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Introduction to the Application of Phase Change Materials under Tropical Climate of Panama

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***Abstract*—Phase change materials (PCM) are materials with the ability to store a large amount of energy (latent heat) during their change from solid to a liquid phase. This takes place at a certain melting temperature. Amid the global energy crisis, multiple applications of these materials have been studied at the theoretical, numerical and experimental approach, obtaining promising results in terms of an increase in the efficiency of these systems. However, the application of these materials is being studied since there are no rules or predictions of the feasibility of its application in diverse weather conditions. The tropical climate condition is one of the least studied in this context. In this work, a review of the main findings of recent studies conducted in tropical climate conditions is presented. Additionally, an analysis of the main challenges and opportunities of the application of PCM in the climate of Panama is performed. It was concluded that some applications in passive cooling and solar water heating systems might have the potential for their implementation. However, further studies are required to take into account other applications.**

***Keywords*—phase change materials, tropical climate, PCM applications**

I. INTRODUCTION

The world population and economic activities are constantly increasing. As a result, the demand for energy has increased proportionally [1]. The irresponsible use of natural resources has led to global warming (as a result of greenhouse gas emissions) and the subsequent climate change [2].

As potential solution to mitigate the effects of climate change, multiple technologies focused on energy storage have been proposed in response to the common dissimilarity between supply and demand of energy resources worldwide. A potential solution widely explored in recent years is the use of phase change materials (PCM) for latent heat storage, since they are capable of store a large amount of residual thermal energy in periods of low demand [3]. Besides, if compared to traditional materials, these systems can store this energy in relatively small volumes.

Essentially, PCM are functional materials that take advantage of their high density of thermal energy storage in a small temperature range [4]. They store latent heat while changing phase, from solid to liquid and from liquid to solid as the heat transfer occurs, between the PCM and its surroundings, as shown in Fig. 1. Traditional materials like rock, sand, gravel, water or masonry, among others, are also used for thermal energy storage applications. In those cases, the energy is store as sensible heat. However, PCM can operate at relatively stable temperatures and store between five and fourteen times the amount of thermal energy per unit volume equivalent to the sensible heat stored by materials other than PCM [5].

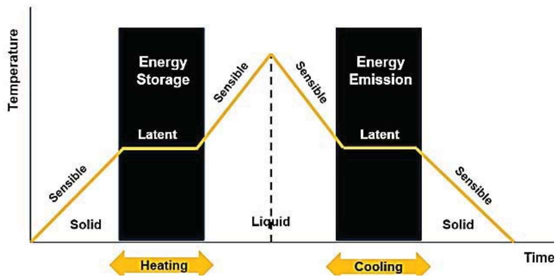

Fig.1 Schematic diagram of the phase transition of a PCM [2].

In recent years, the PCM application has grown rapidly in various industries, such as the space industry [6], the electronics industry [7], cooling systems and solar air conditioning [8], solar dryers for agricultural industry [9], photovoltaic systems [10], food preservation and pharmaceutical products [11], waste heat recovery systems and water heating systems for domestic use [12], [13]. PCM have been implemented in the buildings sector, especially in applications related to air conditioning [14].

However, there are still limitations in terms of weather conditions in the application of PCM in buildings and other fields [4]. Currently, there are no systematic rules or regulations regarding the application of PCM. However, little is known about the maximum potential expected when applying them in different regions. For example, the application of PCM in buildings in countries with tropical climate is still uncommon. This could represent a strategy to minimize the cooling load [15].

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The present article contains a literature review oriented to identify the most significant aspects regarding the use of phase change materials in the weather conditions of Panama. The possible challenges and opportunities of the application of PCM in humid tropical climate conditions were briefly addressed for energy consumption in buildings.

II. PCM: ENERGY STORAGE MATERIALS

A. *Classification of Phase Change Materials*

The phase change in PCM can be classified into four states: solid-solid, solid-liquid, gas-solid and gas-liquid [12]. Only the solid-liquid variety can be used for cooling or heating buildings since the other varieties have technical limitations for this purpose [16]. The solid-liquid phase change PCM usually used can be classified as organic, inorganic and eutectic, as shown in Fig. 2 [17].

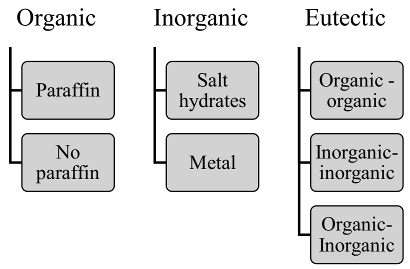

Fig. 2. Different types of phase change materials [17].

a) *Organic PCM:* Organic PCM have a series of characteristics that make them useful to store latent heat in various elements for construction [12]. They are more chemically stable than inorganic substances. These materials are non-corrosive, have a high latent heat storage capacity per unit weight. They are recyclable, melt congruently, have stable phase change temperatures without segregation phase and exhibit little or no subcooling. Oppositely, organic PCM have poor thermal conductivity and are usually flammable [17].

b) *Inorganic PCM:* Compared to organic PCM, inorganic PCM have an appropriate thermal conductivity, higher heat of fusion per unit mass with lower cost and flammability [17]. However, these can present a super cooling phase, segregation, lack of thermal stability, corrosion and decomposition [18]. This category includes salt hydrates, saline solutions, and metals. Salt hydrates are the best-known variety and numerous studies have implemented them [19].

c) *Eutectics:* The eutectic PCM consist of a combination of at least two PCM. During the freezing process, they form a crystal of the mixture that can consist of inorganic/inorganic, organic/inorganic and organic/organic PCM [17].

The eutectic PCM have the advantage of allowing the adjustment of their melting point by combining different percentages by weight of their components. This can be achieved without subcooling or phase segregation that is the development of concentration gradients inside the material due to solidification out of equilibrium. These materials can achieve high thermal conductivities and densities. However, they usually have low latent heats and specific heats [20].

B. *Criteria for Selection of Phase Change Materials*

From the economic point of view, the selection of a suitable PCM is essential to store and release a greater amount of thermal energy. The main parameters needed to select a PCM are the melting temperature and the latent heat capacity. When selecting these materials, their possible disadvantages must be taken into account according to the expected operating conditions [8].

TABLE I. CRITERIA FOR SELECTION OF PCM ACCORDING TO THEIR PROPERTIES [3].

Criteria for PCM Selection	***Chemical Properties***	Non-corrosive
		Non-Flammable
		Chemical Stability
		Non-toxic
	Thermal and Physical properties	High thermal conductivity
		High latent heat of fusion per unit volume
		High specific heat and high density
		Small changes in volume during phase change
	Kinetic properties	High nucleation ratio
		High crystal growth rate

Then, it is necessary to consider the rest of its thermal, physical, chemical and kinetic properties, which are presented in Table I. As of today, no PCM can fully satisfy all the properties required for optimal long-term performance [21]. Therefore, technical solutions have been suggested:

- To obtain PCM compounds that achieve the desired temperatures and latent heat storage of phase change [22].
- To maintain the shape of the PCM through a encapsulation that has a higher phase change temperature, non-corrosive, non-reactive with the PCM and inexpensive [23].
- To improve the thermal conductivity of most non-metallic PCM by adding high thermal conductivity materials [24].

Finally, many studies have pointed out that the selection of a PCM based on a specific phase change temperature in a climatic region is not necessarily appropriate for other regions. Some of the important factors that govern the selection of PCM for building applications include local climate, type of PCM, design, and orientation [25].

C. *Encapsulation Methods of Phase Change Materials*

The high PCM leakage potential during the change from the solid to liquid phase and the possibility of diffusion of low-density liquids throughout the material. This suggests the need for encapsulation for the efficient use of PCM [26].

In addition, the PCM encapsulation can increase thermal conductivity and improve heat transfer between the PCM and the surrounding environment [27]. In the same way, the encapsulation can diminish the effect of harmful environmental factors, avoid corrosion; as well as allowing the handling of volume variation during phase changes [28].

The encapsulations can be macro (> 1000 μm), micro (1-1000 μm) or nanometric (1-1000 nm). Smaller encapsulations greatly increase the relationship between surface area and material volume, which improves heat transfer significantly [29].

D. *Common applications of phase change materials*

In the literature, it is common to find multiple applications of PCM, which are mainly related to their fusion [30]. PCM with medium-low melting temperature (5 °C to 40 °C) are often used for passive heating and cooling applications for buildings, air conditioning systems, among others. In contrast, for solar water heating applications, PCM medium melting temperature (40 °C to 80 °C) are usually used [3].

Table II presents a review of studies focused on medium-low and medium melting temperature applications. In all the studies considered, the results support the technical viability of the PCM in each of their applications.

TABLE II. MAIN APPLICATIONS OF MEDIUM- LOW AND MEDIUM MELTING TEMPERATURE PCM

Melting temperature	Main applications	Location of the PCM	Reference studies
Medium- low	Air conditioning systems	Absorption chiller	Khan et al. [8]
		Return pipe	Chaiyat y Kiatsiriroat [31]
		Free cooling (mechanical natural ventilation)	Mettawee et al. [32]
	Passive cooling of buildings	Ceilings	Yoon et al. [33] Chung et al. [34]
		Windows	Durakovic et al. [35] Silva et al. [36]
		Block interior	Lee et al. [30]
		PCM plate on walls	Yao et al. [37] Kong et al. [38]
Medium	Solar thermal energy storage	Water storage tank	Álvarez- Padiñas et al. [13] Mousa et al. [39]
	Electronic devices	Heat sinks	Assi et al. [7]

III. APPLICATION OF PHASE CHANGE MATERIALS IN TROPICAL CLIMATE

Ideally, a PCM must undergo a complete phase change cycle once a day. However, the lack of guidelines for the PCM selection for diverse weather conditions is uncertain for applications in buildings [25]. There is still a need for a detailed description of the effect that could be expected for several PCM in various climates.

Particularly for tropical climate, the experimental studies and simulations available are still very limited [15]. Table III presents relevant information on projects carried out under tropical weather conditions. This compendium of research results emphasizes the strengths, weaknesses and some relevant observations about the study.

One of the main obstacles to the application of PCM in the tropical climate is the limited variation of the diurnal temperature. This implies a high probability of the incomplete cycle of fusion and freezing of the PCM, which compromises the heat absorption of the PCM in the next cycle. It has been shown that the variation in daytime environmental temperature must exceed 10 K to ensure the effective thermal storage of PCM as a passive cooling strategy [40]. It is usually difficult to reach in Panama.

IV. APPLICABILITY OF PHASE CHANGE MATERIALS IN PANAMA

Table III presents studies available for tropical climate. Panama's climate coincides with five of the subcategories proposed by Köppen for the tropical climate[41]. These researches were conducted in conditions of two of the main climates of Panama: Tropical Savannah (Aw) and humid tropical (Am). The results of these studies were promising for the implementation of PCM. This could help to identify possible challenges for large scale implementations of PCM.

A. *Temperature Considerations*

It is observed in Table III that the majority of the available research conducted in tropical climate were focused on passive cooling. Firstly, this application is considered.

Table IV presents a compendium of the daily average temperatures, obtained from ETESA [42], of some relevant locations in Panama. Potential PCM with melting temperatures that match the Panamanian climate conditions were analyzed based on their technical data and are suggested. It is also shown in this table, the possible temperature to reach when using these PCM as passive cooling strategy.

ClimSel C24 and hs24 are salt hydrates. The PCM called Eu1 and Eu2 in table IV, are eutectic PCM. Their chemical structures are $50\%\ CaCl_2 + 50\%\ MgCl_2 . 6H_2O$ and $66.6\ \%\ CaCl_2 .6H_2O + 33.3\%\ MgCl_2 . 6H_2O$, respectively.

About the suggested PCM, first of all, it was used the criteria $T_{max}>T_{melting}$, $T_{min}<T_{freezing}$ and $T_{freezing}>T_{av, env}>T_{melting}$,where $T_{av, env}$ is the average environmental temperature, in order to discard several PCM. This criterion was followed since it allows to discard all those PCM that would not complete a melting-solidification cycle, just by taking advantage of the daily temperatures as thermal source.

Then, it was calculated the difference between the average melting temperatures of the remaining PCM and the average environmental temperatures of every selected location. These values resulted on the possible maximum temperature decrease in a place using the respective PCM.

TABLE III. REVIEW OF STRENGTHS, WEAKNESSES, AND REMARKS OF THE APPLICATION OF PCM IN TROPICAL CLIMATE ACCORDING TO PREVIOUS STUDIES

Implementation of PCM in Tropical Climate					
Reference	***PCM***	***Location / Climate***	***Strengths***	***Weaknesses***	***Remarks***
Pasupathy et al. [43](2008)	Eutectic (salt hydrate and water)	Chennai, India / Tropical Savannah	A double layer of PCM on the roof of a test house caused an increase in the upper surface of the roof with PCM, which implied a lower air temperature in the enclosure.	When using a layer of PCM the increase of the temperature was variable and, in some cases, negligible for different months. A double layer of PCM was required.	It was concluded that it was not enough to use the melting temperature as a selection parameter. It was suggested to carry out design simulations with PCM that contemplate this climate, design, and orientation of the structure.
Guichard et al. [44](2015)	Paraffin Wax (DupontTM Energain)	Reunion Island / Tropical Humid	A simulation was made comparing a house with a traditional roof, and a house with a roof that included PCM. The results showed that the indoor air temperature was lower in the house including PCM. The maximum difference was 2.4 °C when comparing with no use of PCM. In addition, the use of PCM delayed the temperature increase.	A difference of ± 1.1 °C was achieved between theoretical and experimental results. The validation criteria were not favorable. The sensitivity analysis showed that the coefficients of heat transfer by convection should be corrected.	The experimental tests were performed under room temperature conditions between 19 °C and 26 °C and humidity between 40% and 84%.
Chaiyat y Kiatsiriroat [31] (2015)	Paraffin Wax	Chiang Mai, Thailand / Tropical Savannah	PCM spheres were placed in the return duct of an air conditioning system. This increased the efficiency of the system and reduced the refrigeration load.	No effect of other parameters other than temperatures were evaluated. Temperatures were higher than 25 °C during the day and between 25 °C and 30 °C at night.	It was included an economic analysis which reflected an electricity saving cost of 9.10% comparing this system with the conventional one. The amortization period was estimated at 4.15 years taking into account the cost of the PCM.
Sanjani et al. [45] (2015)	Paraffin Wax	Kuala Lumpur, Malaysia / Tropical Humid	Theoretically, a higher thermal efficiency was obtained from a solar water heater system with the inclusion of PCM in certain conditions, which depends on the climatic conditions and the flow rates. The system was more effective on cloudy and rainy days.	No specific information was provided about the weather conditions in which these tests were carried out. It was presented in terms of sunny, cloudy and rainy weather.	The effect of changing the supply water flow on the temperature was lower for the PCM system than for the conventional system.
Lei et al. [40](2016)	Derivatives of paraffin (n-Octadecane)	Chennai, India / Tropical Savannah	The cooling load of a building was reduced by using a 10 mm PCM layer on the walls. Thus temperatures between 21 ° C and 32 °C were observed throughout the year.	The heat gain was reduced by increasing the amount of PCM. However, the efficiency and cost-benefit of PCM also decreased with increasing thickness.	It was pointed out that, unlike other climates, in the tropical climate, it is possible to take advantage of the PCM throughout the year. In other regions, they are only effective in certain seasons.
Thantong y Chantowong [46](2017)	Paraffin Wax	Bangkok, Thailand / Tropical Savannah	The behavior of a solar wall system with PCM for water heating and thermal load control was studied. It reduced the thermal load of the tested house by 61.76%.	The velocity of the air in the solar wall was measured, but not significant contribution as identified in the results.	The environmental temperatures of the tested site varied between 21 °C and 38 °C during the day. The temperature of the hot water varied between 25 °C and 51.8 °C.
Wonorahardjo et al. [47] (2018)	Coconut Oil	Bandung, Indonesia / Tropical Humid	Coconut oil was promising for control of internal air temperature above 20 °C.	The selection of the volume of the encapsulation for this PCM was fundamental, given its low thermal conductivity. The selection was empirical.	The experimental tests were carried out with a heat exchanger with direct contact with ambient air. Diameters of 8 cm, 12 cm and 16 cm were tested.
Memom y Bigamangetova [48] (2019)	Paraffin Wax (DupontTM Energain)	Bangalore y Kolkata (India) / Tropical Savannah	The PCM plates on the walls caused an energy reduction of 31% in Bangalore and 16% in Kolkata.	The results were different between Bangalore and Kolkata. This can suggest that the location of the site and the weather conditions of the site directly affected the results.	The outer layer of PCM showed better control of the interior temperature during sunny days when there was a significant difference between daytime and nighttime temperatures.

The possible reached temperatures obtained do not agree with the comfort temperature of 24 °C suggested by the Air Conditioning and Ventilation Regulation of Panama [49]. However, the cooling load could decrease considerably, considering these values, implying the possibility of the use of PCM as an auxiliary source of cold.

In Table III, another application considered in tropical climate was the storage of solar thermal energy through hot water storage tanks with PCM. Therefore, it is important to consider the research works presented by Sanjani et al. [45] and Thantong y Chantowong [46], which focused on it. Both investigations report a better functioning of this type of system using PCM. Perhaps it is because in this application it is easier to meet the requirement of temperature variation during the period of operation [40].

TABLE IV. SUGGESTED PCM AND POSSIBLE REACHED TEMPERATURE IN SOME LOCATIONS IN PANAMA WHEN APPLYING PCM AS A PASSIVE COOLING OPTION

Location	Climate	$T_{av,env.}$ (°C)	Suggested PCM and possible reached temperature (°C)			
			Clim Sel C24 [50]	*hs24 [51]*	*Eu1 [52]*	*Eu2 [52]*
David	Am	28,4	25.5	24.5	25	25
Los Santos	Aw	29,3	25.5	24.5	25	25
Tocumen	Aw	28,3	25.5	24.5	25	25

B. Humidity and Corrosion Considerations

Table III shows that most of the studies available for tropical climate have not considered humidity as a parameter of relevance. All them agree to consider the temperatures variations. It was observed that paraffin wax and coconut oil were used in most cases. This can be associate to the non-corrosive properties of these PCM. Salt hydrate was only used for an application in the Tropical Savanna climate [43]. It could imply that despite having a good potential for passive cooling in terms of temperature, ClimSel C24 and hs24 (salt hydrates) could have technical problems in humid tropical climate of David (see Table IV).

On the other hand, the low conductivity of paraffin wax can regularly be improved with metallic particles. It is necessary to evaluate the benefits of increasing the thermal conductivity concerning the corrosive effects and how to minimize them, depending on the application.

V. CONCLUSIONS

A review of the characteristics of different types of PCM, selection criteria and multiple applications has been carried out. The analysis of previous studies in tropical climate conditions was emphasized to contemplate the implementation of PCM in the climate of Panama. However, these investigations are limited, and concerning Panama, there is no previous research. Despite the positive results of these works, some weaknesses were identified and also, the climates of their locations are not equal to the Panamanian climate. It is necessary to conduct specific researches in Panama to identify if these results can be extrapolated.

From the applications found in the literature for the tropical climate, our analysis focused on the passive cooling and the storage of solar thermal energy to heat for water heating with PCM. For passive cooling, our preliminary results show that PCM could significantly reduce the cooling load. On solar thermal energy storage, the literature reports on a better functioning of this type of system using PCM. Experimental tests and more rigorous studies (numerical and experimental analysis) should be considered to corroborate the technical applicability of PCM in the Panamanian climate. It was not possible to make predictions of the possible effects of moisture and the incidence of corrosion on the long-term operation of these systems, since the available information is limited.

Our preliminary studies did not reflect any organic PCM as a good option for passive cooling, despite being the most used in previous research in the tropical climate. Future research work should consider more types of organic PCM and an extensive meteorological data to test their potential. Their use could have positive impact in tropical territories, since they present attractive properties when considering corrosive environments.

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