Potential of Phase Change Materials for Enhancement of Thermal Performance of Buildings, Review and Perspective for Algerian Energy Efficiency

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ABSTRACT

Algeria is aiming to reduce energy consumption in different sectors including building. A program is underway to thermally insulate new as well as existing buildings. In this perspective, potential of smart materials such as phase change materials (PCM) is reviewed aiming to support this energy efficiency program by indicating research gaps and recommendations for decision makers. In this paper, PCM is firstly introduced with its available types and advantages over conventional insulation materials. Then, the technical aspect particularly how to incorporate PCM in buildings is presented. Moreover, research on PCM is reviewed and thermal performance is highlighted. This review showed the lack of research on PCM applied to the Algerian environment. Limitations, research gaps, and recommendations are provided as conclusions of this paper.

I. Introduction

Final energy consumption in Algeria has increased by 5.6% between 2000 and 2017. Energy consumed in building has known an increase of 80% with annual average increase of 3.6% [1]. Building represents thus the main sector in terms of energy consumption in the country. This high energy consumption is caused by improved living standard in a hand and on the other hand the increasing number of buildings due to population growth. Algeria has launched in 2011 a program for development of renewable energy and energy efficiency. This program has been updated in 2015. The aim of this program is to achieve 30% of green electricity by 2030 as well as promotion of energy efficiency in the main sectors i.e. transportation, industry, and building. For the latter considered as the main consumer, various measures have been taken including economic lighting through a program referred to as ECO-LUMERIERE, support of solar water heater ALSOL program, and particularly the program called ECO-BAT aiming insulation of buildings. The latter is based on conventional insulation materials.

The extreme climatic conditions in some regions in the country is determinant of energy end-uses. For example, Setif, Tiaret and Djelfa provinces are the biggest energy consumers for heating using natural gas because of the cold weather in these regions in winter, while in Laghouat, Ain Salah, and Adrar provinces for instance, the high energy consumption is due to cooling using air conditioners because of the extremely hot weather that lasts for several months of the year.

The building envelope is a weak barrier for heat loss/gain, leading to high energy demand for thermal comfort. It is subjected to all types of climatic conditions and must be built using materials with adequate mechanical properties such as compressive strength, toughness, hardness… etc. The major thermal property in the wall materials is the thermal conductivity. Usually the external walls consist of an air-gap or an insulation positioned in the middle to further decrease the heat transfer from the outside into the building and vice versa. In an effort to minimize the heat gain and loss and reduce the dependence on the HVAC systems, the use of thermal insulation in the construction of buildings is encouraged.

Thermal insulation material should have low density, high thermal resistance, cost-effective so it can conserve energy and lower the use of natural resources. Their benefits also include fire protection, decreasing noise levels, being environmentally friendly and being applicable in different fields. Thermal insulation materials are classified into four groups: organic, inorganic, combined and advanced materials. Inorganic materials such as glass wool and rock wool are the most available in the market, followed by organic ones such as polyurethane (PUR), polyisocyanurate (PIR), extruded polystyrene (XPS), expanded polystyrene (EPS). These insulation materials are the most favorable due to their low thermal conductivity and low cost.

Figure 1. Characteristics of insulating materials

Low thermal conductivity and high thermal capacity of the construction materials must be provided to ensure thermal comfort and reduce energy consumption. If the insulation materials are of low thermal conductivity, their thermal capacity is not high enough.

There is another class of material than can ensure high thermal inertia, these materials are referred to as phase change materials (PCM). PCM can be incorporated directly or indirectly into the construction material (bricks, concrete, mortars…). The direct method consists of a macro-encapsulation of the PCM, which has proven to be disadvantageous in most cases since it reduces the mechanical properties of the construction material. The indirect microencapsulation is a better alternative and is more acceptable for commercial use.

II. Classification of PCMs

PCMs are classified into three main categories: Organic, inorganic, and eutectic PCMs (Figure 1). They are classified based on their chemical properties and identified by their melting temperatures and heat of fusion among other thermo-physical properties such as density, thermal conductivity, and their source [2]. Each of three categories is then grouped into subdivisions and each type has certain advantages and disadvantages. The choice for PCMs depends on many criteria

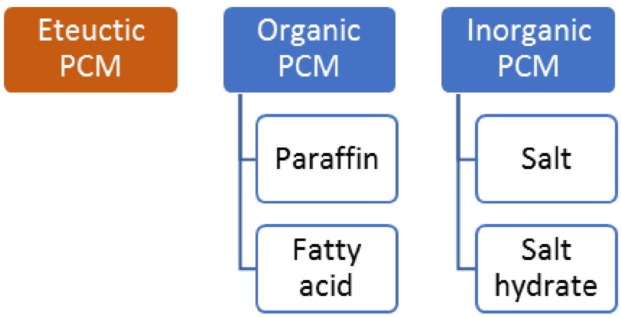

Figure 2. Classification of phase change materials

II.1. Organic PCMs

Organic PCMs include paraffinic and non-paraffinic PCM. They exist in a wide range, but the pure n-alkanes and the fatty acid substances are the ones most known and used in thermal engineering. They are chemically and thermally stable, recyclable, no subcooling, non-corrosive, and they have a suitable phase change temperature range (0°C -150 °C). However, they are flammable, non-compatible with plastic supports, have a low thermal conductivity and a great volume change during phase change.

Paraffins are chemical products that consist of carbon and hydrogen atoms in the form of C_nH_{2n}+2. Increasing the chain length increases the latent heat and the number of the carbon atoms determines the state of the substance (1-4 gaz, 5-17 liquid, more than 17 solid). If the n is between 20-40, then it is considered paraffin wax. [3]. Fatty acids are carboxylic acids with the formula CH_3 $(CH_2)2_nCOOH$. They are non-toxic, have high thermal and chemical stability, low corrosively rate and they can be found in natural products [3]. However, compared to paraffins, fatty acids are more expensive.

II.2. Inorganic PCM

Inorganic PCMs are salts and salt hydrates. They offer fewer advantages compared to organic PCMs, namely they have higher latent heat and are non-flammable. But they are corrosive, thermally unstable; they suffer phase segregation, decomposition, and subcooling which requires the use of a nucleating agent [3]. Another disadvantage of inorganic PCMs is their incompatibility with metals. Salt hydrates are inorganic salts with water molecules. At room temperature they are solid, and at the melting point, the salt starts to dissolve in their own water crystal [3]. Salts have lower enthalpy than salt hydrates but higher temperature ranges [3].

II.3. Eutectic PCMs

Eutectic PCMs are the result of combining different pure PCMs (organic–organic, inorganic–inorganic, or inorganic–organic) but unlike pure inorganic PCMs, they do not suffer segregation and the compounds won't be separated during solidification. Their melting point is close to that of a pure substance, the mixture's elements transit into liquid phase simultaneously and their latent heat is higher than that of pure organic PCMs. The major drawback of eutectic PCMs is the lack of data, tests and applications.

III. PCM Selection Criteria

Choice of PCM for building application depends on many thermo-physical, kinetic, chemical, economic and environmental properties. Hardly any material ever meets all the criteria so trade-off is necessary with a few improvements to achieve the optimum performance. It is impossible for a PCM to meet all these criteria and much research and methodologies have been proposed to determine the best choice of the PCM depending on the different applications and the desired results [4]. All the same, the most important properties are the suitable melting temperature, high heat of fusion, small volume change, chemical and thermal stability and the non-toxicity. The other properties are either compensated or improved by certain measures such as nano-enhancement, the use of extended surfaces.

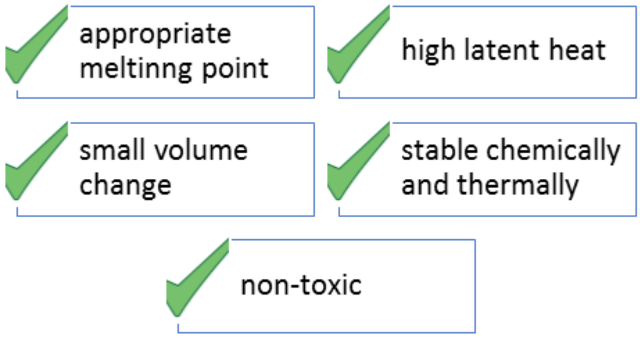

Figure 3. Selection criteria of phase change materials

IV. PCM incorporation methods

There are many methods to incorporate PCM into the construction materials of buildings, including direct incorporation, immersion, and encapsulation. PCM can be directly mixed with construction materials such as gypsum, concrete and bricks. It is the simplest method to apply and also the most economical. However, it is rarely used in buildings for technical and performance reasons. Leakage of PCM has been observed as well as the interaction between the PCM and its porous container that leads to deterioration in the mechanical properties of the containers [5]. Encapsulation is the method most widely applied in the building sector. The PCM is encapsulated before being used in the construction material. This method has many advantages. It solves the issue of leakage of the PCM into the construction elements, it also acts as a shield to protect the PCM from extreme environmental conditions and from deteriorating when it comes to thermal performance. It is classified based on the diameter of the capsules: macro-encapsulation (1mm and more), micro-encapsulation (1µm to 1 mm) and nano-encapsulation (less than 1µm). Macro-encapsulation is the easiest to construct and can be applied in buildings as well as in heat exchangers. The containers can be spheres or tubes and can be made of metal or polymer. Still, some PCMs have low thermal conductivity which results in the phase change at the edges of the contact surfaces and an increase in the charging/discharging time. The relatively big size makes the capsules exposed to potential destruction and deterioration and thus, research is still ongoing to find solutions to this issue so it can be applied in building safely. Micro-encapsulation is the method most applied in buildings due to its many advantages. The small size of the capsules means an increase in the heat transfer and therefore the phase change process and a decrease in the charging/discharging rate. Another advantage of the small size is the small volume change in the phase change and the avoidance of leakage. They can be manufactured in powder form or dispersed in a liquid. The shell of the capsule can be a polymer or an organic substance and the core is a PCM. Nonetheless, micro-encapsulation decreases the latent heat storage capacity and just like macro-encapsulation; it affects the mechanical properties of the construction materials.

Unlike the two other encapsulation methods, nano-encapsulation is used to enhance the performance of a phase change material by enhancing its thermal conductivity. Nanoparticles of a material with high thermal conductivity such as Al_2O_3, TiO_2, CuO, SiO_2, Cu, Graphen, which are the nanoparticles most used in PCM enhancement, are dispersed in PCM which act as the base fluid. Still, the nanoparticles do not influence only the thermal conductivity, but also the latent heat, the phase change temperature, as well as the thermal cycle. The influence is not always positive, especially in the latent heat of the PCMs. The different concentrations of the nanoparticles dispersed in the PCM result in different thermal behaviors which necessitate comparative studies to determine the optimum percentage. These nanoparticles can be carbon-based, ceramic-based, polymer-based, and semiconductor [6].

V. Use of PCMs in building envelope

In recent decades, researchers investigated the use of PCMs in buildings and conducted many experimental studies to validate the numerical studies. Baetens et al. [7] conducted a comprehensive review on the PCM applications in buildings. Agyenim et al. [8] provided a review on the PCMs used for domestic heating applications and summarized that, compared to conventional sensible heat energy storage systems, the PCMs had a more desirable effect due to their high energy storage density. Soaresa et al. [9] conducted a review on the research previously done on the passive latent heat thermal energy storage systems with PCM in buildings and their related performance covering different characteristics, thermal properties, and selection criteria of PCM. Cabeza et al. [10] compiled a review about the PCM usage requirements, classifications, available materials and problems that might come with this technology as well as possible solutions. More attention was given to integrating them into all parts of a building and therefore, walls [11] [12] [13], floors [14] [15], roofs [16] [17], windows [18] [19], window shadings [20] and shutters [21] were all investigated to determine the effect of the PCMs on the building's overall energy consumption.

The building's external walls are one of its main heat loss or gain sources, therefore, thermally insulating them is necessary to reduce the energy consumption. Many studies showed that integrating PCM into the brick walls is an efficient way to save energy since they add a thermal mass to the wall and can absorb a great amount of heat during the phase transition process. Abbas et al. [22] carried out a numerical study that was validated experimentally on the integration of PCM capsules into the hollow bricks for insulation purposes and found that compared to the base wall, the temperature in the inner wall and the room was decreased by about 4.7°C and the temperature fluctuation was reduced by about 23.84%. In another study, Zhang et al. [23] found numerically that the use of PCM in brick wall is beneficial for thermal insulation and indoor thermal comfort for the fluctuating outdoors temperatures, the same results were obtained in [24]. For three different seasons, a composite PCM wall was tested by Wang et al. [25] and a 24.32% reduction was found for the cooling loads while for the heating loads, the reduction can be 10-30% and so for the year round, the PCM-wall had an excellent thermal behavior. Diaconu and Cruceru [26] performed another study for a year round energy saving and found that when two PCMs with different melting points were integrated into two layers of a building material that are separated by a middle layer consisting of a conventional thermal insulation, the peak cooling load reduction found in this study was 35.4%, where the value of the annual energy savings for heating found was 12.8%. When integrated into concrete walls, Cabeza et al. [27] conducted an experimental study and found that the microencapsulated PCM lead to an improved thermal inertia and a decreased inner temperature. Castell et al. [28] experimentally proved that integrating PCM into brick walls results in a 15% reduction in energy consumption. However, in his study, Pirasaci [29] found that even though the PCM reduced the consumption of energy, using it is not suitable since it did not undergo any phase change. Many optimization studies were conducted for the PCM integrated into walls such as [30], [31], [32] and [33] where all found that the location of the PCM within the wall and its thickness, greatly affects the performance while Gao et al. [34] conducted a numerical study that was validated experimentally on the filling of PCM in brick walls and found that the best choice to fill in PCMs in the inner cavities of hollow bricks.

VI. Conclusions and perspectives

This review shows that smart materials such as PCM are advantageous in terms of thermal performance of building. They can effectively ensure thermal comfort and reduce energy consumption thanks to their excellent heat capacity that increases thermal inertia of buildings. The review reveals the lack of studies on PCM for the Algerian building. Therefore, studies should be carried out to determine suitable PCMs for various climate zones of Algeria enabling effective implementation of this new king of material in the Algerian building. For economic feasibility, a local industry and market of PCM should be promoted by the government to make PCM available at low cost. Knowing that organic PCM can be easily produced based on oil which is largely available in Algeria. Other bio-PCM can be extracted from plant, there is also a lack of studies on bio-PCM in Algeria. This industry and market would also have social impact mainly by supporting employment. Certification of PCM should also be considered to ensure effective and durable implementation. Finally, building reglementation should include this new class of materials in the Algerian building industry. This smart material can enhance thermal performance and save energy which will have positive impact on both environment and economy of the country.

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