of the wall. The combined effects of heat capacity and thermal conductivity on ϕ and f were calculated for several building materials. The authors showed that with constant properties, the change of the inner surface temperature follows the outdoor temperature while for PCMs the inner wall temperature varies non-linearly.

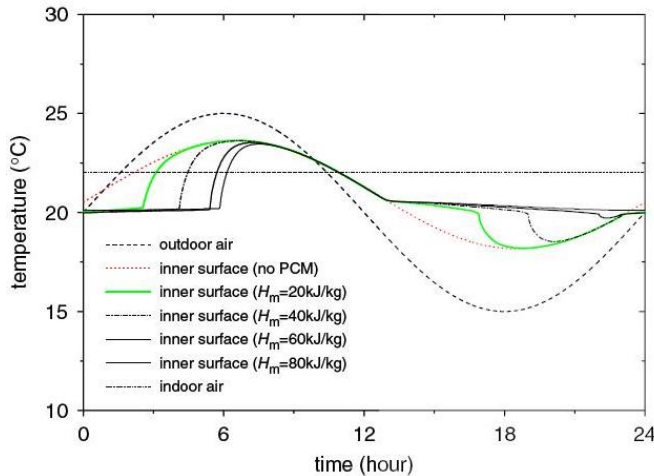


Fig. 3. Temperature of PCM wall's inner surface with variable outdoor temperature, $20^{\circ}\text{C} \leq T_o \leq 25^{\circ}\text{C}$, fixed indoor air temperature, $T_i = 20^{\circ}\text{C}$, $T_m = 20^{\circ}\text{C}$, and different heat of fusion [20].

These results indicate that PCMs shift the maximum temperature on the inner surface in time event for materials with relatively low heat of fusion. An average PCMs with $H_m \approx 200$ kJ/kg would event prevent the inner wall temperature

to reach the indoor air temperature.

B. Indoor walls

The wallboards are suitable for PCM encapsulation. For instance, paraffin wax, fatty acids, or liquid butyl stearate impregnated walls can be built by immersion. One of the interests is the shifting of heating and cooling loads to off-peak times of electric utility, the other is to reduce peak power demand and down size the cooling and heating systems. Although much work has been done on impregnation techniques, analytical studies, and optimal melting temperatures, much has to be done to include such advanced wallboards in actual buildings.

Although gypsum wallboards are naturally considered as they are cheap and widely used, building blocks and other building materials impregnated with PCM can be used in constructing a building. This could result in a structure with large thermal inertia without the usual large masses associated with it.

C. Floors and ceilings

Farid and Kong [21] constructed slabs containing encapsulated PCMs in spherical nodules. The plastic spheres contained about 10% empty space to accommodate volume expansion. Athienithis and Chen [22] investigated the transient heat transfer in floor heating systems. Savings up to 30% were reported. Space heating systems that incorporate PCMs located in the ceilings were also developed.

D. Off-peak storage

Latent heat storage systems were proposed to utilize off-peak electricity. Using this electricity, PCMs are either melted or frizzed to store it in the form of latent heat thermal energy and the heat/coolness is then available when needed. These systems are generally embedded with active systems to reduce the peak load and thus eventually reducing the electricity generation costs by keeping the demand nearly uniform.

E. Solar water heating

Solar water heater is getting popularity with increasing costs of energy since they are relatively inexpensive, simple to fabricate and install, and easy to maintain. To increase the capacity of systems without ultimately requiring huge volumes or high temperatures, these systems were designed with PCMs either located on the bottom, top, or vertical walls. The PCMs were especially interesting when it came to deliver hot water the morning after solar collection [23]. In this study [23], the author used 17,5kg of paraffin wax (m.p. 54°C) in one heat exchanger and water in the other to enable the comparison.

F. Solar air heating

The problem of solar air heating with systems involving PCMs has been studied for more than 30 years as evidenced by the pioneering work of Morrison, Abdel Khalick, and Jurinak [24]-[25]. The main conclusion of their studies was that the PCM should be selected on the basis of the melting point rather than its latent heat and also that systems based on sodium sulfate decahydrate as storage medium needs about one fourth the storage volume of a pebble bed and one half

that of a water tank. Recent research involving hybrid systems and shape-stabilized phase-change material was found to yield improved thermal comfort in the winter. Zhou et al. [26] indicate that 47% normal-and-peak-hour energy savings, and 12% overall energy consumption reduction were observed.

G. Green houses

Another application that has a major impact on power demand is the use of PCMs in green houses for storing the solar energy for curing and drying process and plant production. The format of the conference papers cannot allow a survey of the key references on this subject. These will be discussed at the conference.

VI. RECENT CONTRIBUTIONS

This section presents some of the recent publications on the subject. An interesting review that pertains to the application of PCM to solar water heaters was proposed by Skula et al. [27]. El Qarnia [28] and Ait Adine and El Qarnia [29] proposed studies that concern solar collectors, heat exchangers, and PCMs in the context of water heating applications and this has a direct impact on electric power consumption. Microencapsulated PCMs used in slurry applications were studied by Zeng et al. [30] and Diaconu [31], [32]. More generally, microencapsulation was investigated in the context of a polyurea system by Liang et al. [33] and in building applications into which electrically heated floors act as thermal storage units by Li et al. [34], [35]. Fang et al. [36] investigated nano-encapsulated n-tetradecane while Zhang and Wang [37] studied micro-encapsulated materials based on an n-octadecane core and resorcinol-modified melamine-formaldehyde shell and Wang et al. [38] described the permeation kinetics of the walls of macro encapsulated PCMs. Applications of PCMs in thermal management of electronic equipment have been studied by Alrashdan et al. [39], Fok et al. [40] et Raoux et al. [41]. PCMs have been mixed, respectively, with graphite, epoxy, and several porous materials by Kim and Drzal [42], Luyt and Krupa [43], and Nomura et al. [44].

VII. CONCLUSION

In this paper, the objectives of the authors were: (1) to provide an overview of phase change materials use in the context of power demand reduction, (2) to open new possibilities for eventual collaboration with the IEEE members; and (3) to be able to promote synergetic solutions and processes in the domain of energy management.

The paper also provides a “tour d’horizon (lookout)” of selected particularly recent references that pertain to the use of phase change materials in building and process applications.

In a near future, PCMs will be more and more incorporated in global energy management solutions as the stress for innovative low environmental-impact technologies, the overall negative effect of energy consumption on the environment, and the cost of energy will all necessarily increase.

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