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PHASE CHANGE MATERIALS: TYPES, PROPERTIES and APPLICATIONS in BUILDINGS

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Abstract

The need to reduce the use of fossil energy, which is running out and harmful to the environment, in response to the increasing energy demand with rapid urbanization, population growth and developing technologies reveals the necessity of research and application of technologies using renewable energy. Phase-change materials (PCM) are one of the most suitable methods for the efficient use of thermal energy originating from clean and sustainable energy sources. PCMs play important roles in a more energy-efficient world. The development of PCMs is one of the most challenging areas of study for more efficient thermal energy storage (TES) systems. This paper first explains the concept of PCMs and then describes the properties of these materials. After mentioned studies for improving the properties of PCMs, then PCM types and advantages-disadvantages are explained. Also, usage areas of PCMs in various sectors are also explained.

Keywords: Heat Storage, Phase Change Materials, Building Applications of PCMs.

FAZ DEĞİŞİM MALZEMELERİ: BİNA TÜRLERİ, ÖZELLİKLERİ VE UYGULAMALARI

Öz

Hızlı kentleşme, nüfus artışı ve gelişen teknolojiler ile artan enerji talebine karşılık kısıtlı kaynaklara sahip ve çevreye zararlı olan fosil enerjinin kullanımının azaltılması ihtiyacı, yenilenebilir enerji kullanan teknolojilerin araştırılması ve uygulanması gerekliliğini ortaya çıkarmaktadır. Faz değiştiren malzemeler (Phase Change Materials - PCM), temiz ve sürdürülebilir enerji kaynaklarından elde edilen ısıl enerjinin verimli kullanımı için en uygun yöntemlerden biridir. PCM'ler, enerjinin daha verimli kullanılmasının planlandığı bir dünyada önemli roller oynayacaktır. PCM'lerin geliştirilmesi, daha verimli ısıl enerji depolama (Thermal Energy Storage - TES) sistemleri için en zorlu çalışma alanlarından biridir. Bu makale önce PCM kavramını açıklamakta ve ardından bu malzemelerin özelliklerini aktarmaktadır. PCM'lerin özelliklerinin iyileştirilmesine yönelik çalışmalardan bahsedildikten sonra PCM çeşitleri ve avantaj-dezavantajları anlatılmıştır. Ayrıca PCM'lerin çeşitli sektörlerdeki kullanım alanları da anlatılmıştır.

Anahtar Kelimeler: Faz Değiştiren Malzemeler, Isı Depolama, PCM’lerin Binalarda Kullanımı.

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1. Introduction

Energy is a key factor for contributing to the evolvement of humankind in various point of view such as technological improvement, environmental protection and economic growth. The rising in living standards and technological progress cause the increasing in the electricity demand. According to the International Energy Agency report, global energy demand is expected to increase by about 30% between 2017 and 2040 [1]. Increasing global energy demand and steps to reduce fossil energy consumption with environmental concerns have led to utilize the alternative energy sources by researchers and industrialists. Solar energy is the most striking type of energy among renewable energy sources due to its wide usage area [2-3]. A major problem for renewable energy sources like solar and wind power is the need for efficient storage when the sun isn't shining and the wind isn't blowing.

Energy storage can be achieved through many different systems. Depending upon the stored energy types, various methods are used to capture and collect the energy. Energy storage methods can be classified as magnetic, mechanical, chemical and thermal methods. Thermal energy can be stored in all kinds of materials thanks to the heat capacity of the materials. In engineering terms, this phenomenon is known as "sensible heat storage" (SHS). With the heat capacity of the used material and the change in temperature, sensible heat can be stored in the charging and discharging processes. In the charging process, the temperature of the storage material increases as energy are captured and are decreased during the discharge phase. However, in this type of storage large amounts of heat storage materials are required. The heat capacity of a sensible storage system can be calculated through the following equation

$$Q_{sensible} = \int_{T_i}^{T_f} mc_p dT = mc_p(T_f - T_i) \tag{1}$$

Here $Q_{sensible}$ is storage capacity (J), T_f is final temperature (K), T_i is initial temperature (K), m is the mass of storage material (kg), c_p represents to the specific heat capacity (J.kg^{-1}.K^{-1}).

Thermochemical storage is another way of storing thermal energy. In the thermochemical storage process, thermal energy is stored in the form of chemical potential and can be used in a reversible endothermic chemical reaction. Thermal energy is stored in the chemical bonds through an energy-

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consuming reaction. In the thermochemical storage method the need of energy is acquired through the reverse reactions where the energy in the chemical bonds is released.

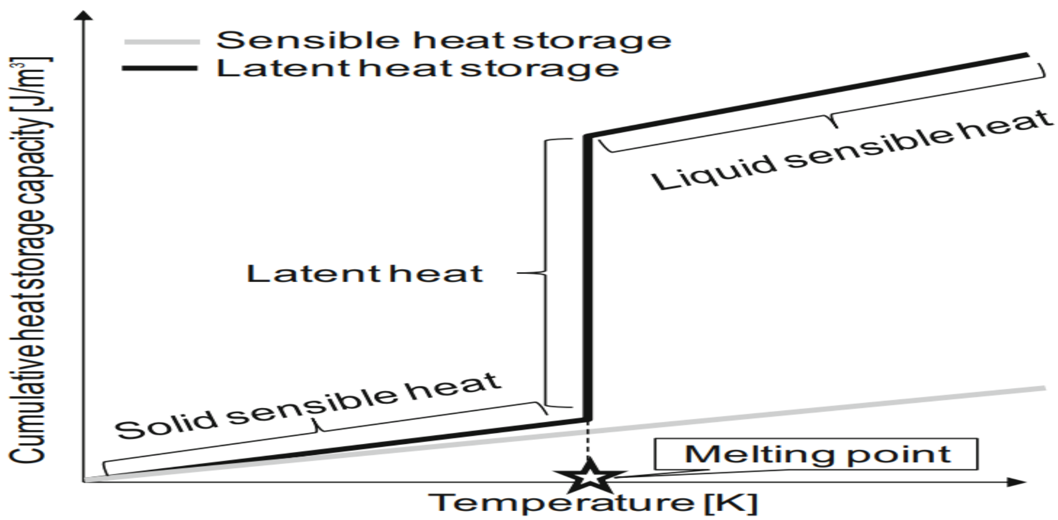

Figure 1. Cumulative heat storage capacity of SHS and LHS [4].

Another storage method is latent heat storage (LHS) and in this manuscript we focus on this type of energy storage mechanism. In this method, the latent heat energy storage occurs when a phase transition appears in the range of operating temperature. In this phase transition duration, the more energy can be stored with respect to the sensible heat storage (Figure 1). One of the advantages of the latent heat storage method is that this method is required much less materials according to the sensible heat storage method [5]. For TES, PCMs were introduced first by Hungarian-American engineer Mária Telkes and this method was used in a solar house in 1948 [6]. The capacity of an LHS system can be expressed as the following equation

$$Q_{latent} = m[c_{ps}(T_m - T_i) + H_e + c_{pl}(T_f - T_m)] \quad (2)$$

In the Eq. (2), Q_{latent} is the storage capacity (J), T_m stands for melting temperature (K), T_i is the initial temperature (K), T_f is the final temperature (K), m is the mass of storage material (kg), c_{ps} is the specific heat capacity of the solid phase (J.kg^{-1}.K^{-1}), c_{pl} is the specific heat capacity of liquid phase (J.kg^{-1}.K^{-1}), and H_e represents to the latent heat of melting (J.kg^{-1}).

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In this review, our main motivation is to investigate the current developments in the PCMs besides investigating their characteristics. The PCMs are very important in the latent heat storage mechanism and the latent heat storage method is widely used in many areas of industry. Hence, we think that investigating the developments in the PCMs can be very useful. This reivew is designated as follows: In sec. (2) we introduce the phase chance materials, in sec. (3) we introduce the types of PCMs, in sec. (4) we introduce the selection criterions of the PCMs, in sec. (5) we mention the improving of the features of PCMs, in sec. (6) we introduce different kinds of application areas of the PCMs, in sec. (7) we introduce the use of PCMs in solar energy applications and in sec. (8) we give results and discussions.

2. What is PCM?

PCMs are materials capturing and storing large quantities of thermal energy during phase transition. One of the critical properties of PCMs is the conservation and storage of thermal energy with a state of thermal equilibrium that occurs after several phase cycles. While PCMs exchange heat in constant phase change cycles, they also supply a more stable environment temperature [7-10]. Materials exist in nature as a solid, liquid or gas phases. When a phase change occurs in a substance, it stores or releases some heat. This stored or released heat is called as latent heat (LH). To illustrate, when the temperature of a solid substance is increased up to its melting temperature, this solid substance melts by capturing a large amount of heat and its phase transforms from solid to liquid (Figure 2). Phase states of the PCMs can change within a certain temperature range [8].

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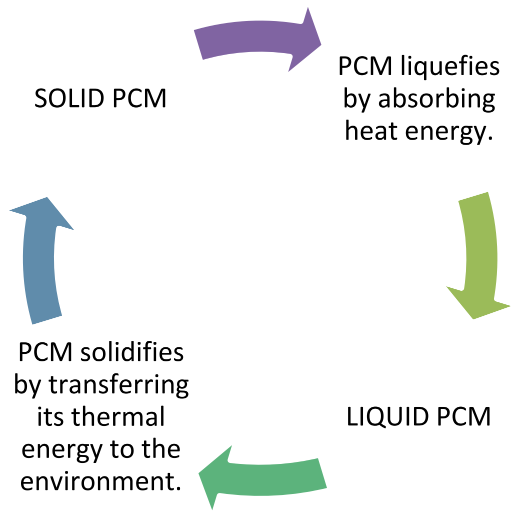

Figure 2. Solid-liquid phase cycling in PCMs [9].

During the processes are carried out in many of the industrial sectors and other applications, heat transfer occurs with phase change. PCMs are studied for a long time for energy storage purposes and this research area is an active research area. It can be seen the related literature gains about 1000 publications per year [11].

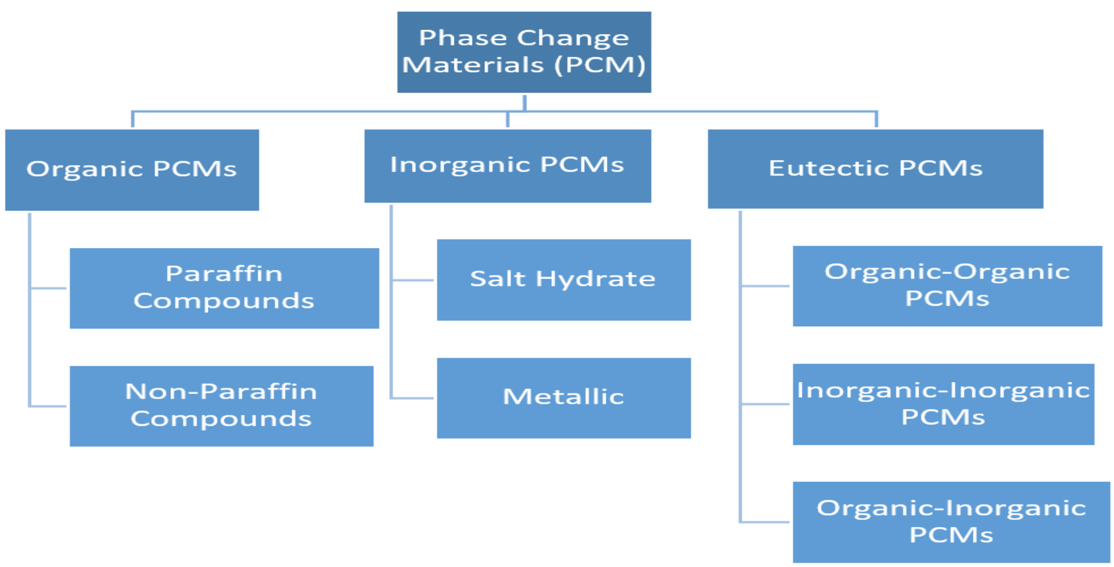

Figure 3. PCM types [9].

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3. PCM Types

Based on the chemical nature of PCMs, they can be categorized into three main categories: organic, inorganic, and eutectics type combining organic and inorganic PCMs (Figure 3). Organic PCMs are basically divided into two main classes as paraffin and non-paraffin materials. Inorganic PCMs include salt hydrate and metal subclasses [12]. Inorganic PCMs will be discussed in details in the section (3.2). In addition, the melting point and fusion heat values of some PCM types are illustrated in Figure 4.

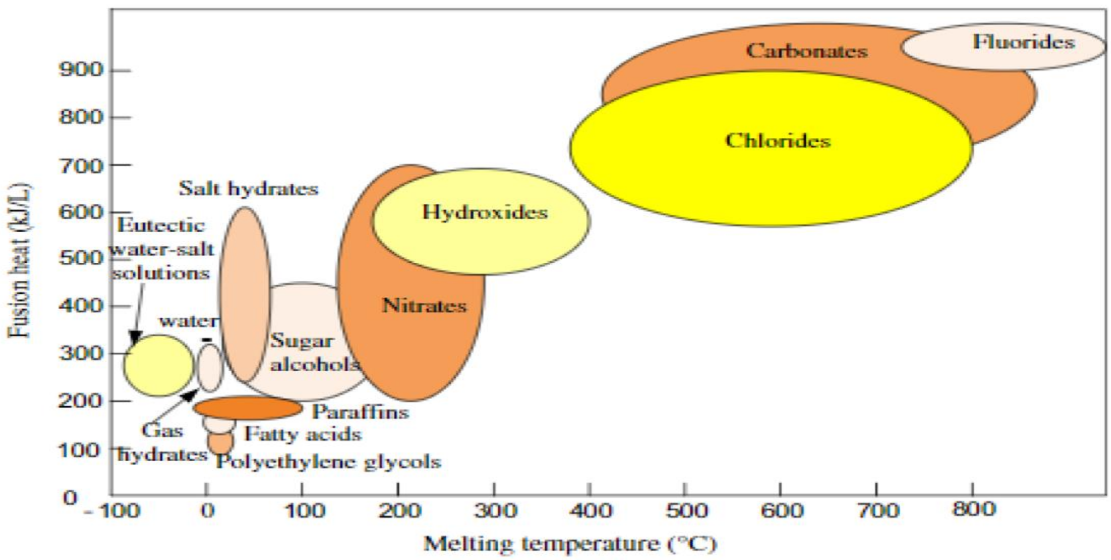

Figure 4. Melting temperature and fusion heat of some PCM variants [13].

3.1. Organic PCMs

Organic PCMs, which are classified into two as paraffin and non-paraffin, are one of the most preferred types of PCMs in use today. Paraffin is among the most utilized PCMs for operations in TES systems [14-15]. Paraffins can be used separately or used in combination with each other at desired temperature ranges. Non-paraffin materials are manufactured from a variety of organic matters, containing esters, fatty acids, glycols and alcohols [16-17]. Among both organic and non-paraffin PCM types, fatty acids have gained the most interest because they include a lot of beneficial features including cost-efficiency, no need for additional encapsulation, readiness for

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applications with tunable dimension and steady form [18-19]. Non-paraffin organic PCMs also contain bio-based PCMs.

Bio-based PCMs; are substances originated from renewable and natural-based sources, agro-food industry outputs and their spin-offs, containing foodstuffs such as palm oil, palm kernel oil, soybean oil and coconut oil [20-21]. Environmental friendliness of commercial materials is becoming more and more important in all sectors of industry to improve sustainability and minimize to the environmental impact and carbon footprint. Paraffin is a petroleum-based substance, and hence the materials used in its production contributes to global warming [22]. Non-paraffin materials are mostly obtained from foods (vegetable oil) and are nature-friendly.

While there is a significant amount of work in the literature on the utilization of food-grade vegetable oil fatty acids as biobased phase change materials, there is insufficient data on the usage of sustainable, environmental-friendly and non-food substances produced from bioresources that could potentially be used as PCMs.

3.2. Inorganic PCMs

Unlike organics, inorganic PCMs are not flammable and are much cheaper. Inorganic PCMs contain metals, salts, salt hydrates, and metal alloys [23]. Salt hydrates are generally formulated as AB_nH_2O; where n stand for the number of water molecules in salt blend [24]. Salt and salt hydrates are abundant sources in salt lakes or seawater, therefore it is cost-competitive with a price of one percent of paraffin. The fair cost and non-flammable characteristics of inorganic phase change materials provide much greater encouragement for commercialization than organics [25]. Salt hydrates have a much greater potential for use in the thermal management systems of batteries than organic phase change materials. However, the usage of inorganic phase change materials in thermal management systems of batteries is not a extensively researched area.

The main obstacles for the implementation of inorganic phase change materials stem from poor stability and low thermal conductivity in long-run usage due to phase separation [26], dehydration [27] or supercooling [28]. Although efforts have been made to resolve dehydration [29], phase separation [30], and supercooling [31], these studies focus each issue individually, in general.

There is no general answer to come through all of the issues of salt hydrate-based inorganic phase change materials. Especially dehydration is a problem that must be solved since it leads to the substances being unsteady.

3.3. Eutectic PCM

Although there are three different types of eutectics, two types are widely used today: organic-organic phase change materials [32] and organic-inorganic phase change materials (Figure 5) [33]. Different compounding techniques can be applied to achieve different practical requirements.

To produce organic complex phase change materials with the preferred melting point and latent heat storage meeting daily practical needs, it is a common method to blend two or more organic PCMs by melting and mixing at different phase change temperatures [34]. The formation of binary eutectic compounds from the fatty acids and fatty alcohols, the production of eutectic poly fatty acids from concentrated fatty acids, and the combination of fatty acids with paraffins for binary PCM are some examples of eutectic PCM formation in the literature.

The poor thermal conductivity of organic PCMs is the main obstacle limiting the use of these substances. Consequently, the production and improvement of organic phase-change materials with better thermal conductivity and higher energy storage density is an active research field where a lot of research is being carried out. To develop the thermal properties of organic phase change materials the combining of substances with better thermal properties by melting-mixing methods is a frequently applied method in the development of PCMs [35].

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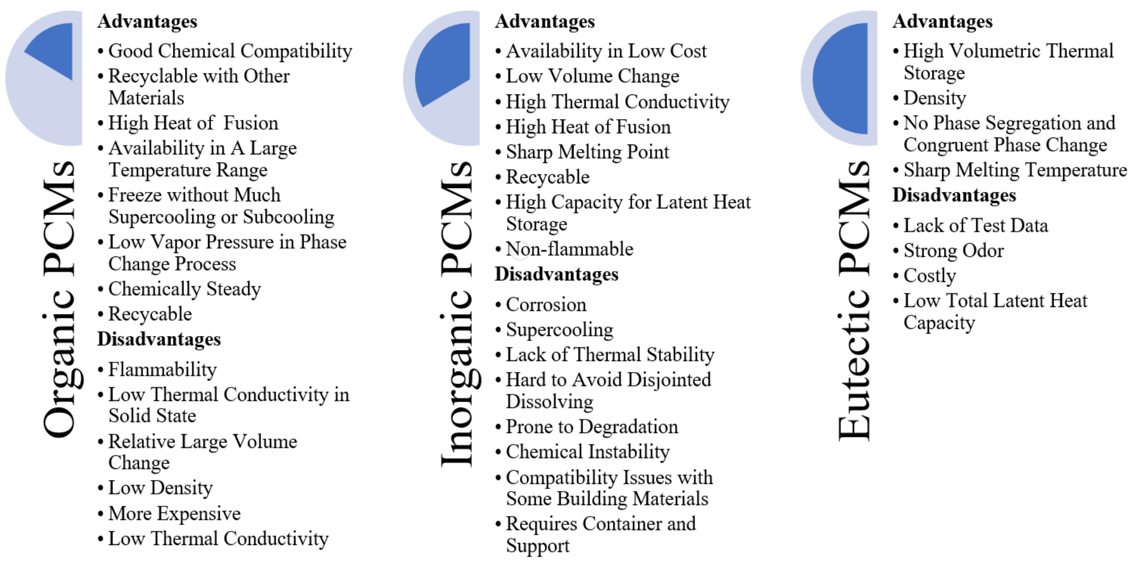

Figure 5. Advantages and disadvantages of PCM types [36-38].

4. Application Areas of PCMs

PCMs have widespread application areas in various sectors such as building applications, daily life operations, energy storage systems, microelectronic temperature management applications, textiles, satellite, telecommunications, transportation, pharmaceuticals and submarine equipment [39].

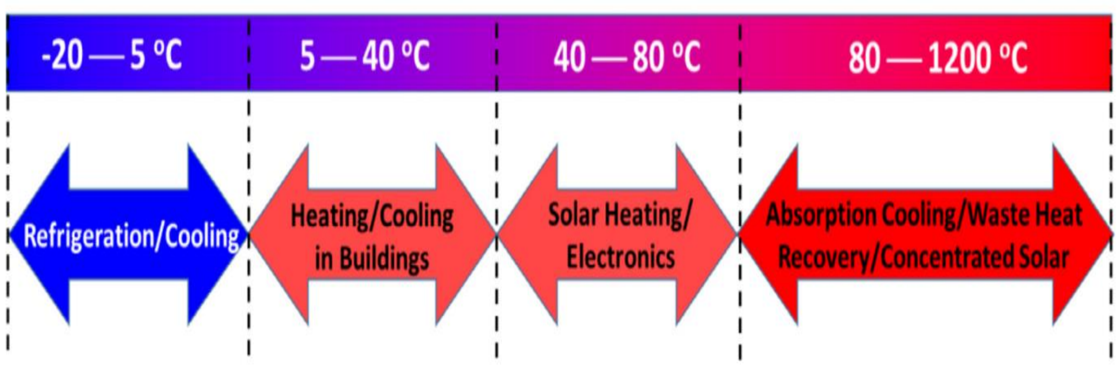

Figure 6. Temperature Ranges of PCMs and Applications [40].

It was mentioned in previous sections that every PCM cannot be used in every application. PCMs have a certain melting temperature range and are used in applications according to these

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temperature values. PCMs can be grouped under 4 main categories according to their operating temperature range (Figure 6). The first temperature range is the low temperature range (-20 °C to +5 °C) where phase change materials are utilized in commercial and residential refrigeration/cooling systems [41]. The second range is the medium-low temperature range (+5 °C to +40 °C) where phase change materials are used in heating/cooling and air conditioning processes in structures [42]. The third temperature range is the medium temperature range (+40 °C to +80 °C) where phase change materials used in solar heating / hot water production systems and heat transfer operations in electronics [43-44]. The final temperature range is the high temperature (+80 °C to +1200 °C) range where phase change materials are utilized in CSP applications, waste heat recovery systems and absorption cooling designs [45].

5. Using PCM in Buildings

PCMs are used in buildings for 2 main purposes:

- Using the heat of the sun for heating and cooling purposes.
- Using the stored heat with heating and cooling processes.

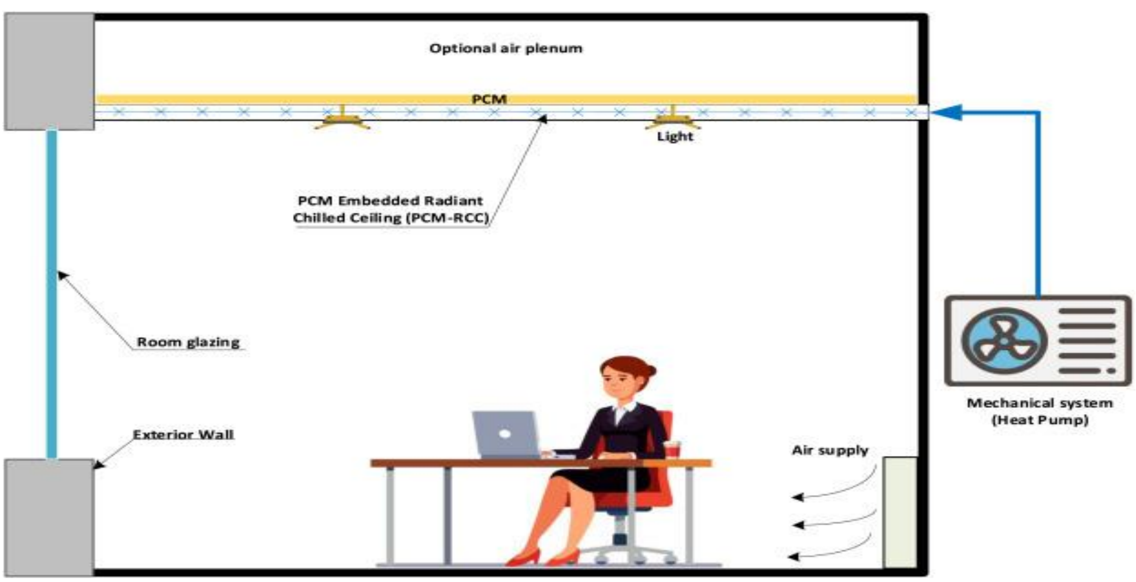

Figure 7. Heat Pump System Enhanced with PCM [47].

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PCMs are generally used in sections such as louvers, solar facades, underfloor heating systems and ceiling panels in buildings. PCMs can be embedded in suspended ceilings and utilized as part of heating and cooling processes (Figure 7) [46-48]. In addition, the use of PCM-equipped walls contributes to lowering the load on the air conditioning applications. By utilizing phase change materials in wall applications, energy can be stored and the load that the building must carry can be reduced by reducing the weight of the wall.

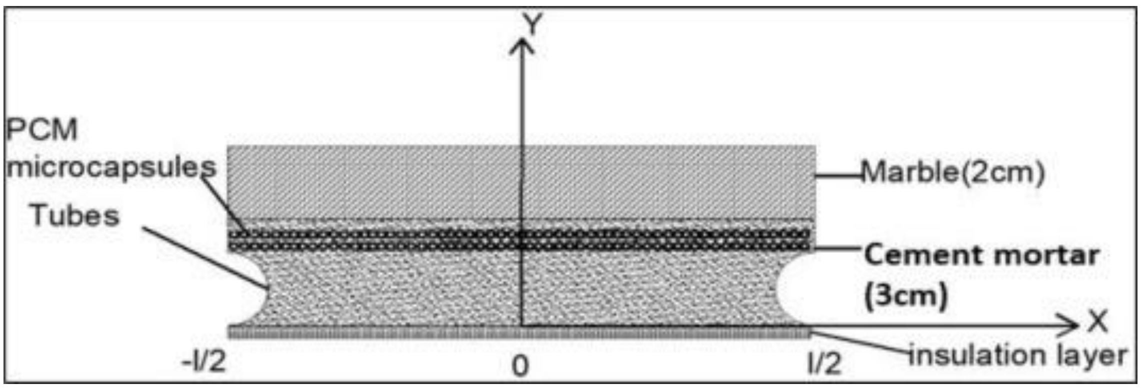

Figure 8. Floor Heating Application with PCM [53].

Floor heating is a superior method to conventional heating systems because of more efficient heating and less space requirement. Compared to electric heating, the use phase change materials in the floor substance can decrease electricity consumption. In floor heating applications with PCM, the system is activated at night when the electricity demand is low, leading to the phase change material to liquified and collect heat (Figure 8) [49-53]. Throughout the day, the heating set of the PCMs shuts down and the heat stored in PCMs is given back to the surroundings. Thus, in addition to the energy savings, the electricity produced by the power plants is also compensated [54-56].

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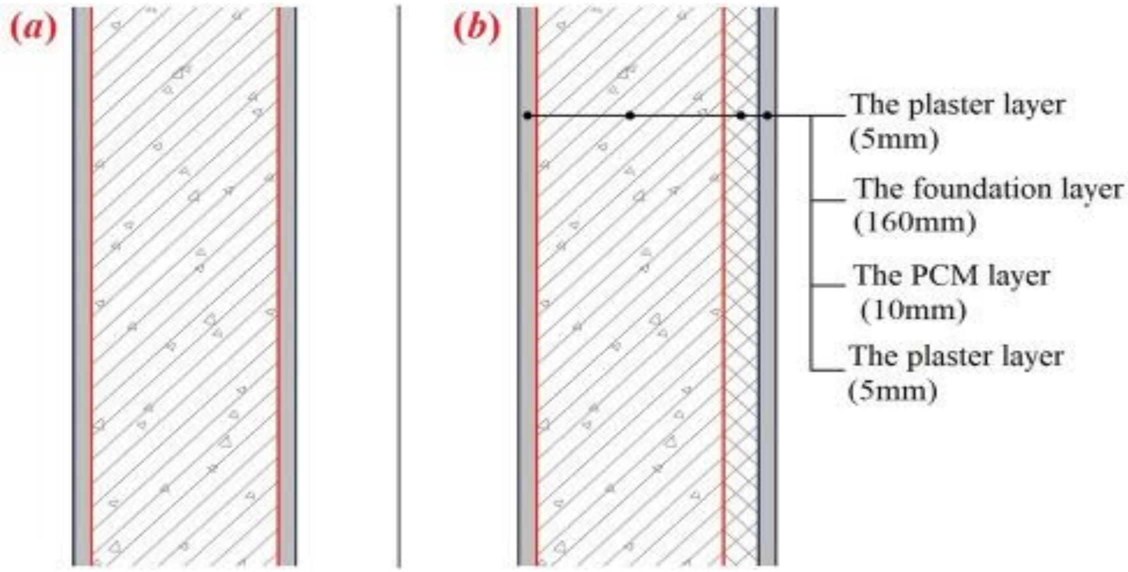

Figure 9. Wall Layers (a) non-PCM and (b) with PCM [71].

The main objective in the building designs made by considering the climatic characteristics of the location is to provide the thermal comfort of the residents against the extreme temperature changes that may occur in different climatic conditions. A building with a suitable climate design should be able to prevent heat flow between the external and internal surfaces. Thus, thermal comfort conditions can be provided by reducing the negative effects of temperature fluctuations on the residents [57-67]. Due to the ability of PCMs to adapt to temperature fluctuations and provide the balance in temperature without the need for any mechanical infrastructure, the temperature can be more stable, especially in the internal volumes of the buildings. By using PCMs in wall design, electricity consumption for heating-cooling processes can be significantly reduced during the periods when electricity is used most intensively (Figure 9) [68-76]. After many tests, it has been understood that the most suitable location for a PCM on the wall is the central section of the wall. PCMs in this location can regulate fluctuations in temperature more effectively than in other locations. By adding PCMs to the wall in this location, it is possible to reduce the heat flux on the inner wall by at least 8% during peak hours. Studies on the use of smart components in energy management and providing the desired temperature conditions in buildings are increasing. Although they cannot be used in commercial applications yet, serious studies should be carried out

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on various parameters and materials in building designs to be done with these smart components [77-78]. At least three tips must be taken into account in the plan of any energy storage system based on PCMs in buildings:

- PCM with suitable phase-change temperature compatible with operating temperature of the design,
- Heat exchanger with heat transfer face in accordance with the heat transfer rate of the design,
- A storage tank for PCMs that can absorb volume changes of phase change materials during melting and is also coherent with it [79-80].

6. Conclusions

In this study; characteristics, types and current usage areas in buildings of PCMs are explained. TES systems using PCMs are an ever-evolving scientific discipline that helps to reduce greenhouse gas emissions, dependence on fossil resources and energy consumption. Depending on the increase in new application areas, the range of sectors in which PCMs are used is also expanding. Heating-cooling and air-conditioning technologies, concentrated solar energy applications, building sections, automotive industry, textile sector are some application areas of PCMs.

Efficiency, total cost, performance and reliability issues are the main problems encountered at the selection stage of PCMs in many sectors. In addition, there are no international or national standards on the use of phase change materials in many sectors. Although various researches have been conducted in many fields on PCMs for many years, there are no standards in the research and development processes of PCMs. Therefore, more serious studies should be carried out on the standards related to PCMs in the future.

Systems involving a combination of different methods such as fins, foams and nanoparticles provide further improvements in the heat transfer properties of PCMs than using these methods individually. Therefore, instead of focusing on only one heat transfer improvement, studying their combination will provide more promising results.

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Some conventional PCMs have flammable properties due to the use of substances such as paraffin and their dangerous and toxic properties. Organic PCMs presented as the next generation of these substances, both do not have the toxic features of previous substances and are non-flammable due to the utilization of natural substances such as soy derivatives and palm oil. In addition, it is recommended to evaluate the use of PCMs in various sectors by analyzing the human health and environmental effects of the use of PCMs.

The use of PCM in buildings is a relatively new method. As explained in the previous headings, the use of PCMs both reduces energy consumption and prevents sudden temperature fluctuations. With future studies, the efficiency of building systems with PCM can be increased or it is possible to manufacture a more proper phase change material for use in structures. In future studies, the reliability and applicability of the designed systems in terms of economic perspective should be expressed through thermo-economic analyzes and feasibility studies.

Abbreviations

CFD	Computational Fluid Dynamics
CSP	Concentrated Solar Power
HTF	Heat Transfer Fluid
LHS	Latent Heat Storage
PCM	Phase Change Material
SHS	Sensible Heat Storage
TES	Thermal Energy Storage

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