

Application of Phase-Change Materials in Buildings

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Abstract: Phase-Change Materials (PCMs) are substances with a high heat of fusion that melt and solidify at a certain temperature range. They are capable of storing and releasing large amounts of energy and have a high capacity of storing heat. PCMs prevent energy loss during material changes from solid to liquid or liquid to solid. They have several advantages such as their self-nucleating properties, and disadvantages such as having low thermal conductivity [4]. There are different types of PCM with a wide range of applications. This paper studies the potential application of PCMs in building as energy conservation materials. The analysis shows the result shows that the use of BioPCM material as an insulation layer in building can decrease the cooling load by 20% in comparison to standard one.

Keywords: Phase-Change Materials, Construction, Cooling Load, Insulation

1. Introduction

Researchers have investigated Phase-Change Materials (PCMs) heavily over the last two decades as energy conservation materials in buildings. The tremendous increase in energy prices has motivated researchers to search for new materials that have the capacity to reduce energy demand. PCMs thermophysical properties that include melting point range, heat of fusion, thermal conductivity, and density, have promoted it as a valid option for energy conservation. Additionally, PCMs can freeze with little supercooling; compatible with construction material; chemically stable; recyclable; and can reduce HVAC load. However, PCMs have a few drawbacks including the requirements of a freezing cycle in order to transfer high heat; and the capacity of its volumetric latent heat storage (LHS) is low making PCMs flammable. Therefore, PCMs need to be stored in a proper container to avoid any of these disadvantages.

PCM can be classified under three categories: organic, inorganic and eutectic [15]. Organic PCMs have technical grade paraffins or paraffin mixtures made of oil that help PCMs obtain reliable phase change points [7]. Paraffin is also available in large temperature ranges, making them accessible, especially because they have a long freeze-melt cycle. PCMs can also be made out of non-paraffin compounds. The benefits for using this organic material in heat storage

are that it has the advantage of not being corrosive or undercooled, but still do cause a lower phase change enthalpy, low thermal conductivity and inflammability. In using inorganic PCM materials for heat storage such as hydrated salts and metallic, have a greater phase change enthalpy despite its disadvantages of undercooling, corrosion, phase separation and lack of thermal stability. The third classification of PCM is eutectic which can be organic or inorganic [8]. They have a sharp melting point and their volumetric storage capacity is higher than organic paraffin compounds. However, its thermophysical properties are limited and are still rather new to thermal storage [9]. To increase heat conductivity in PCM without affecting the energy storage, Mehling et al. [5] and Py et al. [6] designed a compound-material made of a graphite matrix to embed the PCM in it. Graphite decreases the sub cooling of PCMs hydrated salts and decreases the volume change of paraffins. This produces high thermal conductivity where there is 8% of the latent heat of fusion per unit mass of the paraffin [3].

When heat is applied to a substance, the energy transfers in one of two ways. The first is that the substance gains heat [2, 3]. For example, if heat is applied to water, it will rise in temperature to a maximum of 100°C, its boiling point. Likewise, if heat is removed, the temperature of the water will fall, to a minimum of 0°C, or its freezing point. This type of heat transfer, or storage, is called sensible heat as seen in Figure 1. The temperature of a substance however,

doesn't always rise when heat is added. Boiling water for example, remains at 100°C no matter how much heat is added which is why the water turns into vapour [2, 3]. Therefore, any substance that absorbs heat reaches either its melting or evaporation point without getting any hotter. Latent heat is this type of heat storage. Without latent heat, PCM's would not be able to act alone in controlling room temperature because when used in construction they

change from solid to liquid at 23-26°C. When PCM melts, they absorb heat from the room to keep the room temperature stable. PCM's only return to its original solid state during ventilation at night. These valuable properties of PCM's shall dramatically reduce cooling and heating energy demand if properly managed and implemented. This paper studies the potential application of PCM's in building as energy conservation materials.

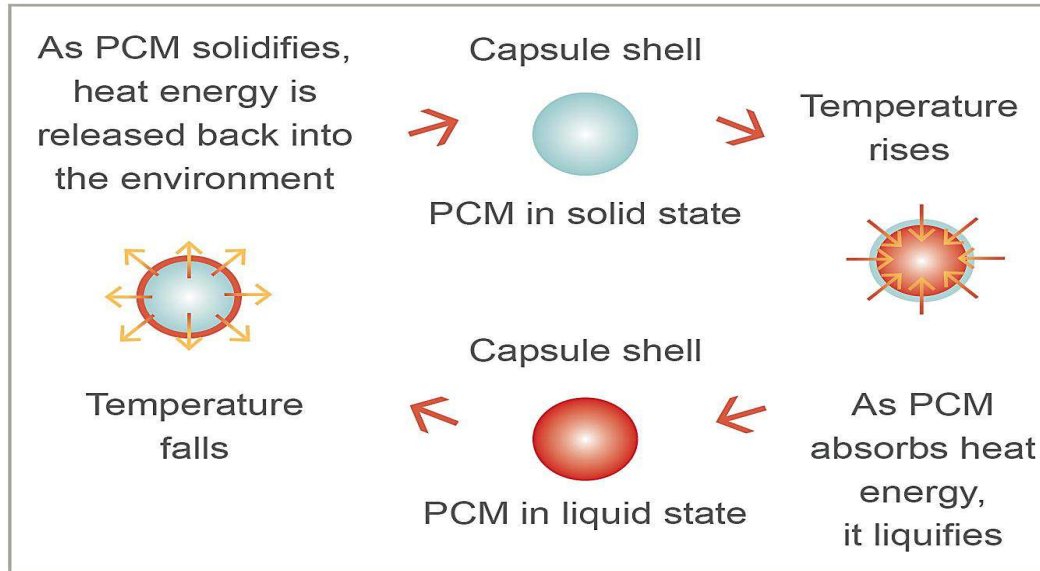


Figure 1. PCM's work by solidifying to release heat energy and absorbing heat energy before being liquidities. [20].

2. Comparison of Pcms

2.1. Water and Gel Packs

Ice and gel packs have become extremely popular for keeping materials cold around 0°C. These devices have the advantages of good performance, low cost, nontoxic, not flammable, environmentally friendly and easy to use. The only disadvantage to these ice and gel packs is that they are only useful at maintaining their surroundings or thermal load at 0°C. If one wishes to obtain a water-based PCM lower than 0°C, then a salt can be added to the water. This will depress the freezing point. However, this significantly decreases the latent heat and broadens the melt/freeze temperature. This technique is familiar by many in applications of adding salt to ice for making homemade ice cream or adding salt to roads during icy conditions in order to lower the freezing point of water.

Similarly, gel packs are types of salts. The predominate compound in many gel packs is sodium polyacrylate. Sodium polyacrylate is the predominant chemical used in diapers. The addition of sodium polyacrylate does change the crystal structure of ice and therefore diminishes the effectiveness of ice as a PCM.

2.2. Salt Hydrates

Salt hydrates as PCM's have been among the most researched latent heat storage materials. Salt hydrates are

often times the lowest cost PCM behind water and gel packs. Numerous trials and sub-scale tests have been carried out on these compounds. The material comprises $M \cdot nH_2O$, where M is an inorganic compound.

Salt hydrates have several problems related to practical applications as PCM's. Foremost, is the limited temperature ranges available to salts in meeting specific temperature needs at the desired temperature. There are few salts that melt between 1 and 150°C. In the absence of salts melting at temperatures between 1 and 150°C, eutectic mixtures and salt hydrates are pursued for these missing temperature ranges. The main problems experienced in the past with salt hydrate-based thermal storage applications were due to the fact that most salt hydrates melt incongruently (e.g., they melt to a saturated aqueous phase and a solid phase, which is generally of a lower hydrate of the same salt)[7]. Abhat[8] specifies the following problem with salt hydrates, "The major problem in using salt hydrates as PCM's is that most of them melt incongruently, i.e. they melt to a saturated aqueous phase and a solid phase which is generally a lower hydrate of the same salt. Due to density differences, the salt phase settles out and collects at the bottom of the container, a phenomenon called decomposition. Unless specific measures are taken, this phenomenon is irreversible, i.e. during freezing, the solid phase does not combine with the saturated solution to form the original salt hydrate." This observation was repeated by Verner[9] and by Lane[10]. Another common problem found in salt hydrates is with the salt hydrates' poor nucleating properties that result in what is termed supercooling of the

liquid salt hydrate prior to freezing. This must be overcome by the addition of a suitable nucleating agent that has a crystal structure similar to that of the parent substance.

Other issues of using salt hydrates involve the volume change, the corrosive nature of the salt hydrate and the toxicity of some of these materials. Often times the volume change in the solid/liquid phase change of a salt hydrate is up to 10%. While this is significant, it can be accommodated in special packaging. The packaging needs to be specific to the type of salt hydrate used. Many salt hydrates are corrosive to metals. The toxicity of salt hydrates also varies widely. Therefore, the safety data sheets should be carefully checked for human toxicity and environmental damage when disposed.

2.3. Paraffins

Paraffins are high-molecular-mass hydrocarbons with a waxy consistency at room temperature. Paraffins are made up of straight chain hydrocarbons. The paraffins are separated into two main sub-groups, evenchained (n-Paraffin) and odd-chained (iso- Paraffin). Typically, iso-paraffins do not make good PCMs because of steric hindrances in their molecular packing. Therefore, we will only focus on the n-paraffins. The melting point of paraffins is directly related to the number of carbon atoms within the material structure with alkanes containing 12-40 C-atoms possessing melting points between 6 and 80 degrees centigrade. These are termed 'pure paraffins' and should not be confused with paraffin waxes. Paraffin waxes contain a mixture of hydrocarbon molecules with various carbon numbers with lower melting points and poorer latent heats than pure paraffins. Paraffin waxes are often considered a low-grade PCM.

Paraffins form a good PCM candidate for certain applications and certain select temperature ranges. Paraffins have good thermal storage capacity plus the materials are proven to freeze without supercooling. Paraffins also have the advantages of chemical stability over many heating and freezing cycles[11], high heat of fusion, they are non-corrosive, compatible with most all materials and non-reactive to most materials of encapsulation.

Paraffins do have some disadvantages associated with them. Literature reports on how pure paraffin products are often reported to have very high latent heats. However, the details are most important in this assessment. Commercially cost-effective paraffins are mixtures of alkanes and therefore do not have sharp, well-defined melting points. For example, 98% hexadecane has a latent heat of about 230 J/g at a melting point of 18°C, but due to the very small amount of hexadecane in petroleum crude oil (small fraction of 1%) and the enormous separation costs (repeated high-vacuum, multi-stage distillation) to achieve a 98% pure product, hexadecane is not a viable commercial product as exemplified by the price of over \$10 per pound. Wax products are commercially viable for a variety of applications including uses in canning and candle making. A C20-C24 canning wax has a latent heat of 150 J/g and melts over a 7°C temperature range—considerably poorer performance than +98% n-paraffin products found in most literature. Pure paraffins are also

limited in their range of melting points that they can target. Table 1 lists 16 of the most common paraffins and their melting points. However, from a practical standpoint, only the evennumberedparaffins are in any abundance in crude petroleum. This takes the number of common paraffins for use as PCMs down to 8 commercially viable paraffins. Many researchers try to expand this temperature range above the 8 common paraffins by creating mixtures of 2 or more paraffins. This, however, has the detrimental effect of broadening the melt/freeze temperature and lowering the latent heats even more.

Other concerns with paraffins used as PCMs are social dynamics. Paraffins are made from petroleum products, which increases our reliance on crude oil. Paraffins prices have followed the unstable price of petroleum. Furthermore, petroleum-derived paraffins have geopolitical consequences and contribute to the increase in carbon emissions blamed for the global warming crisis.

2.4. Vegetable-based PCMs

In the past, the phase change material market has been dominated by paraffin products and salt hydrates. Paraffins have recently become more popular than the salt hydrates. However, the use of vegetable compounds has started to make strong inroads in this PCM market. The ability of vegetable compounds to compete in this market depends on their price:performance characteristics relative to paraffins.

The Department of Agriculture and the National Science Foundation has sponsored research to investigate the potential vegetable-derived compounds becoming significant in the PCM market[12-14]. During these investigations the researchers were able to produce around 300 different fat-and vegetable oil-based PCMs ranging from - 90°C to 150°C with latent heats between 150 and 220 J/g.

The safety, environmental and social benefits of using vegetable-based PCMs are significantly greater than those of paraffins. Paraffins can be toxic and have laxative effects when ingested. Many vegetable-based PCMs can be considered, "food grade" or have no effect when ingested. Researchers under the Department of Agriculture research program also discovered that many vegetable-based PCMs had lower flash points and 10-20% longer horizontal flame propagation rates than did their temperature-comparable, paraffin-based counterparts. Paraffins are long chain alkanes. This means that there is no "active" site on the paraffin molecule for microbes and bacteria to begin their breakdown. While this is attractive for the life of the PCM, it presents environment problems when the paraffin is disposed in a landfill. The paraffin would stay undegraded for decades. Many vegetablebased PCMs have shown stability after 30 years of accelerated aging tests[15]. However, these same vegetable-based PCMs will degrade in six months or less when discarded in a landfill. Many vegetable based PCMs can be derived locally using common agricultural crops. This leads to a more stable price and regionally based feedstocks. Vegetable-based PCMs are considered to be nearly carbon neutral, as recently ranked by the USDA Bio Preferred

program[16]. Vegetable-based PCMs are able to provide price: Performance characteristics superior to paraffin PCM chemicals because 1) the natural vegetable-based feedstocks are available at relatively low prices and 2) multiple reaction-modification schemes provide many degrees of freedom to produce a variety of premium products. These vegetable-derived chemical building blocks are available at concentrations considerably greater than any particular n-paraffin is available in crude oil. Because of this, vegetable-based PCMs have a distinct competitive advantage over paraffins and could corner the PCM market. Vegetable-based PCMs are able to provide a price: Performance characteristic superior to salt hydrate PCM chemicals over most of the temperatures between -90°C and 150°C because viable salts or salt hydrates simply are not available over much of that temperature range. For the limited temperatures where viable salt PCM chemicals are available, vegetablebased PCMs have advantages of 1) being renewable and more environmentally friendly and; 2) being compatible with wall boards or similar materials that would absorb water from hydrates and render the salt hydrates ineffective as PCM chemicals; 3) vegetablebased PCMs are capable of being microencapsulated, whereas salt hydrates are not.

3. Pcms Applications in Buildings

More than 500 natural and synthetic PCMs are known in addition to water [11]. They differ from each other by their altering phase change temperature ranges and their heat storage capacities. Other properties of PCM for a high efficient cooling system with thermal energy system (TES) include [9]:

- A melting temperature in the desired operating range, in construction this would be 23°C or 26°C .

- A high latent heat of fusion per unit volume. In other words, they can store a large amount of heat per unit of volume, minimizing the area of PCM tiles that are needed.
- High thermal conductivity. The quicker the PCM reacts to changes in temperature, the more effective the phase changes will be.
- Minimal changes in volume. Substances expand or contract when they change state. Because PCMs in construction need to be contained within a cassette, large changes in volume could create problems.
- Congruent melting. This means that the composition of the liquid is the same as that of the solid, which is important to prevent separation and super cooling.
- A completely reversible freezing/melting cycle.
- Durability over a large number of cycles.
- Non-corrosiveness to construction materials.
- Non-flammable.

PCMS can be for heating and cooling in buildings as seen in Figure 2[12]. PCM can be placed in porous construction material such as plasterboard to increase heat [13]. As for cooling, air conditioners with PCM collect and store ambient air during the night. PCMs can also be placed in thermoelectric refrigeration to improve effectiveness of the heat sink such as using a window with a PCM curtain [13, 14]. A PCM curtain fills up the double sheeted gap between the window and the air vent, and upon freezing the PCMs would prevent the temperature of the air from decreasing and this reduces overheating around the window [15].

By altering the state of aggregation of a PCMs in a specific temperature range, applications of PCMs can be placed in apparel, blankets, surgical tools, antibacterial and hygiene applications, insulation, clothing and many more [11].

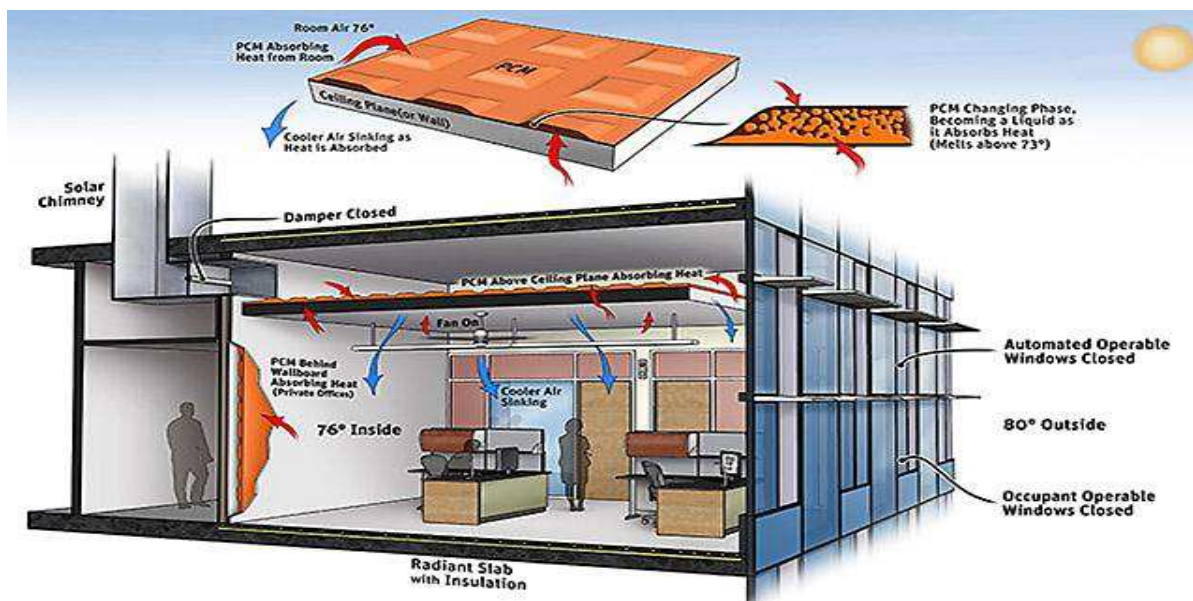


Figure 2. All types of PCM applications in a building [19].

Additionally, PCMs have multiple applications for solar energy storage due to their hydrated salts, alkanes, waxes or paraffin's [10]. Many of which are organized in Table 1 below [17, 18].

Table 1. PCM-TES applications [4].

Applications
1. Thermal storage of solar energy
2. Passive storage in bioclimatic building/architecture (HDPE + paraffin)
3. Cooling use of off-peak rates and reduction of installed power, ice-bank
4. Heating and sanitary hot water: using off-peak rate and adapting unloading curves
5. Safety: temperature maintenance in rooms with computers or electrical appliances
6. Thermal protection of food, transport, hotel trade, ice-cream, etc.
7. Food agroindustry, wine, milk products (absorbing peaks in demand), greenhouse
8. Thermal protection of electronic devices (integrated in the appliance)
9. Medical applications: transport of blood, operating tables, hot – cold therapies
9. Cooling of engines (electric and combustion)
10. Thermal comfort in vehicles
11. Softening of exothermic temperature peaks in chemical reactions
12. Spacecraft thermal systems
13. Solar power plants

4. Case Study of Pcms Applications in Buildings

PCMs can smooth temperature variability's in a building especially when used in air conditioning applications. This can have substantial economic and environmental benefits. To evaluate the value of PCMs materials in air conditioning application the cooling load needed for the building shown in Figure 3 was estimated with the application of PCMs materials and without. The building is located in the Dammam City in the Eastern province of Saudi Arabia where the average outdoor temperature (T_o) be about 45 °C and indoor temperature (T_i) is about 24 °C. The cooling Load (CL)

was estimated based on the following equation:

$$C.L = Q(t) + Q(s) + Q(l) + Q(o) + Q(e) + Q(v) \quad (1)$$

Where, the heat transmitted through structures is represented by $Q(t)$, the heat emitted by the sun is $Q(s)$, the light gained is $Q(l)$, the heat of the occupants is $Q(o)$, the heat of the equipment is $Q(e)$, and the heat of ventilation is $Q(v)$. Therefore:

$$Q(t) = \sum U \cdot A \cdot (T_o - T_i) \quad (2)$$

Where, U is the overall heat transmission coefficient ($W/m^2 \cdot K$), A is the area, T_o is the outdoor temperature, and T_i is the indoor temperature.

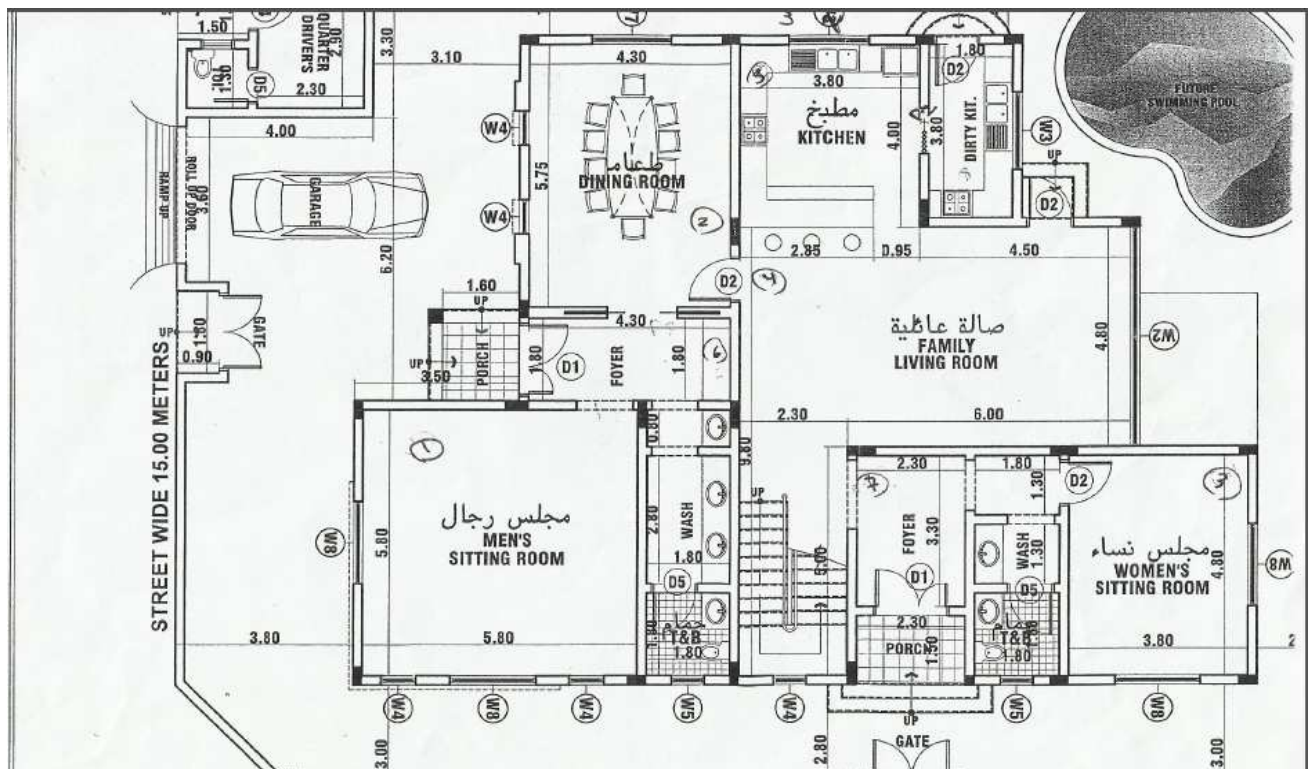


Figure 3. Comparing a normal wall with a PCM wall.

The standard materials for the walls are made of 20mm brick wall, 2mm insulation of polyurethane. Whereas the

BioPCM properties are given in Table 2 below:

Table 2. BioPCM properties.

Description	BioPCM	GR27	Water
Melting Point (°C)	29	28	0
Density (kg/m ³)	860	710	1000
Specific Heat (kJ kg ⁻¹ °C ⁻¹)	1.97	1.125	4.179
Latent Heat (kJ/kg)	219	72	334
Viscosity @ 30 °C (cp)	7		0.798
Boiling Point (°C)	418		100
Thermal Conductivity (W m ⁻¹ °C ⁻¹)	0.2	0.15	0.6

5. Results

The cooling load from a normal wall and the cooling load

from a PCM wall were calculated for each room in the building. The analysis shows a total reduction of needed cooling load for the whole building of about 20% when utilizing PCMs in the building. The total cooling load for the building with normal construction materials was estimated to be about 16 tonnes while with PCMs was estimated to be about 13 tonnes. More details are provided for the men sitting room in the building. Table 3 shows the cooling load calculation results for Men sitting room with normal construction materials is presented in Table 3. While the cooling loads with PCMs material for the same room is presented in Table 4.

Table 3. Cooling load for men sitting room estimate for a normal wall.

Location	Area	U	SC	CLF	Tin-To	Q (w)	
Wall	N(inner)	17.4	2.36			0	0
	S (inner)	11.46	2.36			0	0
	E (inner)	17.4	2.36			0	0
	W (inner)	14.7	2.36			0	0
	N(outer)	17.4	2.34			21	855.04
	S (outer)	11.46	2.34			21	563.14
	E (outer)	17.4	2.34			21	855.04
	W (outer)	14.7	2.34			21	722.36
Floor		33.64	1.5			0	0.00
Ceiling		33.64	1.5			21	1059.66
Window	S	5.94	2.07	0.57		21	147.18
window	W	2.7	2.07	0.57		21	66.90
Door	N	2	0.26			0	
Sum of Q(w)					4269.32		

Table 4. Cooling load for men sitting room estimate for a PCMs wall.

Location	Area	U	SC	CLF	Tin-To	Q (w)	
Wall	N(inner)	17.4	2.36			0	0
	S (inner)	11.46	2.36			0	0
	E (inner)	17.4	2.36			0	0
	W (inner)	14.7	2.36			0	0
	N(outer)	17.4	1.1			21	401.94
	S (outer)	11.46	1.1			21	264.73
	E (outer)	17.4	1.1			21	401.94
	W (outer)	14.7	1.1			21	339.57
Floor		33.64	1.5			0	0.00
Ceiling		33.64	1.5			21	1059.66
Window	S	5.94	2.07	0.57		21	147.18
window	W	2.7	2.07	0.57		21	66.90
Door	N	2	0.26			0	
Sum of Q(w)					2681.92		

6. Conclusion

The potential use of PCMs in construction material, heat transfer and other applications are promising given the magnificent thermophysical properties. PCMs should be incorporated further in global energy management solutions due to the stress for innovations with a low impact on the environment. The results gained from analysis shows a 20% reduction of cooling load when utilizing PCMs materials in comparison to standard construction materials. Accordingly, PCM wall is a promising solution for the problem of depleting fuel resources in the form of latent heat storage

materials. PCM should be used in buildings, ceiling tiles, air conditioners, thermal heating and many other applications. Further research is recommended in PCMs application in the construction industry due to its magical properties and potential wide applications.

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