An Assessment of Utilizing Phase Change Materials (PCM) Towards Energy Performance in Building Enclosures

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ABSTRACT

This paper assesses the opportunities of utilizing Phase Change Materials (PCMs) in building enclosure systems to improve energy performance and thermal comfort in buildings. The building sector continues to grow along with population growth, which will further increase energy consumption that is needed for space heating and cooling to provide thermal comfort for occupants. With many practical applications, PCMs are capable of storing and releasing significant amounts of energy by melting and solidifying at a given temperature and can play an important role as a thermal energy storage device by utilizing its high storage density and latent heat capacity. PCMs not only have the potential to reduce air conditioning energy consumption in residential and commercial buildings, but also have the potential to improve occupancy comfort by better maintaining desired surface temperatures. PCMs can be utilized to decrease the overall required energy of buildings by shifting part of the heating and cooling loads to off-peak hours when there is less energy demand within our utility grids. One of the potential applications for PCMs in buildings is to incorporate them within the building enclosure for energy storage. Our research investigates PCMs in an experimental study, from which we will extrapolate results to apply for residential application in different U.S. climate zones. The research extrapolation will be supported by simulation tools, which are capable of simulating PCMs in the building context. The study will also explore different factors contributing to other thermal performance criteria, such as the thermal conductivity and applicable temperature ranges of different PCMs. The results will be presented for better understanding of PCMs' thermal behavior as well as demonstrating the applicability of using PCMs towards improving building performance and overall energy consumption in different climate contexts.

INTRODUCTION AND BACKGROUND

Buildings are designed to create an isolated space from the surrounding environment and provide desired interior environmental conditions for occupants. The essential role of any building is to provide users' needs and to protect humankind from climatic extremities. Individual needs vary from person to person and from area to area. This means the requirements in building components in one geographic area do not have to be the same as in another area. Therefore, the properties of buildings are different based on location, and they are designed with considerations for climatic conditions that keep the inside spaces cool in summer and warm in winter.

Construction practices continue to change as new equipment is developed, new materials are innovated, and housing requirements are changed. The difference between interior and exterior temperatures in summer and winter require high-energy consumption. In 2009, the United States Department of Energy (DOE) performed an energy consumption survey on residential buildings and found that residential heating and air-conditioning consumes 49% of all residential energy usage in the United States (US Department of Energy 2009). Proper building materials, such as high performing insulation, are considered essential for most building construction in order to provide thermal comfort inside buildings (Arafah et al. 1995).

At the same time, Phase Change Materials (PCMs) play a major role as Thermal Energy Storage (TES) in different successful applications such as transport and storage containers, clothes for human body, packaging for medical and food supplies, and electronic equipment. TES allows heat and cold to be stored and used later. It can be stored under two methods: physical methods and chemical methods. PCMs have the ability to absorb thermal energy, which means removing or reducing the need for heating and cooling by using sensible and latent heat storage as shown in Figure (1) (Building for Change 2010).

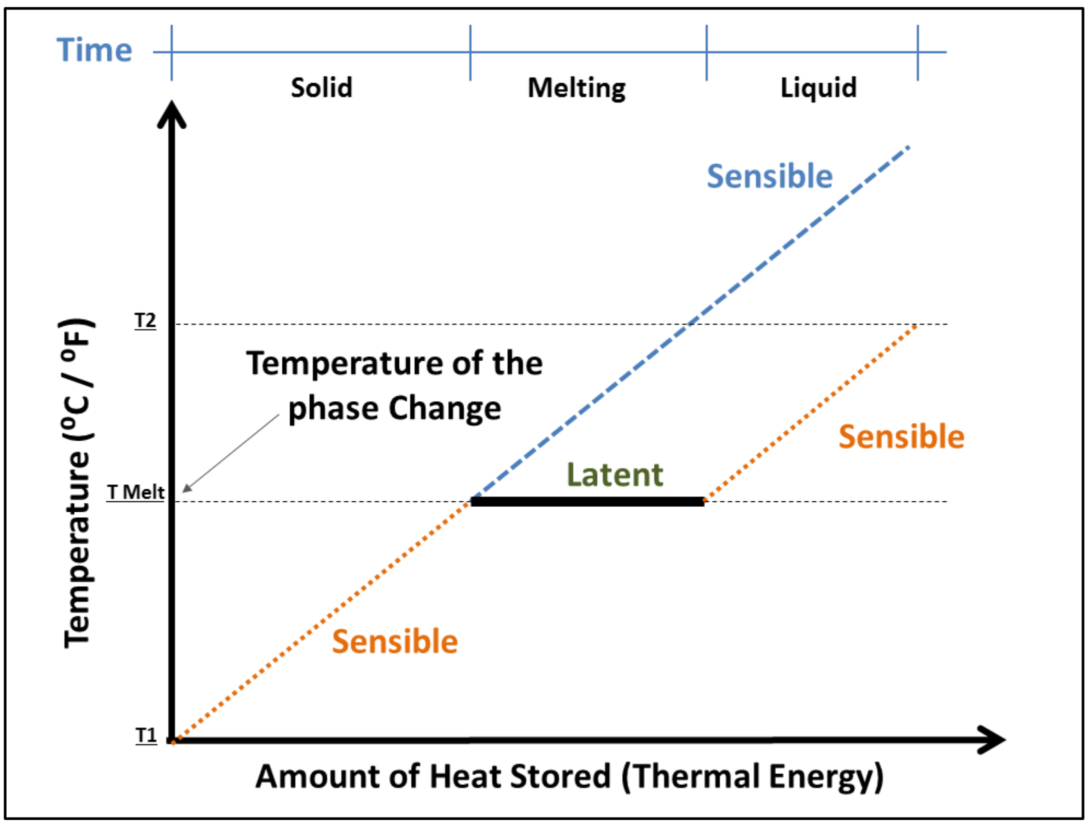

Figure (1):Temperature profile for changing phases by sensible and latent heat (Bayern 2015).

PROBLEM STATEMENT AND RESEARCH GOALS

Air conditioning energy consumption in different seasons represents a challenge in many areas with hot or cold climates. Providing thermal comfort for building occupants is a very important task for architects, engineers, and contractors. PCMs work efficiently in many fields as a temperature controller, but their application in building construction is very rare. PCMs are ideal products for thermal management solutions. This is because they store and release thermal energy during the process of melting and freezing—which refers to the change from one phase to another. Yet, high performance PCMs are still not used frequently as thermal storage in building construction, and some challenges exist regarding applying PCMs as building materials to be used in the building enclosure. For example, the affordability of organic PCMs, the availability of inorganic PCMs with high enough thermal resistance values, or the role of some architects and their knowledge in regard to selecting PCMs in building construction remain challenges that currently limit the use of PCMs in construction practice.

There are several significant potential applications of integrating PCMs in buildings that allow for reducing energy demand, but further investigations are needed to assess their actual utilization and benefits. This paper focuses on an assessment of utilization options of PCMs towards energy performance in building enclosures.

PROJECT GOAL, OBJECTIVES, AND SCOPE

The overall goal of our research direction is to bridge the gap between known and functional applications of PCMs in various fields outside of construction and their potential utilization specific for building enclosure systems of residential buildings.

To achieve this goal we define the following three core objectives in this research path. First, we need to study existing PCMs that have the potential to be used in construction practice. Second, we will have to define and conduct field experiments to assess the practical utilization of PCMs in building enclosure systems, mostly from a thermal performance perspective. Third, we will have to identify and measure the respective thermal performance values of the most common types of PCMs that can be used in buildings and compare them with relevant insulation building materials to clarify and justify any possibility of using PCMs in building construction practice.

The scope of this study will be limited to an assessment of the most popular PCMs that have the potential to be used in building construction in order to utilize them as thermal control materials in residential construction. This study will focus on the applicability of using PCMs as insulation materials in the building envelope for residential construction.

ASSESSMENT OF PCM APPLICATIONS

PCM Definition

Phase change materials (PCMs) as defined by Tyagi and Buddhi (2007) are latent heat storage materials, which can be used as a temperature controller. PCMs are a substance with a high heat of fusion that are able to store and release a large amount of energy when they melt or solidify while more or less staying at this certain temperature until the phase has completely changed (Haghighat 2013) and (Sharma et al. 2009). As they store and release heat by using chemical bonds and thermal energy transfers occur when the material changes from solid to liquid or vice versa, these processes are called a change in state or phase (Vuceljic 2009) and (Tyagi and Buddhi 2007). PCMs can be viewed as a thin layered version of larger mass walls that can be used to create the thermal comfort in the interior environment of buildings, and they are able to cycle continuously through changes of state without losing their attributes and preventing loss in mass through evaporation (Rohles 2007). Figure (2) demonstrates the concept of PCMs capability of absorbing and releasing heat with repeated melting and freezing cycles (Pazrev 2015).

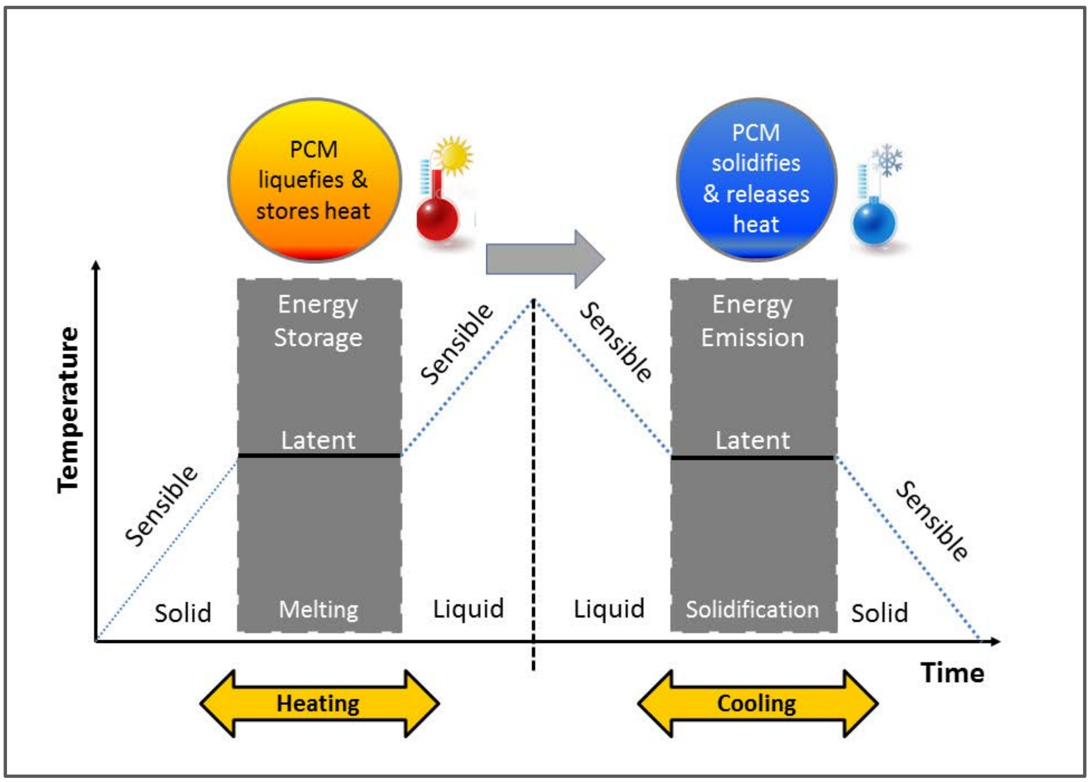

Figure (2) The concept of PCMs capability of absorbing and releasing heat with repeated melting and freezing cycles (Pazrev 2015)

Cooling and heating have their effects on PCMs. They change the state of the materials from solid to liquid or liquid to solid, and during this process the heat is absorbed or released. Figure (3) shows the cooling and heating effects on PCMs (Shim et al. 2001).

PCM Properties

Sharma et al. (2009) mention that PCMs have different thermo-physical properties, chemical properties, and kinetic properties. High thermal conductivity, solid and liquid phases and acceleration time of charging and discharging of energy, are examples of PCMs' thermo-physical properties. They also list some examples of chemical properties, such as chemical stability and absence of degradation after a large number of freezing and melting cycles. Nucleation rate, which is beneficial for avoiding super cooling of the liquid phase, is an example of kinetic properties (ibid).

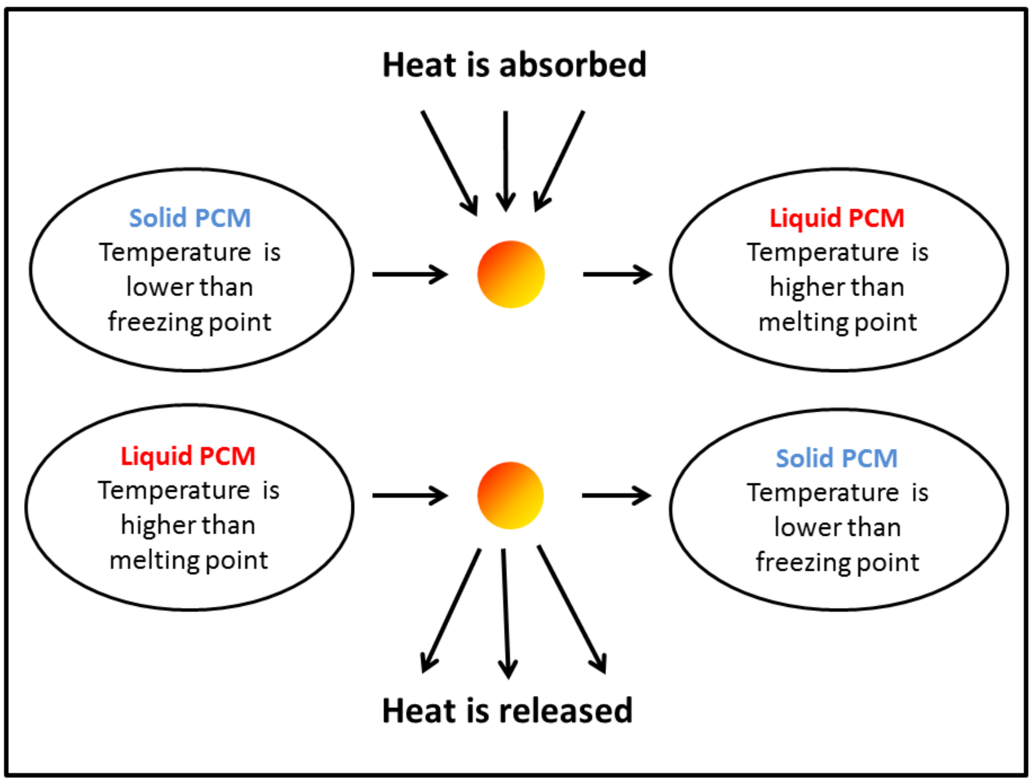

Figure (3) Cooling and heating effects on PCMs (Shim et al. 2001)

The core property of PCMs is based on their latent heat storage capability around their melting points, because large amounts of energy can be stored in a comparatively small volume of PCMs (Madhumathi and Sundarraja 2012).

PCM Types

There is a large number of PCMs , which can be classified based on different criteria, such as their melting temperature and latent heat of fusion, the changing of phases, or their source material (Haghighat 2013). Khudhair and Farid (2004) and Vuceljic (2009) clarify the types of PCMs based on their most common criteria—which is their sources and components. The main sources can be classified into organic compounds, inorganic compounds, and the mixture of two or more components, creating a kind of hybrid type, called eutectic, as shown in Figure (4).

Advantages and Disadvantages of PCM types

Although organic and inorganic compounds both have high latent heat, which is the most significant feature of PCMs, each type also presents distinct advantages and disadvantages. On the one hand, organic compounds have some advantages such as a low volume change at phase change as well as chemical and thermal stability. On the other hand, organic compounds have some disadvantages such as their rarity, a rather low thermal conductivity, and greater cost in comparison with inorganic PCMs' compounds (Harland et al. 2010). Moreover, organic PCMs are typically highly flammable, though this can be alleviated in some applications by a proper container (Dubey and Mishra 2014).

Conversely, inorganic compounds have a lower performance of thermal insulation than organic compounds, and have rather high thermal conductivity, while at the same time being more affordable (Harland et al. 2010). Some of their main disadvantages are a lack of thermal stability and change of volume after repeated melting and freezing cycles (Mondal 2008).

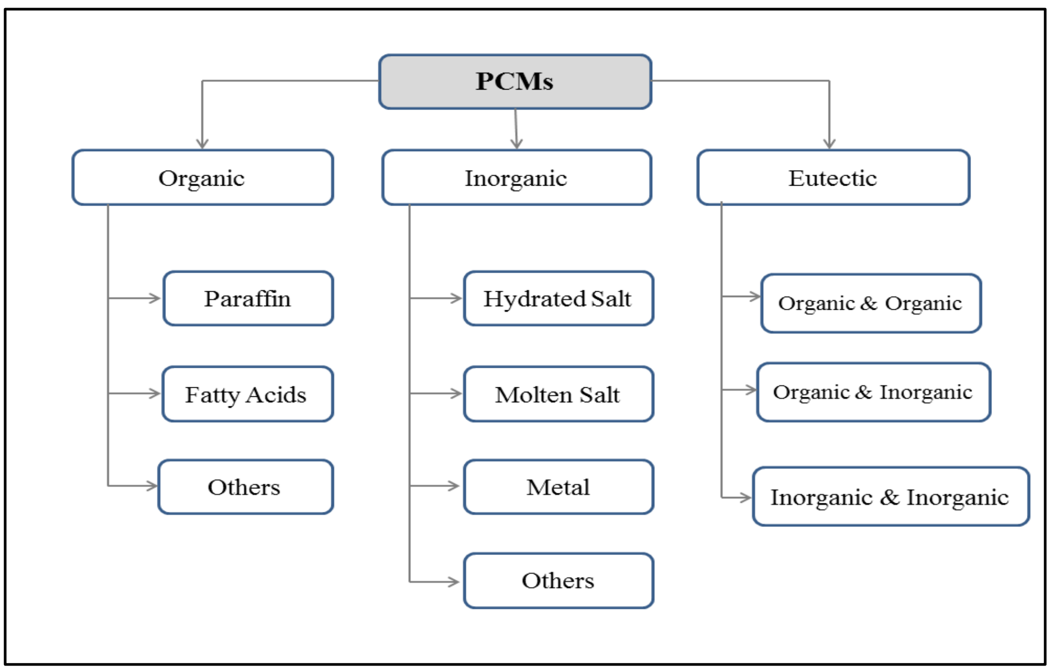

Figure (4): Types of PCMs according to their sources (Khudhair & Farid 2004 and Vuceljic 2009)

Eutectic compounds, the third type of PCMs, are a combination of the inorganic and organic types try to bridge advantages from different base materials. The development of less expensive but highly capable PCMs at a desired temperature, such as fatty acids, is currently being explored (Harland et al. 2010). Also, the authors examined some eutectic products that express the beneficial functions of PCMs specifically to create thermal comfort and reduce the energy consumption for cooling or heating (ibid).

In summary, organic, inorganic, and eutectic PCMs each have their own advantages and disadvantages. Table (1) shows a brief overview of the advantages and disadvantages of PCMs according to their classification.

Table (1): Advantages and disadvantages of PCMs (Mondal 2008), (Sharma et al. 2009), and (Nath 2012).

	Organic	Inorganic	Eutectic
Advantages	• High latent heat • Non-corrosive • Chemically & thermally stable • Little sub-cooling • Durable and recyclable • Efficient for thermal comfort • High heat of fusion • Low vapor pressure	• High latent heat • High melting enthalpy • High density and latency • High thermal conductivity • High heat of fusion • Sensible heat storage • Non-flammable • Low volume change • Affordable	• Sharp melting Temperature • High volumetric thermal storage density
Disadvantages	• Not affordable • Low melting enthalpy • Low density • Low thermal conductivity • Rare availability • Flammability (depending on containment) • Volume change	• Sub-cooling • Corrosive of container materials • Phase separation • Phase segregation • Lack of thermal stability • Instability of volume after repeated change cycles	• Lack of test and limited data of thermo-physical properties

Broader Application of PCMs

Depending on their positioning PCMs have the properties for both, to harvest energy from solar gains where desired, or to protect against solar gains, due to their high thermal storage characteristics. Typically this protection is used during transportation or storage of goods to provide thermal comfort against heat and cold (Prim 2013). Therefore, PCMs have different applications that are currently used to reduce or avoid heat exchange between different temperatures in areas/spaces that need to maintain these properties for different purposes.

There are many applications that benefit from PCMs' useful ability to stabilize temperatures—such as protection of solid food, cooked food, beverages, pharmaceutical products, blood derivatives, hot and cold medical therapy, electronic circuits, clothing, and many other applications yet to be discovered (Prim 2013). More importantly, possible PCM applications include the utilization in refrigerators and freezers that can use less energy, high-performance textiles that provide relief from hot and cold climate conditions, and shipping containers that maintain goods at the desired temperature for longer periods.

Currently, the global PCM market is experiencing high growth due to an increasing demand for eco-friendly and energy-saving materials in industries such as thermal energy storage, refrigeration, textiles, and electronics. Table (2) shows an overview of some examples of existing applications of PCMs in different fields (Mantz 2014) .

Table (2): Examples of PCMs' applications (Mantz 2014)

Field	Examples of Applications
Consumer Products	**1)** Textile **2)** Apparel & Shoes **3)** Furniture **4)** Car Seats **5)** NASA Dive Suit **6)** Lunch & Beverage Containers **7)** Outdoor Gear (sleeping bags, etc.)
Packaging	**1)** Medical **2)** Pharmaceutical **3)** Chilled Food **4)** Vaccines **5)** Drug & Laboratory Testing **6)** Chemicals & Biological samples
Bedding	**1)** Mattresses **2)** Mattress toppers **3)** Protectors **4)** Pillows **5)** Linens **6)** Quilting **7)** Ticking
Electronics	**1)** Computer parts **2)** Outdoor electronics **3)** Laboratory equipment **4)** Handheld devices & phones **5)** Remote telecom stations

PCM Applications in Building Construction

PCMs as latent heat storage materials can be an efficient way of storing thermal energy, and they are applicable to materials and products that can be used as temperature-controllers in construction and architecture (Vuceljic 2009).

The concept of storing heat within a building's walls has been around since 1881 (Pacson 2011). The first documented use of a house using a PCM for passive solar heating was done by Dr. Maria Telkes in 1948 (Harland et al. 2010). Tyagi and Buddhi (2007) mention several forms of bulk encapsulated PCMs that can be used in building construction in their research. These materials provided for active and passive solar applications during the 1980s (ibid). In addition, they found that most encapsulated commercial PCM products at that time were inadequate for delivering heat to the building passively after the PCM was melted by direct solar radiation. This can clearly be seen in the buildings' envelopes, which offer large areas for passive heat transfer. The need for proper building materials with high performance insulation is considered one of the most important building construction applications to create thermal comfort in buildings (Arafah et al. 1995).

- **Current Applications of PCMs in Buildings**

The uses of PCMs in buildings as thermal storage systems has been of great importance since the second half of the twentieth century (Kośny 2015). Most frequently, latent heat storage materials are used to stabilize interior building temperatures. The application of PCMs in air conditioning systems reduced room temperature fluctuation by lowering the high temperatures from the external daily temperature and reducing home heating and cooling loads by reducing the electrical power consumption (Zalba et al. 2004). Also, the use of PCMs to store coolness has been developed for air conditioning applications and reduced the energy consumption, where cold temperature is collected and stored from ambient air during the night, and is released indoors during the hottest hours of the day (Zalba et al. 2004).

The main applications of PCMs in buildings are when spaces are directed to the sun and require larger thermal storage units to be used as an insulation layer within building envelop components. PCMs were traditionally used to provide a comfortable interior building temperature (Vuceljic 2009). PCMs are currently utilized by using a packaging method in micro- or macro-encapsulated cells for some applications such as interior wall construction that are adjacent to insulation and wallboard, between attic joists, above ceiling panels in a drop ceiling, and floor tiles (James and Delaney 2012). Jaworski and Abeid (2011) reference three existing ways of incorporating PCMs in building structures:

1. Blending PCMs with building materials during the manufacturing process of construction elements such as bricks or plasterboards in wall components.
2. Incorporation of macro-capsules with PCMs in free spaces inside the building such as placing PCMs above suspended ceilings or under floors.
3. Incorporation of PCM in parts of furniture or window blinds.

Tyagi and Buddhi (2007) list a number of major applications of PCMs in buildings, which they classified into two different methods for temperature control. The first application deals with passive storage systems, such as PCM trombe walls, PCM wallboards, paints, PCM shutters, PCM building blocks, and air-based heating systems. The second application relates to active storage systems, such as floor heating and ceiling boards. PCMs are used to enhance building performance in many building elements. The following are some examples of current applications:

1. PCM enhanced solar thermal storage walls
2. Impregnated concrete blocks and ceramic masonry
3. PCMs enhanced gypsum board and interior plaster products
4. Use of PCMs to enhance wall cavity insulation
5. PCMs to enhance thermal performance of floor and ceiling systems
6. PCMs utilized in roofs and attics to enhance insulation
7. PCM enhanced windows and window attachment products
8. Use of PCMs for pipe insulation and HVAC systems
9. Implementing PCMs for fireplace protection
10. PCMs to enhance wallboards and insulation foams

As expected, each of these PCM types has different applications in building construction. Table (3) shows some example of existing PCM products that are currently used, and list their location of implementation.

Several studies analyze PCMs as energy saving materials due to their flexibility and applicability. PCMs are gaining popularity due to their properties of reduced heat transfer in lightweight materials. The search for capable, efficient, economical, and achievable sources of energy is a continuous attempt carried out by researchers, practitioners, and scientists.

Table (3): Examples of PCMs' applications in Building Construction (Jaworski and Abeid 2011)

PCM Product	Application
Micro-encapsulated Paraffin Wax	Wallboard
	Ceiling Tiles
	Floor Panel
	Interior Wall Construction
Bio – Based (organic) Materials	Interior Wall Construction
	Attics / Drop Ceiling Plenum Floor
Eutectic Salt Mixtures	Interior Wall Construction
	Attics / Drop Ceiling Plenum Floor

- **Motivation for utilizing PCMs in building construction**

In the last decade, the demand for air conditioning has increased greatly and large demands for electric power have led to an increase in efficient energy applications (Vuceljic 2009). In building construction, there is a lot of energy saving potential and possible ways for improvement. Vuceljic (2009) found that electrical energy consumption varies significantly between day and night, and how PCMs can be helpful in building materials because of their high storage density and small temperature swings. The author supposes that encapsulating or embedding suitable PCMs within envelope surfaces will enhance thermal energy storage in the building enclosure. The author further states that PCMs can either capture solar energy directly or capture thermal energy through natural convection. The thermal storage capacity of PCMs can provide a valuable solution for the supply and demand of electrical energy, and shift the peak of energy consumption for HVAC systems to cheaper off-peak hours. PCMs can increase human comfort by decreasing the frequency of internal air temperature fluctuation and provide the desired temperature in the indoor building environment for a longer period (Vuceljic 2009). PCMs can reduce the electrical power consumption by lowering the high temperatures in comparison to the external daily temperature and reducing home heating and cooling loads (Zalba et al. 2004).

The motivation for the use of PCMs in building construction can be found in two main factors: 1) Effects of PCMs on electrical energy consumption and 2) Effects of PCMs on thermal performance and comfort of buildings.

1) Effects of PCMs on electrical energy consumption

In many countries, cooling and heating of any type of building contributes significantly to the electrical consumption and this demand of electricity is critical when it occurs during peak times (Al-Hadithi 2011). For example, according to the US Department of Energy (2009), in Arizona, 25% of electrical energy consumed in homes is for air conditioning, which is more than four times the national average. Figure (5) shows the comparison between Arizona and the U.S. overall regarding electrical consumption.

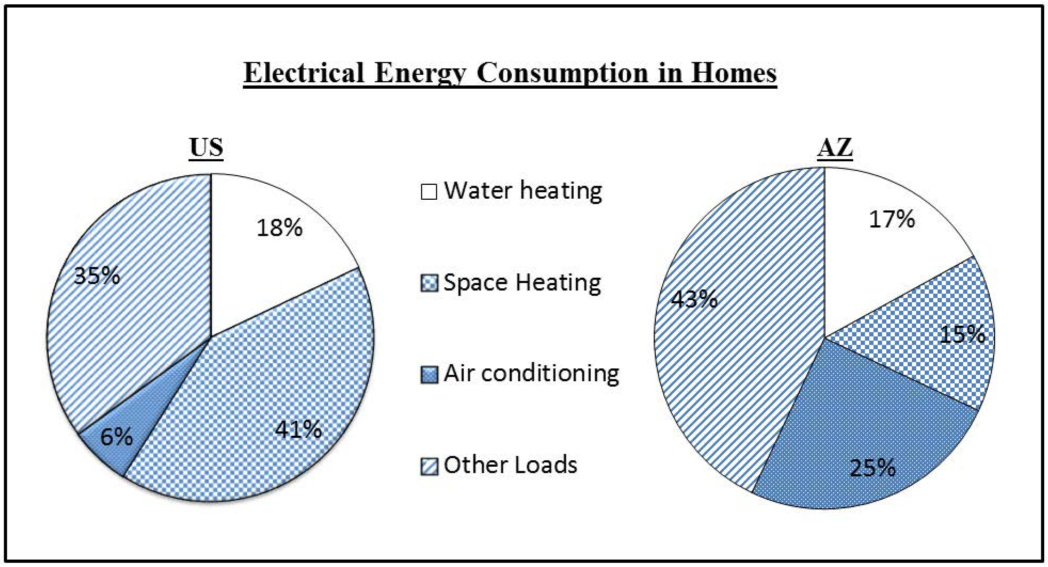

Figure (5): Electrical energy consumption in homes (US Department of Energy 2009)

Currently, providing electrical energy is often achieved with extra equipment and cost, and the use of PCMs in construction practice could reduce or avoid the need for this energy (Sharma et al. 2009). Creating a comfortable environment inside most buildings requires a large amount of energy expense and costs a large share of the building's operating cost. From an economical perspective, PCMs can remedy the trend of increased energy consumptions in building. This, combined with a renewed interest in many aspects of conservation, has led to creating thermal comfort in buildings with minimum expenditure of conventional energy. It should be noted, however, that electrical energy's actual performance for residential buildings, which is integrated with the building component and the consumption of energy, also depends on building design and the operated environmental context (Harland et al. 2010).

2) Effects of PCMs on thermal performance of buildings

PCMs can be used in building construction for thermal storage in conjunction with both passive and active solar storage for heating and cooling (Tyagi and Buddhi 2007). A PCM's temperature remains constant during the phase change, which is useful for keeping the subject or object (e.g. the surface of an exterior wall) at a uniform temperature and can thus provide a comfortable environment inside the building when they are used in the building enclosure (Sharma et al. 2009).

The applications of PCMs in construction practice could reduce or at times entirely avoid the need for cooling or heating energy (Sharma et al. 2009). Moreover, PCMs provide similar functionality for improving the comfort of the interior space in buildings and reducing electrical energy consumption as compared to high density materials typically used for thermal storage. However PCMs now achieve this without the issue of adding significant mass, which can be inappropriate at some levels of construction (Harland et al. 2010). Figure (6) compares PCM with different conventional building materials and shows the necessary thickness to store as much heat as a 1 cm thick layer of PCM based on certain temperature interval (Mehling and Cabeza 2008).

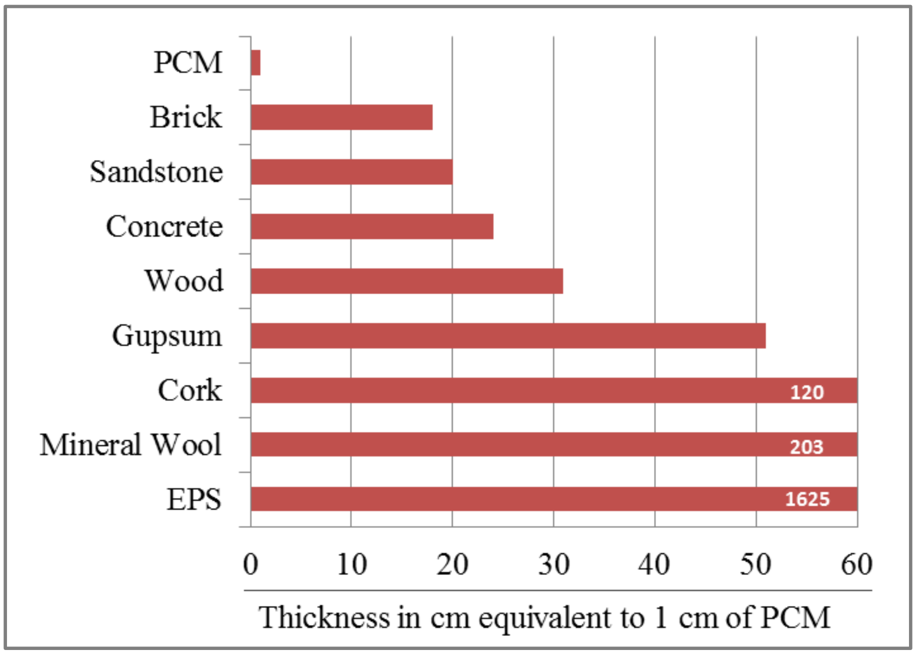

Figure (6) Necessary layer thickness of different building materials to store as much heat as a 1cm thick layer of PCM (Mehling and Cabeza 2008).

Therefore, the use of PCMs is desirable for improving building performance and creating thermal comfort with the reduction of electrical energy consumption because of the discrepancy between the indoor day temperature and the outdoor night temperature (Zalba et al. 2004). For example, in the summertime, peak heat flow crossing a painted roof deck using reflective insulations and PCMs sub-venting air channels was reduced by about 70% compared with the heat flow penetrating a conventional shingle roof (Kosny et al. 2008). This specific application clarifies the impact of PCMs can have on building performance, which subsequently affects the thermal comfort of the physical indoor environment (Kosny et al. 2008), and indicate the necessity of conducting further experimental studies to assess the effective utilization of PCMs in building enclosures and their impact on building performance.

- **PCMs in the Market and their Possibility in Building Construction**

In 2010, varieties of different PCMs were available on the market. The two most common forms were paraffin waxes and salts, which can provide a large range of melting temperatures. In 2013, the commercial market had more than 100 PCMs that were available at different melting temperatures within the range of $0^{o}C$ to $100^{o}C$ with latent heat of fusion in the range of 100 to 300 kJ/kg (Milisic 2013). In the immediate future, it is probable that the market for PCMs in construction will become affordable to local-area applications, mainly because of the PCM resources are becoming cheaper to use and more efficient to apply by conventional methods (Milisic 2013). According to a report from Mordor Intelligence LLP (2015), PCMs were valued at $563.53 million in 2014 and they are expected to extent to reach $1,674.29 million by 2020, presenting a compound annual growth rate of 19.9%.

The opportunity of reducing energy consumption and improving the indoor environment and thermal comfort of buildings is obtainable by using PCMs in building construction. However, the application of PCMs in building materials depends on climate parameters, building location, as well as the individual PCM's properties, and its actual position within different building components. Climate parameters in a building location and thermal characteristics of the building not only have an influence on building components themselves, but also on the thermal comfort of the interior space (Al-Hadithi 2011) and (Fernandes and Costa 2009). Additionally, solar radiation, cloudiness, heat absorption and reflection of the ground, wind speed, and atmospheric pressure all can have a major effect on the indoor comfort environment under natural conditions (Rimkus et al. 2007).

PCMs do not require a thicker layer of building materials as thermal mass to provide thermal comfort for buildings in hot or cold regions because of their absorbing and releasing properties from reactions using the latent heat of fusion (Vuceljic 2009). Therefore, they are mostly suitable to be used in lightweight construction because of their impact, which is similar to thermal mass in the building (Building for Change 2010). Moreover, PCMs can be used in both new building and existing buildings, but when using PCMs in existing buildings, some criteria have to be taken in consideration such sound absorption properties of surfaces or moisture control within enclosure components. Bouguerra et al. (2011) emphasize the possibility of using existing microencapsulated PCMs, which are made with paraffin waxes embedded in small spheres of polymer in building construction, by mixing them with building materials or facing wallboard. They also found that the available PCMs in the market can easily be added to plaster, and can thus be installed in new construction or during the renovation process of an existing building.

Most of the applications of PCMs in buildings focus on heating or cooling by using natural or manmade resources to match the required thermal comfort (Mehling et al. 2002). Therefore, the materials containing PCMs can absorb and release heat more effectively than most of the traditional building materials, and they can be successfully used in components of building enclosure to provide the thermal comfort for interior spaces (Madhumathi and Sundarraja 2012). For longer periods of time, PCMs can provide hours of comfort to the interior space while occupied (Manioglu and Yilmaz 2008). However, PCMs must be selected and applied very carefully, specifically in accordance with fire and other building codes following sound engineering practices.

In hot dry regions, where temperature changes during a 24-hour period are more significant, PCMs applications become an even more relevant driver, as they can reduce and absorb daytime heat gains and provide improved thermal comfort for interior building environments (Madhumathi and Sundarraja 2012). Thus, PCMs are especially suitable in arid and semi-arid areas, when the solar irradiance is maximized during the day, and the energy demand reaches the peaks because of air-conditioning loads (Nath 2012). Also, using PCMs in buildings is suitable to create thermal comfort because of their ability to adapt to the differences between indoor day temperatures and outdoor night temperatures (Zalba et al. 2004).

CONCLUSION AND FUTURE RESEARCH

This paper described in brief the existing situation of PCMs' application in different fields and the opportunity of utilizing them in building construction practices. Also, it discussed the opportunities of utilizing PCMs to improve building performance by using natural resources with less energy consumption. However, providing occupancy comfort by better maintaining desired surface temperatures as well as decreasing the overall required energy of buildings by shifting part of the heating and cooling loads to off-peak hours are perhaps the more significant parts of this study. While this first stage of a larger research agenda discussed the existing applications of PCMs in different fields and explored the possibility of using PCMs in different areas of building construction, the authors identified several areas of future research needs. First, there is a lack of practical experiments for real world assessment of applying PCMs towards energy performance in building enclosures in different climatic contexts. Second, there is a need to study and compare actual temperature distributions and latent heat storage processes in the building enclosure system, when building components contain PCMs and when they are built without PCMs, and are exposed to the same exterior and interior boundary conditions. Third, further research needs to establish performance metrics to measure and assess actual heat transfer across different wall systems and to compare the applicability of these systems for available simulation software, since ultimately designers will have to evaluate thermal performance of enclosure systems that use PCMs.

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