

Review

Phase Change Materials for Building Applications: A Thorough Review and New Perspectives

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Abstract: The purpose of this paper is to provide a comprehensive report on the state of the art on the technologies used in the modeling of energy storage systems by latent heat in buildings, and draw lines on perspectives on the technology evolution in this sector. In the first part, the emphasis is put mainly on the two main lines of research: experimental and numerical. In the second part, the main trends of research in this sector have been followed. An anatomical operation of more than 100 documents (published between 2006 and 2016), on the behavior of storage systems integrating Phase Change Materials (PCM), covering a large number of configurations treatment and their applications in thermal comfort of buildings area, has shown that the information published in this topic are very diverse and enormous, but in many cases are insufficient. The results show that, with suitable design, the PCM can contribute to the reduction of costs and achieve energy reductions in buildings, guaranteeing a comfortable interior environment. The evaluation of this multitude of documents gave the following remark: The effectiveness of any proposed approach to a numerical study is a concept with ambiguities, depending upon the method used, its precision, the problem to be modeled, the convergence criteria and the input parameters choice. The diversity of experimental conditions and the variety of results revealed that the published works are not directly comparable.

Keywords: latent heat storage with PCM; energy storage modeling; simulation tools for integration of PCMs in buildings; thermal storage review; application of PCM in buildings

1. Introduction

Energy consumption is a challenge in many usages. That is why there is a great trend in research, nowadays, to the possibility of finding means and solutions for energy savings and reductions in greenhouse gas emissions (GES) [1]. In this context, finding new outlets to exploit, store and reuse renewable energies becomes an urgent necessity, first for reducing energy consumption and secondly, for improving indoor thermal comfort.

One of the approaches to fulfilling this objective is the use of high latent melting heat change materials (PCM) to increase the thermal mass of buildings and to store energy from solar radiation as latent heat [2]. These materials have received an increased attention due to their ability to store large amounts of thermal energy within narrow temperature ranges. This property makes them ideal for storage of passive heat in building envelopes [3].

Indeed, when incorporated into building lightweight envelopes, PCMs can increase thermal inertia of these envelopes and therefore, provide a natural regulation of internal temperature, which leads to a reduction in indoor temperature fluctuations, an increase in energy efficiency and, consequently, an improvement of thermal comfort for occupants. The bases of working of these

systems are generally built on the storage of the heat of phase change at quasi-constant temperature, while these materials change phase (as shown in Figure 1).

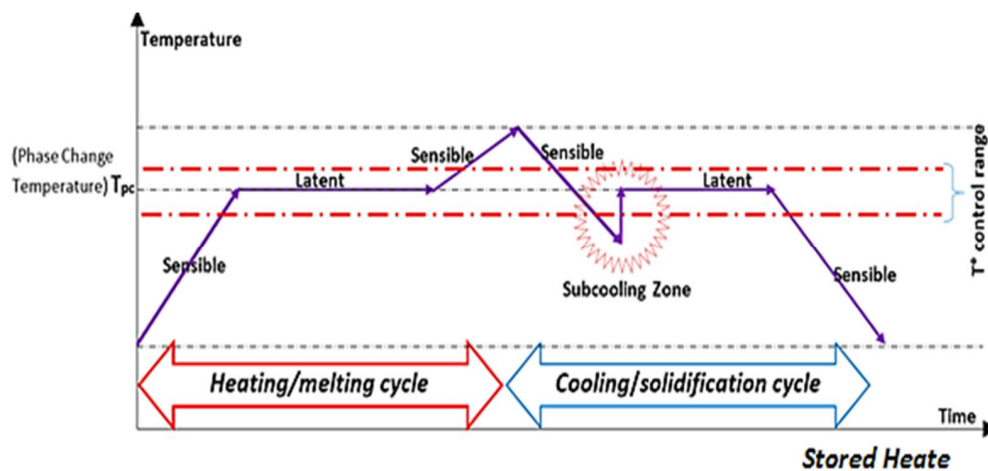


Figure 1. Diagram of temperature change through heating and cooling of a Phase Change Material (PCM) (general case).

For applications in buildings at low temperatures (0 °C to 100 °C), only phase changes solid/liquid and solid/solid are attractive for use in thermal energy storage systems, since, they imply only a small change in volume during phase transition (less than 10%) [3].

This research provides a global reading of the publications on systems that deal with the behavior of PCM in building envelopes, and highlights some limitations of these systems and related research topics.

2. Latent Thermal Energy Storage Systems: Key Elements

2.1. Thermal Comfort: Regulations and International Standards

A sustainable building envelope design should not only consider energy saving issues—as claimed by several regulations and International Standards/programs [4–6]—but have to be consistent with high thermal comfort levels. In this context PCM materials play a crucial role, being effective for stabilizing indoor temperature fluctuations. Several parameters can affect this complex equilibrium in which the man is at the center:

- The design,
- The conditioning of the building space,
- The ambient relative humidity,
- The speed of the air,
- The overall energy performance of the building,

Nevertheless, the constraint is that we must find a compromise between the reduction of energy consumption and the optimization of all these conditions [4]. This operation requires several actions: the energy audit to describe and analyze the energy consumption, a selection of insulating building materials, the installation of a ventilation system, etc.

In this context, the use of renewable energy sources according to the standards required by international laws and research programs, such as the European Horizon 2020 and the environmental standards of ASHRAE [5,6], becomes an optimal outcome to address these issues.

For a concrete case, and thanks to the efforts of some countries, the global level of exploitation of renewable energy reaches a rate of 6.2%, for example, Italy reached 7.9% of solar energy in the

exploitation of its energy and 7% in Germany [6]. In general, 164 countries have renewable energy targets and 145 countries have put in place mechanisms and strategies to support renewable energies [6].

2.2. Thermal Energy Storage Systems by Latent Heat

The objective of Thermal Energy Storage Systems (TESS-PCM) is to detach energy production from the energy resource, so its choice for a given application depends on several parameters, including storage time, cost, temperature, storage power and heat loss.

These systems, as reported in the literature, have become key elements of the future energy smart grid. The ability of these materials to reduce peak loads is much documented [7,8]; several researchers have indicated that insulation strengthened by PCM can reduce up to 40% of the cooling loads generated by walls during peak hours [9].

Several TESS-PCM types have been developed in recent decades and numerous storage technology proposals have been made to facilitate the use of thermal energy at different scales [10,11]. These innovative systems offer a particularly interesting outcome in the contribution to the GES reduction solution used in current systems. Likewise, to the reduction of the frequency of internal temperature variations of the air and maintaining the ambient temperature near the temperature of the comfort for a sufficient period, by storing large quantities of thermal energy in the buildings envelope [12].

The realization of a TESS-PCM model goes through several steps:

- The model design,
- Realization of the simulation system,
- Analysis of the simulation results, in particular: the storage capacity, the efficiency of the charge/release and the heat transfer,
- Make changes to the edges,
- Modeling of the alternative aspect of the system,
- Comparison of the preliminary design with the modified one,
- Implementation of a proposal on the TESS-PCM configuration for a future test.

Nevertheless, improving the thermal inertia of buildings using TESS-PCMs depends on a number of parameters, such as climate, orientation, design, building geometry and compactness, properties of PCMs used, glazing performance, etc. [13,14], which makes the use of these systems more complex. In order to overcome this problem and find a compromise between the optimal properties of PCM and ideal building characteristics, the modeling and the simulation of effects and thermal behavior of PCMs prove essential.

With the computer technology progression, many computer simulations have been achieved to study the impact of these materials in real buildings. These techniques provide fast and inexpensive processes [15], though they are paradigmatically complex. This complexity ascends, on the one hand, from the treatment of nonlinear phenomena, which simultaneously changes in time and space, and, on the other hand, from the large number of parameters involved in the studies of these systems, which imposes several restrictions on the conditions of these studies, either in transient regime or in two-dimensional problems [16].

2.3. Around the Walls of Buildings

TESS-PCM is an economical and promising solution for the environment; it finds a wider use in improving the energy efficiency of buildings:

- Insulation supplement for the improvement of the inertia of buildings walls,
- Thermal management systems: Passive conditioning, solar power stations, etc.,
- Textile and clothing sector,
- Automotive engine cooling,

- Thermal protection of electronic components and circuits: Electronic chips to avoid act at extreme temperatures.

Agri-food and healthcare industry: Transportation and storage of perishable food, medicines and pharmaceuticals. Building envelopes are not only structures, but they also provide protection against external weather conditions while taking into account local climatic requirements. For that, the building envelope is one of the most studied elements of research and regulation, due to its relatively more effective heat exchange area and more convenient implementation, also, it offers a huge opportunity for reduction in energy consumption (see Figure 2) and demand, it permits the energy costs control and optimization of energy efficiency, environmental and economic impact. The methods of integrating PCM into envelopes, identified in the literature, are the direct method “immersion” and indirect method “attachment” [17] (as represented in Figure 3).

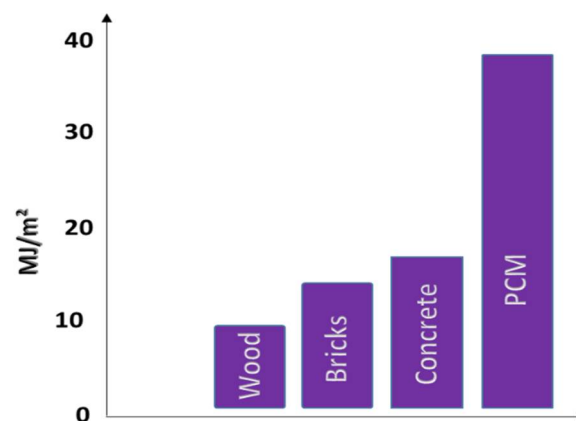


Figure 2. The energy storage density (for a material heating from 20 °C to 26 °C).

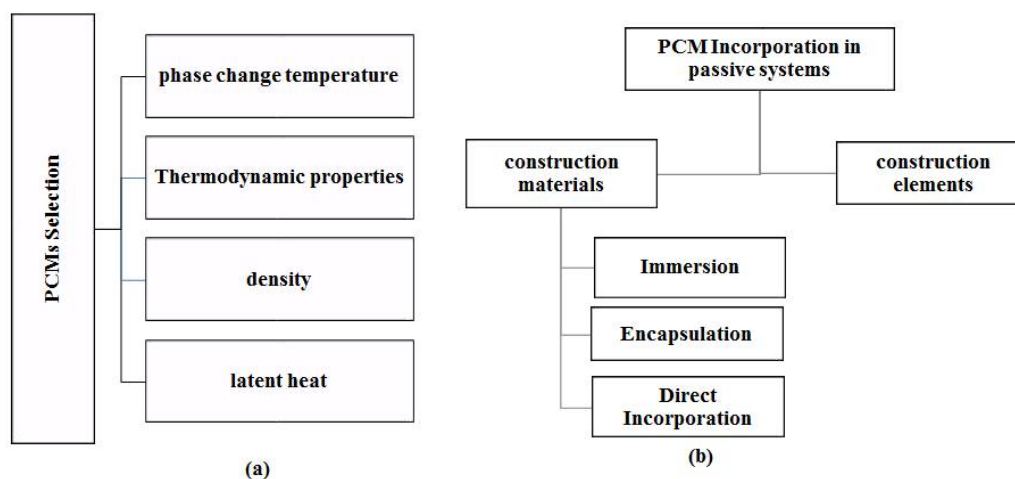


Figure 3. Researches in PCM process: (a) study in materials properties, (b) Methods of integrating of PCM into building envelopes. Adopted from [18].

Much work has been developed in recent years on insulation [19,20], and thermal inertia [21–23]. A number of researchers have proposed the inclusion of PCM to replace the masonry walls in passive walls [24,25], the active walls [26] and hybrid [27,28] with the aim of constituting optimal visions on improving the energy and thermal performance of buildings. These performances depend mainly on the different target applications, using specific dispositions and specificities.

Many studies are carried out, but it is still possible to improve the design of the envelopes, since they are real active solar systems, coupling the techniques of solar capture to latent heat storage.

However, despite the multitude of these studies, it is still possible to improve the design of envelopes, since they are real active solar systems, coupling the techniques of solar capture with the latent heat storage.

However, the envelope insulation is not an exclusive way to improve energy efficiency. The optimization of energy system performance, the improvement of heating, domestic hot water (DSC), ventilation, lighting and auxiliary systems (items considered by the maximum conventional consumption of primary energy: CepMax in RT2012) represent a strong lever in the reduction of energy consumption and CO₂ emissions [29]. In this context, a number of solutions are designed simultaneously with the development of the building envelope inertia to extend the performance of set-up equipment and energy systems [30–33].

3. Contribution of PCM to Energy Storage in Buildings

In order to provide a knowledge base and illustrate the design and performance factors, a full review of available technologies in the latent heat storage of building elements has become necessary. Thus, a wide variety of relevant literature published on this subject has been critically examined and an information extraction approach has been carried out to adjust, analyze and realize a method for the optimal design of PCM parameters, and to estimate the other parameters' potential such as boundary conditions, geometric forms and input parameters.

Generally, a description of the works achieved on modeling of three heat transfer modes modeling, management of boundary conditions and transitional thermal analysis, gives a clear vision on the thermal domain. The results confirm that the temperature peaks in a local equipped with PCM insulation could be reduced up to 5 °C (various studies achieved proclaim temperature reductions between 3 and 5 °C), and the electricity consumption linked to air-cooling system could decrease by 30% [34]. The possibility of storing energy also avoids using heavy materials, such as concrete and creates a high inertia, which can lead to overheating during weighty internal loads [35].

In this research, three main axes are explored (as represented in Figure 4):

- Materials Studies: Features and reactions:
 - ✓ Thermal transfer optimization by development of new PCMs,
 - ✓ Studies of thermal transfer mechanisms within composite materials (construction materials and PCM),
 - ✓ Analysis of the properties and the state of PCM (the number of melting/solidification cycles that they can undergo without degrading, a good definition of fusion/liqefaction range, potential harmfulness, etc.),
- Transfer systems studies: Design, dimensioning, optimization, etc.,
- Buildings Study: Consumption, comfort, simulation,

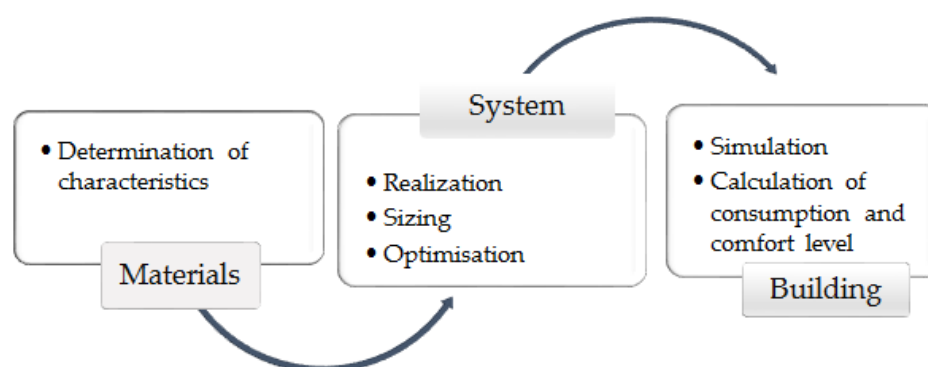


Figure 4. Research axes in the energy storage area of buildings.

The use of solar radiation is an alternative; one can characterize several ways of exploiting it:

- For the production of heat, from raw radiation (principle of the Trombe wall or the solar thermal panel) or concentrated (concentrated solar power plants),
- For direct production of electricity from radiation (photovoltaic solar panel) or concentrated photovoltaic (CPV system).

4. Statistical Analysis

In an increasingly constrained energy context, the building sector is required to play a considerable role in limiting energy consumption. For this vision, the latent heat energy storage has been widely studied in the literature by different methods: Experimental, numerical and theoretical, and between these aspects: hybrid modeling (or gray model).

Generally, analytical and numerical solutions are realized from theoretical models and compared with experimental measurements, in order to extract useful parameters for operation of the study model. Several methods have been developed for a long time for modeling and treating the problem of heat transfer through the walls.

Engaging in the quantitative analysis of textual documents is a relevant choice if there is a guarantee of obtaining results even if they are not exhaustive and definitive. The method used here is based on a statistical study of a stack of 100 papers produced during the period 2006–2016.

Among the resolution methods of heat transfer problem, the enthalpy method ranks first, while the second order is occupied by the apparent heat capacity method [36]. For Numerical approaches, the finite elements method is considered as the first tool used in research [37] followed by the differences finite method (see Section 6).

Concerning materials used in research studies, they are given generally by use priority: Paraffin family organic Compounds, hydrates and eutectic components [38]. Each of these MCPs has its own properties, which can be improved by different configurations by adding onto these characteristics such integration of metal strands to increase its thermal conductivity; the addition of a nucleating agent can eliminate the super-cooling and the use of a suitable PCM thickness can prevent the incongruous fusion. Figure 5 shows a classification of these materials. The distribution of material families, inventoried through their usage in the literature, is presented in Figure 6.

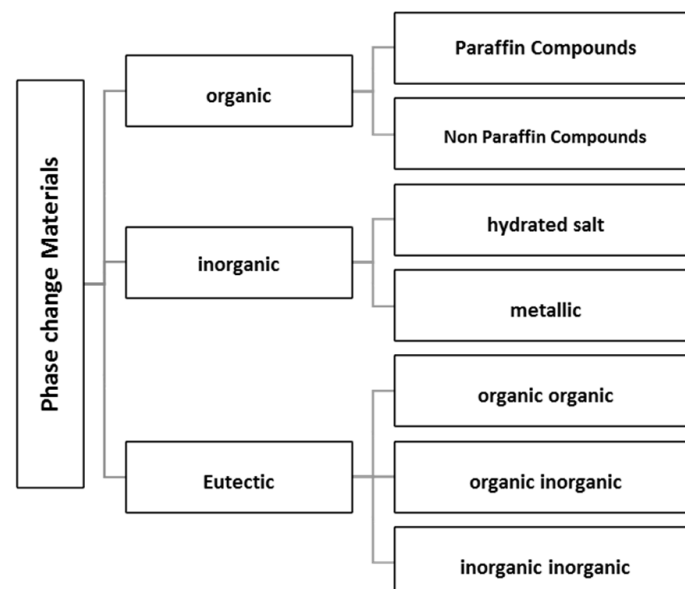


Figure 5. Diagram of PCM classification [17].

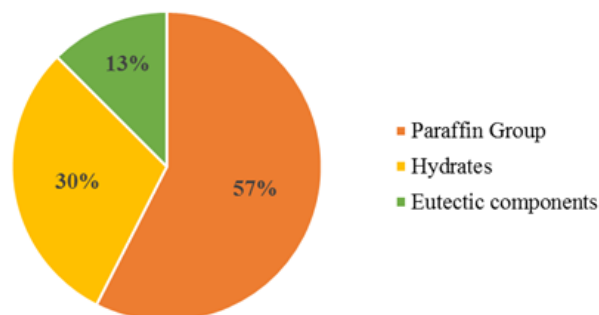


Figure 6. Distribution of families of materials inventoried in the studied literature through their usage.

4.1. Researches by Subjects Dealing with PCM in the Building Sector

The majority of energy consumption in the construction field is used as a resource of active systems for the cooling and heating of indoor spaces. The research themes existing in literature cover all phase-change thermal application parts, therefore, it is not easy to have a clear picture of the information updated, because some new outcomes may gainsay the ancient results [39]. Nevertheless, we can present an overall view on the subjects dealing with PCM in the building sector in the table below (Table 1) and in the graphic (see Figure 7)

Table 1. Subjects dealing with PCM in the building sector.

Group	Percentage	Subject
A	17%	Development of new PCMs
B	21%	Treatment of existing PCMs by studying their thermophysical and structural properties and their temperature range of phase transition
C	13%	Processing of specific applications and potential technologies using PCMs
D	35%	Measurement techniques Study in order to define the thermal properties of Existing PCM
E	14%	Incorporation of phase change materials into building elements

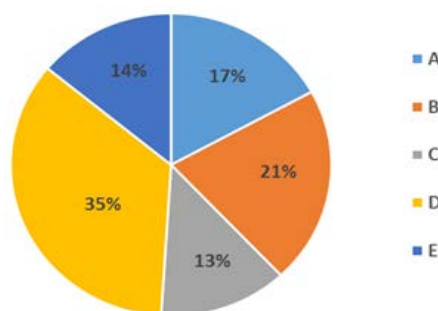


Figure 7. Topics dealing with PCM use in buildings.

4.2. Methods of Solving Thermal Differential Equations

Mathematical language is necessary to describe physics laws. These laws are, generally, translated by Partial Differential Equations, which are usually time and space dependent on independent variables x , y , z and t . These methods can be classified into four main groups:

- Analytical methods,
- Semi-analytical methods,
- Numerical Methods,
- Hybrid methods (Analytical/Numerical).

In general, the Fields studied with these equations are:

- Temperature variation as a function of time,
- Temperature variation as a function of thickness,
- Evolution of the solidification process,
- Evolution of enthalpies.

In the thermal domain, we can find several techniques of treatment, measurement and determination of phase change problems solutions, among them numerical, experimental, analytical and hybrid methods. In this sample, it is noted that the first and the second are the main methods used in the papers examined (see Figure 8) [40].

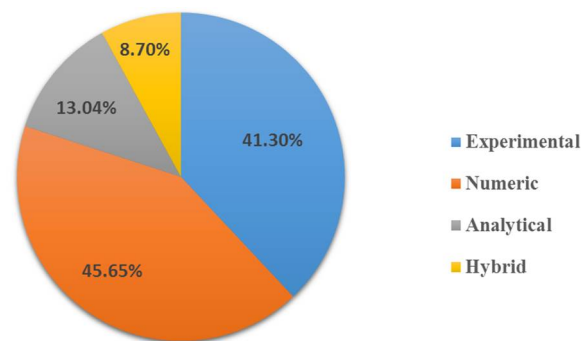


Figure 8. Types of study methods used in the sample.

5. Experimental Study

The experimental studies of storage and retrieval dynamics, which have been conducted, are intended to permit the observation of thermal and mechanical behavior of materials in their different states and the incorporation effect of these materials on improving the energy efficiency of buildings. The research has been carried out in two structures: conventional structures and improved structures [41].

In experimental studies, we generally work with thermal measurement methods which are schematically represented in Figure 9, such as Differential Scanning Calorimetry (DSC), Hot plate method, Graph method, Hot wire method, Thermocouple method, Flash Method, T-history method, and Method of variation of thermal sensitivity of luminescent substances (Thureau Method) [42].

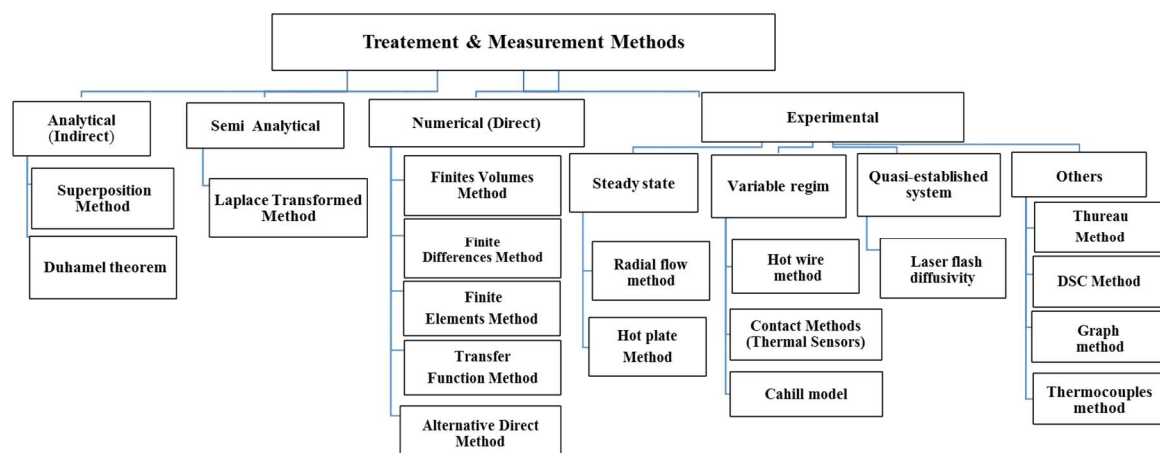


Figure 9. Different techniques of treatment, measurement and calculation in the thermal domain. Adapted from [43].

It is found that the Differential Scanning Calorimetry (DSC) method appears to be the prevailing method in use by researchers. About a third of researchers use it, thanks to its versatility and its instructive power; it is used in several domains, from pharmaceuticals and polymers to Nanomaterials and food products [44].

Moreover, there is group of methods that measure the evolution depending on temperature, time and physical atmosphere or chemical material properties, when the material is subjected to continuous temperature programming (TGA: Thermo-Gravimetric Analysis, DTA: Differential Thermal Analysis, TMA: Thermo-Mechanical Analysis, EGA: Evolved Gas Analysis, DSC: Differential Scanning Calorimetry). This series of thermal measurement methods is presented in Figures 10 and 11.

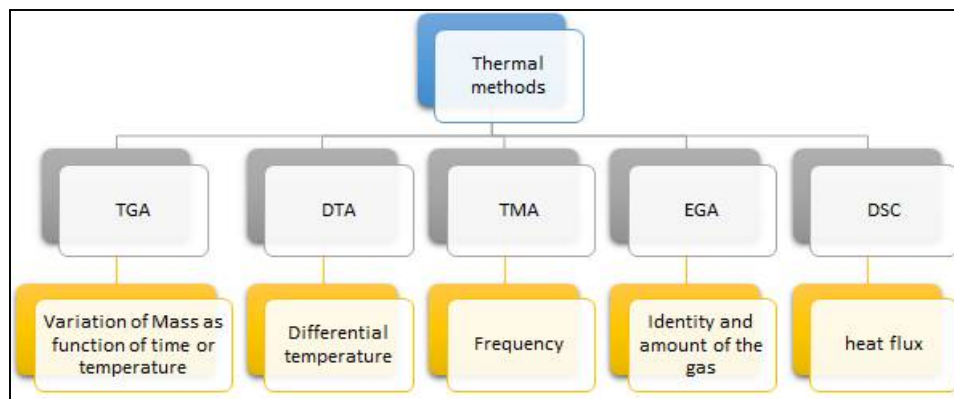


Figure 10. Experimental measurement methods (thermal analysis).

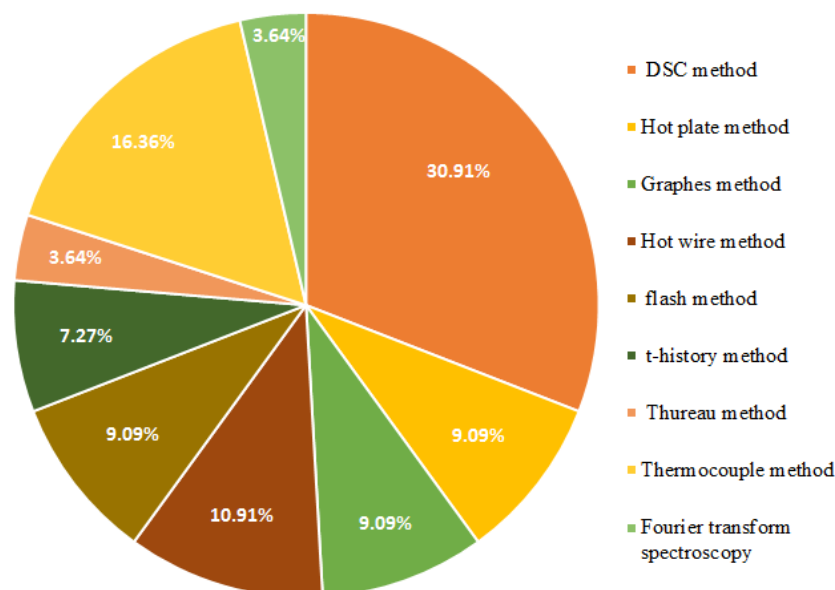


Figure 11. Distribution of Experimental treatment through Type used in examined literature papers.

6. Analytical and Numerical Approaches

The analytical approach is done by solving mathematical formulations, reduced by valid assumptions, for very simple case of 1D geometries, whose boundary conditions are very special, without being generalized to cover the actual treatment. It is achieved by reducing the difficulty of the problem by a simple description of the system, which enables faster processing speed. Its importance appears in the phase change resolution for the one-dimensional problem and simple geometries (cylindrical, spherical or plane), which requires powerful numerical techniques to study.

Models are a powerful tool to predict the behavior of thermal systems from a detailed description and to optimize their design by solving the mathematical formulations that describe the phenomenon to be modeled. Its advantage is the possibility of applying all the possible conditions on a virtual system in order to analyze the behaviors, which will allow designing the necessary changes to optimize the final product.

All numerical methods are based on the techniques of discretization of mathematical equations dominating the physical phenomenon. Three main methods are identified in this area; statistical study has raised their percentages of use in research, as represented in Figure 12 below.

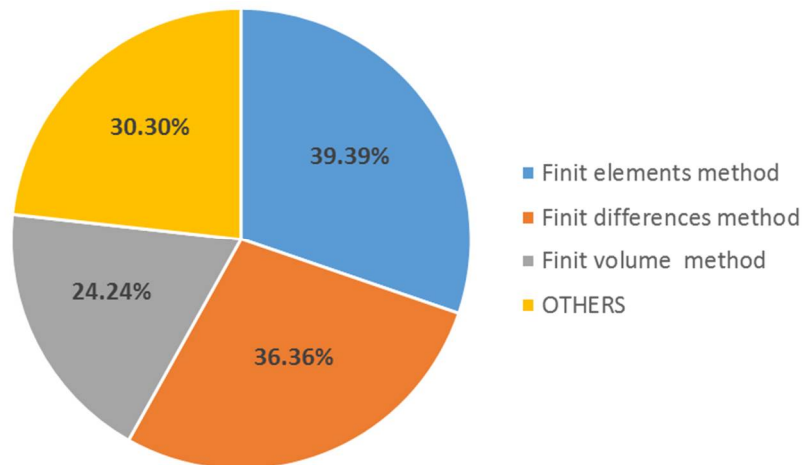


Figure 12. Different numerical methods in the thermal domain.

Another classification of the phase change resolution strategies is based on other treatment techniques, such as apparent thermal capacity, enthalpy method, discontinuous integration method and method of change of the independent variable. For this distribution, the frequently used process is the enthalpy method based on the following implicit equations:

$$\rho \cdot \frac{\partial H}{\partial t} = \nabla [\lambda (\nabla T)] + S_{\text{sens}} \quad (1)$$

where H is the enthalpy, ρ is density and S_{sens} notes sensible heat.

Equation (1) can be formulated in the following form:

$$C_p \frac{\partial T}{\partial t} + C_p \nabla T = \nabla \left[\frac{\lambda}{\rho} (\nabla T) \right] - L \left(\frac{\partial f}{\partial t} + \nabla f \right) + S_{\text{sens}} \quad (2)$$

where

$$f = \begin{cases} 1 & T < T_s \\ \frac{T - T_s}{T_l - T_s} & T_s < T < T_l \\ 0 & T > T_l \end{cases} \quad (3)$$

where H is the enthalpy, ∇ is the thermal conductivity, T_s is the solid and T_l the liquid temperature. Although the solution of this equation requires a convergence criterion of the scheme and a knowledge of the enthalpy temperature functional dependency, the enthalpy method is more suitable than the apparent thermal capacity method (Figure 13), since the modeling of the latter, in a temperature range containing that of the phase change, is very delicate.

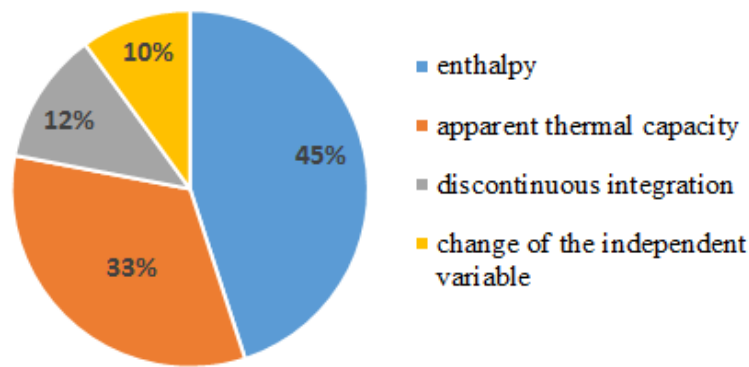


Figure 13. Different methods used in the thermal domain.

For analysis of randomly PCM systems the differential energy equation in rectangular coordinates (x , y and z) is represented as:

$$\frac{\partial}{\partial x} \left(\lambda \cdot \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \cdot \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \cdot \frac{\partial T}{\partial z} \right) = \rho \frac{\partial h}{\partial t} = \rho \frac{\partial}{\partial t} \int C_p dT \quad (4)$$

And the boundaries conditions are given by:

$$\begin{cases} (\forall y \in \Gamma_{PCM}); \phi(0, y, z, t) = -\lambda \cdot \frac{\partial(T_{PCM}(x, y, z, t))}{\partial t} \Big|_{x=0} = h_1 \cdot (T(0, y, z, t) - T_{out}(t)) \\ (\forall y \in \Gamma_b); \phi(0, y, z, t) = -\lambda \cdot \frac{\partial(T_b(x, y, z, t))}{\partial t} \Big|_{x=L} = h_2 \cdot (T(L, y, z, t) - T_{int}(t)) \end{cases} \quad (5)$$

With: b is the subscript relating to the concrete, Γ_{PCM} the side of the studied system containing PCM, Γ_b the side of the studied system containing the concrete, ϕ is the temperature flux and h_1 and h_2 are respectively convection coefficients of two sides. Indeed, the value of the thermal capacity has a divergence aptitude in the phase transition zone, when the latent heat is high and the temperature interval $[T_s, T_l]$ is narrow [42].

Furthermore, this kind of study can be broadly categorized [44] as follows:

- Unidirectional heat equation in a single wall,
- Two dimensional heat equation in a single wall,
- Unidirectional heat equation in the wall, energy balance in a room,
- Two or three dimensional heat equation in the wall, energy balance in a room.

7. Simulation Tools for Integration of PCMs in Buildings

This section presents a global review of the literature on available commercial tools that can be used to simulate the behavior of integrated PCMs in concrete, in conventional bricks and in alveolar bricks form building envelopes, in order to determine their pros and cons.

It is impossible to use prototypes in the thermal of buildings to test new results. Each building is specific in its design, construction and equipment. In this context, the simulation has become a quite unavoidable decision support tool in the construction sector, since it is used to model the buildings energy performance, improve the thermal comfort of residents, reliably estimate the forecast consumption of the building in operation over its full life cycle and optimize construction and operation charges.

The majority of these tools was developed initially to estimate the heating and cooling requirements of a building, based on the characteristics of its envelope. For this purpose, they assess the energy requirements and the level of buildings thermal comfort more precisely than the simplified methods based on monthly or yearly balances.

Examples of such softwares proposed to the building actors, DOE 2 (2.3, James J Hirsch & Associates, Santa Rosa Valley, CA, USA), ENERGY PLUS (8.8.0, University of Illinois, Chicago, IL, USA), ESP-r (University of Strathclyde, Glasgow, Scotland, UK), SIMBAD (1, CSTB, Marne-la-Vallée, FRANCE), TRNSYS (18, Solar energy laboratory (SEL), Madison University, Madison, WI, USA), PLAIED-COMFIE (4, IZUBA ÉNERGIES, Fabrègues, France) and CoDyBa (KoZiBu, JNLOG, Lyon, France) [45,46].

To meet the requirements of the use of the existing tools in the research area and the commercial domain, and to study the performance and precision of the proposed tools, numerous studies have been carried out on the analysis of the sensitivity of these tools by varying several parameters. However, it would be interesting to compare different software on the same building with the same conditions [47].

The purpose of thermal simulation software is to reduce the number of prototypes and experiments that must be performed when designing and optimizing the thermal process. Therefore, these tools contribute to a fast understanding of the phenomena involved, which motivated the new conceptions [48]. Most of these software packages consist of a processing and calculation engine, which allows detailed thermal simulations based on input and output files established by simple texts. These engines contain mathematical algorithms that are used to determine the energy performance according to the motor model [49].

The reading of the existing bibliography on simulation tools shows that there is a wide range of tools for simulation and modeling phenomena of the energy storage in buildings' components. The continuous evolution of these tools, over time; has allowed them to enrich themselves, to the detriment of a complexity for apprehending the physical reality: from 1D to 3D, larger and larger systems, laws of increasingly complex behavior, from the linear to the non-linear, and so on. However, through this study, it was found that the simulation results depend upon a very large number of own modeling sensitive parameters to the given values that are often specified by default and may be inappropriate.

Even experts do not have a good understanding of the relevant values of these parameters, their impact on the modeling of the thermal phenomenon or access to adjust their values according to the cases studied. These tools can be categorized, in terms of access and exploitation, in commercial software and free software [50].

Concerning commercial software such as TRNSYS and COMSOL Multiphysics, they are very popular in the heat transfer applications. They can solve problems by coupling them with other solvers or numerical simulation software such as ANSYS FLUENT™ (14, ANSYS, Canonsburg, PA, USA), which is considered a platform for the study of fluids, fusion, combustion, multiphase and convection. These tools are also restricted by universities authorizations or industrial purchases and by the complexity of their implementation. Moreover, they do not treat the effect of PCM integration in buildings. These limitations apply to almost every available tool of this kind today. As for free software, it is used in consulting, research and teaching contexts. EnergyPlus and ESP-r are references in the domain [51].

Software such as Softwares PLEIADES+COMFIE (4, IZUBA ÉNERGIES, Fabrègues, France), Simulink (9.1, The MathWorks, Natick, MA, USA), DYMOLA (2018 FD01, Terasoft, CA, USA), SPARK (2.01, Lawrence Berkeley National Laboratory, California, USA) and DesignBuilder (5.0.1.024, DesignBuilder, Vincennes, Ile de France, France) come in the second place. These types of tools are considered to be building modelers with powerful functions for estimating construction, energy, and life cycle costs. These tools include optimization modules that determine building parameters to make a compromise among cost, comfort, GES [52,53]. The distribution of the simulation tools by their usage is presented in Figure 14.

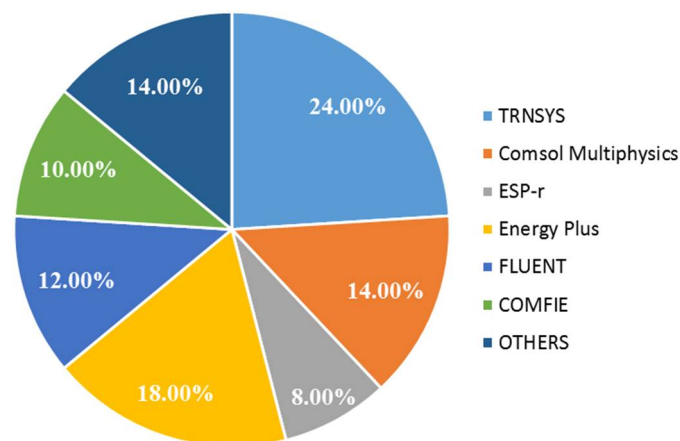


Figure 14. Analysis and simulation tools per their usage in the analyzed research papers.

The manner of simulating each type of system and parameterizing is very different from one software to another. However, the standard parameters that are used in comparison of these different types of software can be summarized as below (see Table 2).

Table 2. Comparison parameters of simulation tools.

Parameter	Description
Usability	User interface; conducting parametric studies; time for learning and training; simulation run time, help for input (graphical, intuitive, import from a file, . . .) ability to cut into uniform thermal zones and duplicate data entry
Prevalence	Availability and Accessibility of documentation, user support, pricing and licensing
Functionality	Geometric detail of comprehensiveness, Details of system modeling
Reliability	Stability and accuracy of results
Sensitivity	Influence of parameters over their uncertainty range and effect of each parameter on the model output data, sensitivity analysis of the predefined parameters characteristic of the design, opportunity to examine the sensitivity of simulation results
Capability in handling material property	Phase change, variable thermal conductivity, Specific capacity . . .
Libraries built into the software	Standard, Full Material Library, possibility of importing, dynamic (definition of walls from library materials, option of creating materials if needed, . . .), Innovative Products (PCM), Predefined Device Libraries . . .

8. Prospective Vision

Solar thermal energy is renewable, clean and free; it can contribute to electricity generation, hot water, air-conditioning of dwellings and lighting for buildings. One of the prospective approaches for storing this energy is the application of PCM [52]. However, before practicing this technology on a large scale, it is necessary to solve several problems in the research, design and development stages. These include the integration of renewable energy systems into existing structures. In addition, priority must be attached to the evolution of regulatory frameworks to master the features and benefits of energy storage systems globally.

Although several studies have been carried out on integration processes, much remains to be completed for advanced PCM integration techniques in real buildings. Especially in the form of building blocks, which can be used in the construction by creating a structure with high thermal inertia deprived of a large mass.

Today, there is a rising emphasis on the environment and mainly on energy consumption. Thermal storage systems reach an industrial stage compatible with system applications. They are active for several applications (buildings, industrial processes, heat grids): case for applications coupled with smart grids. The evaluation of this evolution allows reaching alternative visions of research in the domain of long-term storage systems. In the near future and in several countries, direct solar radiation is and will be considered one of the prospective energy sources.

In the future, the PCM will be increasingly adopted as global solutions for energy management due to the advancement of innovative technologies which lessen environmental impact. To achieve this, we must promote synergistic solutions in the solar energy sector.

After reading the literature, the following findings are raised:

- The technologies and the applications corresponding to specific climates and buildings' typologies are not reachable solely by the information published,
- Heat and mass transfer phenomena occur in the building: between the building and the environment, in each building element, between the inhabitants and the building, between air and envelopes and between air of various areas,
- Due to internal and external loads and the complexity of the building as a thermodynamic system, designing buildings with positive energy is very difficult,
- Most PCM studies are geared towards their use, when they are integrated into the building envelope for heating applications and their integration into the envelope of buildings with low thermal inertia for the purpose of improving summer comfort, on the other hand,
- Several results of PCM studies have been tested at the laboratory scale. However, with technological development, computer simulations are performed to study the effect of PCM in real buildings,
- Many materials have been the subject of advanced studies to be used as phase change materials; nevertheless, few are available and marketed today,
- All models in the considered studies are adjusted to a number of constraints, geometry, boundary conditions, initial conditions, working hypotheses and thermal regimes (stationary, quasi-established, variable),
- At present, there are no large capacity latent heat storage facilities. However, many projects are underway, notably in the United States: The Metallic Composites Phase-Change Materials for High-Temperature Thermal Energy Storage project, led by MIT, on molten nanomaterial.

9. Conclusions

This work includes a descriptive study on the different technical solutions applied in the modeling of PCM integration systems in building envelopes and on the simulation tools used in this technology. We followed the technological approaches used in system modeling of solar energy storage.

The literature devoted to the manipulation of these techniques and approaches in the field of solar energy management system technologies is constantly increasing and this is due to the potential of this resource, which has become an issue for the economy. Indeed, the storage of thermal energy using adequate forms of PCM is an ongoing challenge for building designers and can play a prominent role in the energy system of the future.

In addition, the future of these smart materials lies in the innovation of the development of computer and electronic components. Similarly, in light of the above remarks, it is concluded that while the development of thermal simulation tools has facilitated the use of results and helped to make decisions, the exploitation of these tools is not an easy task to perform. This is because it requires a precise knowledge of the processes in the building.

Despite extensive research in this area, as with other technologies, TESS-PCM has some obstacles that prevent it from taking a place on the market. In fact, a more judicious evaluation of the different PCM integration systems in the building structure is essential, especially in practical use conditions.

In the case of numerical studies, particular consideration should be given to the modeling hypotheses and the personalized parameterization of the simulation tools: convective heat transfer coefficient, use of the phase diagram, the choice of time and space steps.

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