ISSN: 2835-7914

Research Article

Biomedical Science and Clinical Research

Integration and Validation of A Numerical Pcm Model For Building Energy Programs

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Submitted: 2023, Sep 04 **Accepted:** 2023, Oct 06 **Published:** 2023, Oct 11

Citation: Nouhaila, B., Bendriaa, F., Mouhib, T. (2023). Integration and Validation of A Numerical Pcm Model For Building Energy Programs. *Biomed Sci Clin Res, 2*(4), 335-356.

Abstract

The envelope of buildings has remained for a long time a passive means of limiting heat loss or heat gain on the one hand, to ensure a certain air conditioning by its thermal inertia. The increase in peak electricity demand in recent years has stressed the importance of peak electricity demand shifting technologies. The overall objective of the project is to improve the living conditions of the local population. The specific objective is to set up a pilot unit using local building materials, with low environmental impact, provided with organic phase change materials also the main objective here is to model, quantify and optimize the impact of the presence of PCMs in a thermal zone subjected to the climatic conditions of Morocco with the ultimate goal of developing low energy buildings and crated the comfort zone . First, a complete numerical model of the thermal behavior of a zone will be developed using the Trnsys, with the possibility of including phase change materials. The achievement of this objective will allow to have available a customized code, fully scalable, able to calculate all the thermal variables of interest in a building interacting with the environment. Such a complex wall technology integrating PCMs must be properly taken into account in order to simulate the energetic behavior of buildings and to evaluate their impact in several domains (environmental, thermal behavior of buildings). Once the thermal characterization of the building has been performed.

Phase Change Materials (PCMs) have a potential to improve the building envelope by increasing the thermal mass as well as contribute to a significant peak shift in whole building power demand. Therefore, special attention is given to properly capture the thermal behavior of PCMs in advanced building energy modeling software. Design of effective PCM thermal storage systems requires accurate energy modeling. There are analytical and numerical models developed during last few decades for this purpose, many have not been fully validated. Based on the current status of literature, the study identifies the limitations and drawbacks of existing methods. A parametric study is conducted to identify the optimum PCM thermo-physical properties

Keywords: Comfort, TRNSYS, Phase Change Material, Thermal Energy Storage, Building Envelope

Abbreviations

AIE (IEA) :Agence Internationale de l'Énergie (International Energy Agency)
ASHRAE :American Society of Heating, Refrigerating and Air-Conditioning Engineers
PCM :Matériaux à Changement de Phase
PMV :Predicted Mean Vote
PPD :Predicted Percentage Dissatisfied
RDC :Rez de chaussée
RT :Réglementation Thermique (France)
RTCM :Règlement Thermique des Constructions au Maroc.
TMY :Typical Meteorological Year (Année Météorologique Typique)
TPF :TRNSYS Project File
TRNSYS :TRansient SYstem Simulation

1. Introduction

These phase change materials are often used to store energy to overcome times of mismatch between thermal supply and demand in a building, such as storing solar thermal energy for space heating in the evening. The lifting of all energy subsidies by 2025 in Morocco will exacerbate the energy disparity. Reducing energy costs is a major challenge in Morocco. This mobilization is justified primarily by the costs associated with energy consumption. Indeed, 10% of Moroccan gross domestic expenditure in 2014 was dedicated to energy expenditure. In addition, such consumption has disastrous environmental consequences in the long term: greenhouse gas emissions, depletion of natural resources, etc. Among the sources of energy consumption, heating and air conditioning systems represent about 50% of the total expenditure in buildings. This considerable proportion can be explained in part by the great temperature variations recorded in Morocco, which make the contribution of air-conditioning or heating indispensable almost at all times. The development of the green buildings passes thus inevitably by an optimization of the use of the systems Heating and air conditioning. In this perspective, a clear difference between the use of systems during the day and during the night has been observed. In fact, during the day, the solar irradiation incident on the facade of a building coupled with the various internal gains (occupancy density, lighting, etc.) density, lighting, etc.), cause a high demand for air conditioning. Conversely, during the night, the internal and solar gains are solar gains are non-existent and the outside temperature is lower: heating is often required. From this point of view, storing the excess loads emitted during the day and re-emitting them during the night when heating is required is an ideal solution for increasing energy efficiency. Indeed, less heat Most materials used in buildings have either a relatively low thermal mass or a high structural mass, which means that they can be used in a variety of ways. or a high structural mass, such as concrete. The provision of thermal inertia is therefore necessary, but is accompanied by disadvantages and restrictions in terms of structural design, aesthetics and ecology. However, there is a type of high thermal inertia and excellent specific properties, which is becoming more and more important in the design of new phase change materials (PCMs). The high thermal inertia of these materials stems from their ability to change phase at a user-adjustable temperature .Depending on the properties of the thermal zone where we are, it is therefore possible to integrate PCMs and to optimize their parameters in order to favorably dephase the energy consumption peaks and energy consumption and, by the same token, significantly reduce the use of the heating and air conditioning system. Consequently, the integration of PCM in the envelopes of new buildings or in renovation would contribute to reduce the energy bill in the building sector in building sector in Morocco. The envelope of traditional buildings has remained for a long time a passive means to limit heat loss or heat input and to ensure a certain air conditioning by its thermal inertia. Indeed, the thermal energy stored in the walls during the hot periods is restored during the cold periods. One of the key objectives of the research on low energy buildings is to find a way to manage the time differences between energy sources and energy consumption. The main objective here is to model, quantify and optimize the impact of the presence of PCMs in a thermal zone conditions of Morocco with the ultimate goal of developing low energy consumption buildings. energy consumption. First, a complete numerical model of the thermal behavior of a zone will be developed using the simulation tool Trnsys, with the possibility of including phase change materials. The achievement of this objective will allow to have at disposal a customized code, fully scalable, able to calculate all the thermal variables of interest in a building in interaction of interest in a building in interaction with the environment. Such a complex wall technology integrating PCM must be properly taken into account in order to simulate the energy behavior of buildings and to evaluate their impact in several domains (environmental, thermal behavior of buildings, etc.) Once the thermal characterization of the building has been completed, the second specific objective will be to process all of the data obtained in order to measure the impact of the presence of CAMs from several perspectives. On the one hand, the average temperature will be examined after integration of the PCMs in a zone. The simulation of a PCM is supported by type 204. The simulations are performed for different indoor convective heat transfer coefficients (h-value), where the h-value increases from 0.5 to 10 W / m².K [1]. The simulation, results show that the heating energy demand increases when the h-value increases, but the cooling load decreases slightly [2]. Bontemps and al, showed the new PCM module was validated with experimental [3]. The results showed that, during the summer, there is a reduction of 2°C in indoor temperature for the room with PCM walls compared to the room without PCM walls. It was also shown that, in winter, the thermal discharge for the wall with PCM in the interior temperature drops to -9°C. Xu et Zhang further investigated the effect of various parameters such as, melting temperature, the heat of fusion and thermal conductivity of PCM on the thermal performance of the building [4]. They found that the heat of fusion and thermal conductivity of PCM should be greater than 120 kJ / kg and 0.5 W /(mK) a large number of numerical studies, which have been recently performed in different countries, helped in better understanding of the physics behind the PCM-enhanced building products and their potential energy performance. For decades, different types of PCM-enhanced building boards and plasters have been the most popular objects of computer simulations. Earliest numerical studies started during the late 1970and had been continued till the1990s. They were mainly focused on gypsum wallboards impregnated with paraffin (Solomon 1979; Tomlinson and Heberle 1990; Kedl 1990; Stovall and Tomlinson 1995;Kissock et al. 1998 [5-9]. A combined experimental–numerical work was performed by Athienitis and al. (1997) , who conducted extensive field testing followed by one-dimensional numerical analysis of a full-scale outdoor test hut with PCM-enhanced gypsum board installed as an inside wall sheathing. In more recent projects, PCM wallboards and plasters containing microencapsulated PCMs (Hawlander and al.2002; Darkwa and Callaghan (2005), Schossig and al. 2005; Kendrick and Walliman2007 have been studied. In addition, the thermal performance of shape-stabilized PCM board products has been analyzed using numerical methods (Kuznik and al. 2007; Virgonet and al.2009;Constantinescu and al.2013 [10-16]. Due to flammability concerns about paraffinic PCMs, a number of numerical models have been utilized recently to analyze the thermal performance of boards and insulation products thermally enhanced with bio-based alternatives kinds to paraffin(Rozanna and al.2005; Riza 2007; Kośny and al. 2009c; Dhanusiya and Rajakumar 2013 [17-20].This work consists

PCMs can store energy in two forms, latent heat and sensible heat. The magnitude and the rate of latent heat absorbed and released depends on material properties [21].

Therefore, the advantage of using PCMs lies in the amount of latent heat a small amount of PCM can store under different storage techniques compared to that in a sensible heat storage material of the same volume. For an instance, a 25 mm thick PCM layer can hold same amount of energy as a 420 mm concrete wall as long as the PCM layer changes phase [22]. Therefore, PCMs can shift peak time periods based on the latent heat capacity, and other physical parameters related to the application of PCMs .

Different thermo-physical characteristics while they co-exist within the enclosure. Enclosure/encapsulation is how the PCM is packed in the particular application. During the phase transition of the PCMs, the liquid state and the solid state are separated by a moving interface. Considering the basic physics, the energy and mass balances should be satisfied in either side of this moving boundary which makes it difficult to model. Either side of this moving boundary is also called two phase/ “mushy” region. The enthalpy change which occurs across this region is quite complex and dependent upon the material properties of the PCMs such as the latent heat, expansion coefficient, melting range and rate of heat transfer [23].

Latent heat of the PCMs defines the heat storage capability of the PCMs. When compared with other building envelope materials like stone, wood, brick and gypsum, PCMs present more attractive thermal storage characteristics. To indicate the importance of the latent heat, Zhang et al. discuss how in order to keep the indoor air in the comfort range for a longer period without heating or cooling load, the heat of fusion of a PCM should be high enough to keep the inner surface of the wall at the melting temperature [24]. This refers to having high latent heat next to the inner surface of the wall so the PCM are not fully melted nor frozen. Furthermore, the latent heat capacity of the material determines the weight/volume fraction of the PCMs required for the optimum performance of the building envelope.

Melting temperature of the PCM is another important property. Melting temperature is usually selected to fall within the comfort range of the occupants and are researched in the existing standards [25]. The exact value of the optimum melting temperature required depends on the building, climate, and the application [26]. Furthermore, a study of a PCM wall in a passive solar house indicates that heat storage occurs with a melting temperature of 1-3 ˚C above the average room temperature [27]. This section discusses these attractive characteristics of PCM in detail.

2. Phenomena of Phase Change of PCMs

Generally, phase change/ phase transition happens from solid to solid, solid to liquid, from solid to air, liquid to vapor and even solid to solid (restructuring of bonds at atomic level). In building applications mostly Solid-Liquid, and Solid-Solid phase change is used. The material can be a pure substance, eutectic mixture, or non-eutectic mixture. Eutectic mixtures change the phase at a constant temperature but, non-eutectic mixtures change the phase during a temperature interval [28-31].

PCMs used in real world applications are not usually pure substances and therefore, temperature interval in which the phase change becomes an important factor [32]. This temperature interval is called the melting range. Kuznik et al. review the phase change process in a multi component mixture of PCMs in great detail [33]. This study indicates that behavior of the system becomes more complex with the presence of multiple melting points from eutectic to non-eutectic mixtures.

Using the phase change behavior, PCM-enhanced building envelopes gain the ability to manipulate the thermal response. They can delay the effects of external thermal excitations reaching the interior of the building [34]. At a warmer exterior weather the interior is kept cooler and at cooler exterior weather the interior is kept relatively warmer. A high thermal conductivity is not required for these applications because the design expectations of the thermal system are peak load reduction and time shift of thermal response. But, there can be other building applications where the enhanced envelope is required to absorb and release heat faster. When fast absorption and release of latent heat is required, PCM properties need to be enhanced. Kosny highlights that, most of the applications seem to use low conductive organic PCMs [35]. Due to thermal comfort considerations the operating temperature of these PCMs are low. Kosny further suggests switching from organic PCMs inorganic PCMs that have 4-5 times higher thermal conductivities would be advisable [36]. This research therefore investigates hydrate-salt inorganic PCMs and is discussed in the later sections.

It is evident that the exact thermal performances expected need to be achieved by carefully managing the contributing characteristics. Parametric and optimization studies help determine these optimum combination of characteristics and properties.

3. PCM Encapsulation Methods

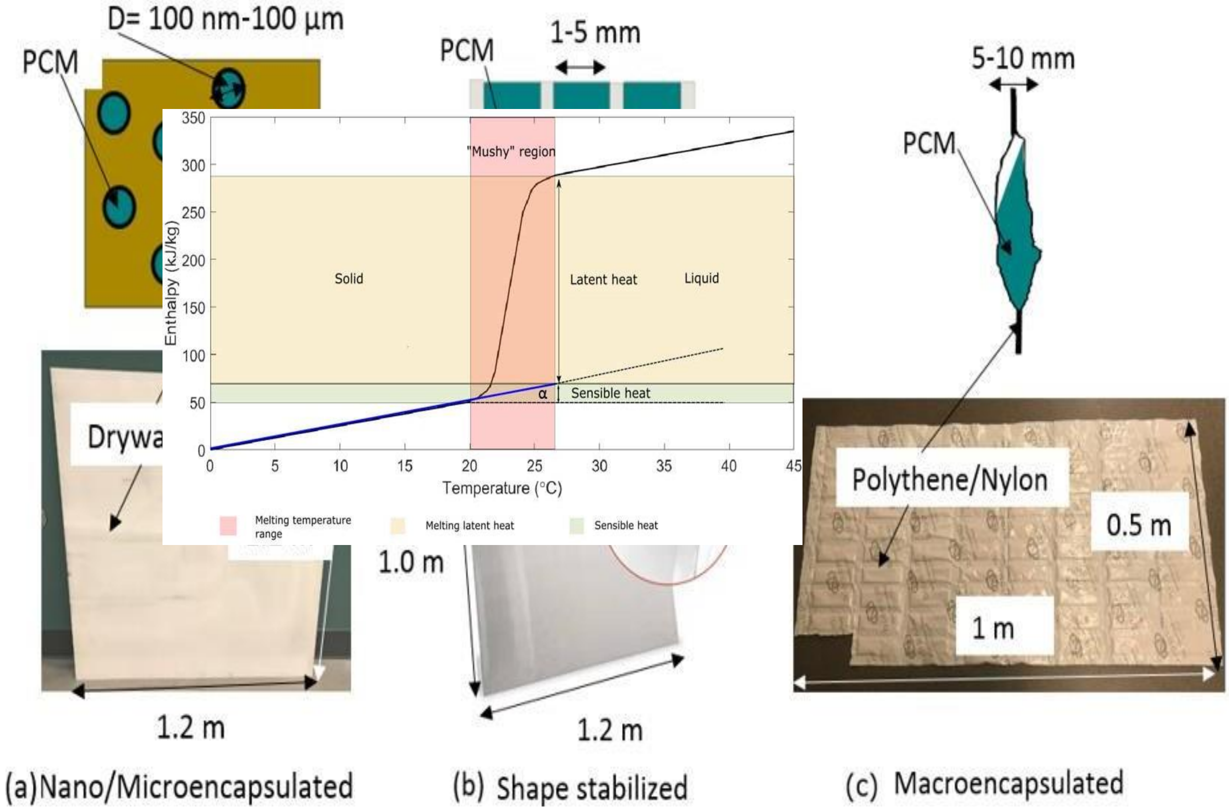
Encapsulation contains the PCM inside a coating or shell material to hold the PCM and to keep it separated from the surrounding material. Separation of PCMs helps to monitor the composition of liquid/solid phases as well as avoids reactions with surroundings. The encapsulation method, resistance, thermal stability, strength, and flexibility.

Offer an adequate heat transfer surface. common way of encapsulating the PCM in a spherical, tubular, cylindrical or rectangular container having milliliters to several liters of PCM and t serving directly as heat exchangers (usually 1-10 cm in size). Wei et al. investigates several types of encapsulation shapes and indicate that, from the heat release point of view, spherical PCM capsules show the highest thermal performance [37]. The skin of the container acts as a self – supporting structure isolating PCM from the surrounding environment. For building envelope applications, plastics (polyethylene, formed white poly-film and heavy-duty nylon films are commonly used as the container materials [38,39]. Metallic encapsulates can increase the heat transfer due to the high conductivity. However, metal vessels are not suitable to encapsulate PCM hydrate-salts due to corrosion and degradation [40]. PCM leakage can be a challenge in macroencapsulation in pouches and to prevent that techniques like improved formed poly-film for encapsulation and mixing PCMs with thickening agents are used [41]. Macroencapsulation is the least complex encapsulation method due to simplicity of containers and the low production costs of the containers.

Phase change phenomena and heat transfer characteristics discussed in the previous section is highly influenced by complex behavior observed in PCMs used in building applications. These characteristics are observed in experimental PCM studies and have presented problems in attempts to model PCMs. Therefore, this section looks into these complex characteristics.

Figure 1 shows the temperature-enthalpy curve of a Bio based PCM comprising of fatty acids, fatty alcohols, esters, emulsifiers, and thickening/ gelling agents. PCMs used in building applications are usually not pure substances and therefore indicate a melting temperature range. The red shaded area shows the melting temperature range of the material approximated by the author using the starting point and the end point of the melting. This temperature interval is also referred to as the "mushy" region of melting.

1a shows microencapsulated PCMs embedded in drywall. This drywall is available in 1.2m x 1.2 m (4ft x 4ft) PCM panels. Figure 2-1b shows the shape stabilized PCMs in thin aluminum foil.



(a)Nano/Microencapsulated (b) Shape stabilized (c) Macroencapsulated

Figure 1: Different PCM encapsulation types: (a) microencapsulated PCMs embedded in drywall, (b) Shape-stabilized PCMs: thin PCM layers enclosed between aluminum foil sheets, and (c) Macroencapsulated PCMs: PCMs enclosed in pouches. Figure shows the dimensions of the single PCM included unit and the commercially available dimensions. Thermal characteristics and properties of PCMs

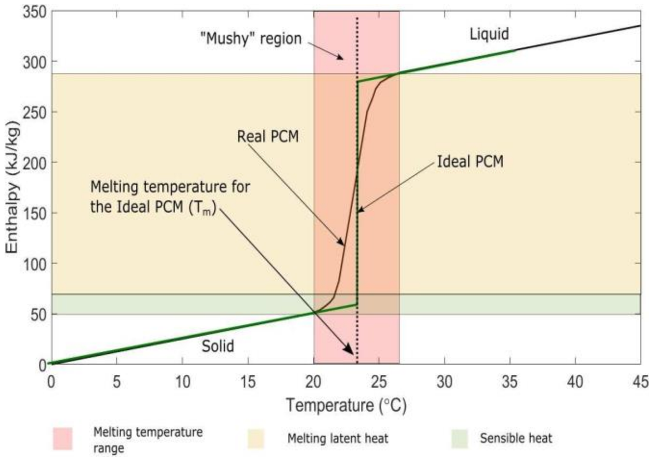


Figure 2: Enthalpy variation across the mushy region and deviation observed in PCMs used in building applications (Real PCM) in contrast to an ideal PCM. Graph shows the melting temperature range, melting latent heat, and melting sensible heat of the PCM

The total enthalpy difference during the phase change comprises of the sensible heat and the latent heat. The sensible heat calculation for each phase is defined in the equation 2-1. Tm,low is low bound of the melting temperature range and then Tm,high is the higher bound of the melting temperature range. $q = c_s,PCM\Delta T, T \leq T_m,low$ $q = cl,PCM\Delta T, T \geq Tm,high$.

Figure 2-3 shows the sensible heat and latent heat contributions to the enthalpy change during the melting process for the Bio-based PCM in Figure 2-2. The cream color shared enthalpy difference is the melting latent heat and green color shaded enthalpy difference is the sensible heat. Phase separation of the material

Phase separation of the material takes place within this "mushy" region of phase change. This phenomenon usually occurs when there is more than one constituent in the substance, which is common practice in commercial PCMs. Kosny discusses how the melting/solidifying temperature of each component might also be influenced by the composition of each constituent of the mixture [42].

4. Subcooling/Supercooling Effect and Hysteresis

Hysteresis PCMs are categorized as real hysteresis and apparent hysteresis. Real hysteresis occurs due to material properties and apparent hysteresis is independent of the material properties. The most common form of real hysteresis is Subcooling. Many PCMs do not freeze at the melting temperature and start crystallization only after a temperature below the nominal melting temperature. Solidification/ freezing of the PCM happens where the solid phase grows with the liquid layer at the interface. As the temperature decreases this interface should occur at a certain point.

At the initiation, there is no or only a small solid particle. This solid particle is also called the nucleus. At the surface of the nucleus there occurs an instance where energy released by crystallization at the surface is lesser than that of surface energy gained. This energy flow barrier exists until the nucleus grow satisfactorily.

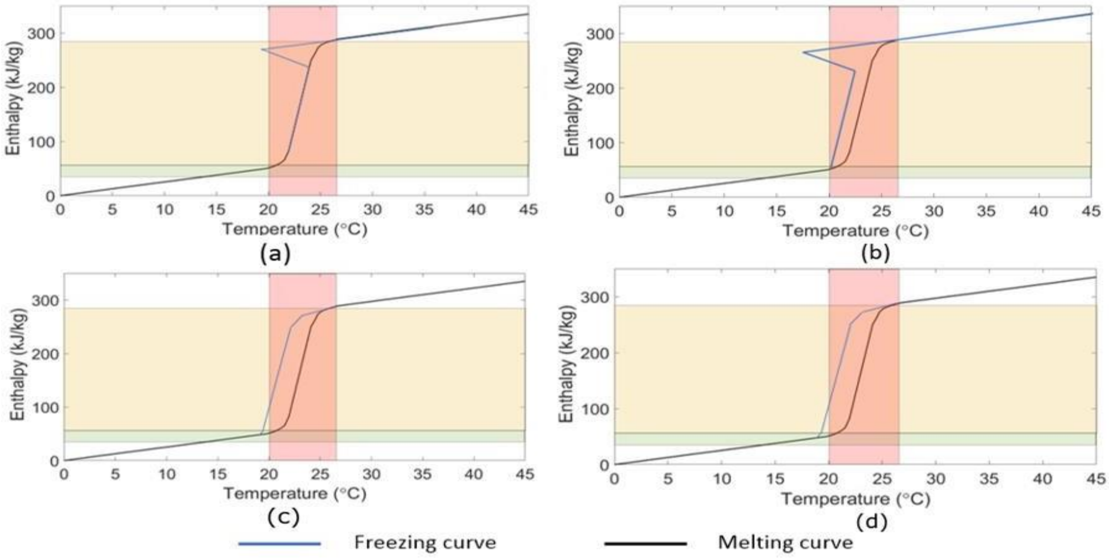


Figure 3: Enhanced view of different PCM enthalpy curve combinations showing hysteresis (a) Subcooling effect and freezing temperature curve comes back and overlay on the melting curve,
(a) subcooling causing separate curves for melting and freezing (c) hysteresis due to slow latent heat release, (d) apparent hysteresis due to non-isothermal conditions in measurements (Enthalpy data available at and the curve concept inspired by [43,44].

If this nucleation is delayed to occur with the temperature decreases below the melting point the Subcooling occurs. Real hysteresis can occur as a result of slow latent heat release. Mehling and Cabeza discusses the reason for the slow heat release being slow formation of the crystal lattice or diffusion processes are necessary to homogenize the sample [45]. The temperature of the sample then drops below the cooling heating temperature. This is not observed in the melting process since the kinetics process occurs much faster [46]. These conditions can separate melting and freezing curve and is shown in Figure 2-4c. Apparent hysteresis occurs due to non-isothermal conditions at measurement for the characterization. This can be caused by the heating rates used in the characterization in melting if high heating rates. If the heating rates are high thermal equilibrium of the specimen could not be reached and the melting curve could be pushed further right in the graph and fro freezing curve it could be pushed to further left. This could cause curves shown in Figure 2-4d. Careful calibration of the instrumentation can minimize the effects of the apparent hysteresis which occurs due to the instrumentation in methods of characterization.

The magnitude of the separation of the curves can depend on the heating rates used, sample size used in the tests, and the data acquisition steps used. All four curves in Figure 2-4 shows effects of hysteresis while only Figure 2-4a and Figure 2-4b showing Subcooling effect.

5. Methodology: Modeling Pcms In Building Envelope

The overall objective of the project is to improve the living conditions of the local population, through welfare and the fight against poverty and social inequalities.

The specific objective is to set up a pilot unit using local building materials, with low environmental impact, provided with organic phase change materials in order to study the improvement of the energy efficiency of residential and tertiary buildings.

The valorization of local materials represents a priority for this project. Clay bricks are the basic matrix in which organic PCMs developed from bio based materials will be incorporated from biosourced materials. One of the tracks considered is the use of PCMs in the form of fatty acids extracted from the transformation of the olive into oil, allowing the valorization and the treatment of these wastes and therefore the protection of the environment .The research work will bring innovation, through the combination of local materials and bio sourced PCM, and will allow the companies of the building materials to develop by making evolve their products. Indeed, the analysis of the environmental performance and economic feasibility of these materials is an important new field of scientific research. The benefits, the energy consumption and the environmental indicator for all stages of the life cycle of the PCM must be evaluated in detail to configure an appropriate energy balance perspective of the material life cycle. Our research strategy aims to examine in detail the topic of PCM use as thermal energy storage materials for the building sector. The aim will therefore be to verify the feasibility and technical performance of PCM as a new way to stabilize the air temperature inside buildings. The study includes a modelling and numerical simulation and an experimental part.

To carry out this project, a model will be developed by taking into account the physicochemical properties of the PCM to be integrated in the building envelope and the local climatic conditions in relation with the thermal comfort. A test chamber equipped with a set of sensors and recorders will be built in Morocco to create a local model based on empirical data. The simulations will be done using the EnergyPlus and Trnsys calculation tools by studying a large parametric analysis to calibrate the proposed model. The modeling of this system is essential to define the specifications of the materials and to determine how these PCMs can be integrated into the building envelope.For several decades, low-income citizens in Moroccan cities have been suffering from thermal inequality, energy poverty and thermal comfort constraints. They resist indoor temperatures of less than 16°C and more than 32°C, which causes the phenomenon of heat stress. The most vulnerable to climate change are people who live in the densest environments with the most limited resources.

The removal of all subsidies by 2025 in Morocco will exacerbate the energy disparity. Reducing energy costs is a major challenge in Morocco. This mobilization is justified primarily by the costs associated with energy consumption. Indeed, 10% of Moroccan gross domestic expenditure. In addition, such consumption has disastrous environmental consequences in the long term: greenhouse gas emissions, and depletion of natural resources. The most vulnerable to climate change are people who live in the densest environments with the most limited resources. Among the sources of energy consumption, Heating, Ventilation and Air Conditioning (HVAC) systems represent about 50% of the total expenditure in buildings . This considerable proportion can be explained in part by the large temperature variations recorded in Morocco, which make it essential to provide air conditioning or heating almost at all times. The development of green buildings thus inevitably requires an optimization of the use of HVAC SYSTEMS. In this perspective, a clear difference between the use of HVAC systems during the day and at night has been observed. This is because,d uring the day, the solar irradiation incident on the façade of a building coupled with the various internal gains (occupancy density, lighting, etc.) Analytical Models

Stefan problem defines the temperature distribution u (x, t) that yields an explicit type solution for freezing/melting of a semi-infinite PCM- layer initially at a constant temperature in a homogenous phase, with a constant temperature at the surface . The analytical solution for the case of heat transfer in a PCM in a 1-dimensional semi-infinite layer is used for our baseline verification purposes and has been used in previous research. Furthermore, recent studies discuss analytical solutions for solid-liquid phase transition of pure PCMs . However, most PCMs do not demonstrate isothermal phase change process and the complex behavior of PCMs have led to more advanced analytical methods. Generally, analytical solutions have drawbacks when capturing dynamic behavior of PCMs with their complex thermal characteristics. For that reason, whole building energy modeling platforms use comprehensive numerical methods.

6. Numerical Models

Approximate numerical models constructed during last several decades use many mathematical methods to recognize PCM behavior. ANSYS Fluent, BSim, COMSOL, DeST, EnergyPlus, HEATING, IDA ICE, , PCMexpress, PowerDomus, RADCOOL, SUNREL, and WUFI are software are capable of modeling PCMs [47]. Among these software, EnergyPlus, ESP- r, and WUFI are considered in this study based on their popularity, key recent applications in literature, and the potential for future research. In addition, an additional model is developed in MATLAB some results are compared to a 2-Dimensional model in COMSOL. This section discusses how these methods are integrated to modeling PCMs and specifically in building applications.

7. Numerical Models: Simulation Methods Heat Source Method

Heat source method splits the enthalpy in to sensible heat and latent heat. Latent heat portion is defined as the heat source . This has been used for different PCM applications designed to take advantage of the off-peak electrical energy for space heating .

8. Capacity Method

The heat capacity method describes the temperature change T(x, t) using the heat capacity cp(T). Within the temperature range of a phase transition, this method deals with heat capacity as a function of temperature. Heat capacity method has been used to evaluate phase change in liquid metals. Most of the modelling algorithms using heat capacity method are built for 1D heat transfer studies [48]. A 3D study by Sa et al numerically compares two PCM-enhanced wallboards with heat capacity defined to vary with the temperature and a Gaussian-type equation and expresses the capacitance-temperature relationship. Heat capacity method shows low accuracy with high temperature gradients in the mushy region .It is suggested in literature that application of heat capacity method in numerical solutions for real PCMs needs further evaluation. TRNSYS software uses heat capacity method to model PCMs in building applications.

9. Enthalpy Method

Eyres et al. introduces enthalpy method, and uses this technique to demonstrate the variations of thermal properties with time (enthalpy change with time) [49]. The enthalpy method deals with a total amount of energy required during the phase-change. This includes both sensible and latent heat. It is one of the most commonly used fixed-domain methods for solving the moving boundary problem, Voller and Swaminathan Studies a general implicit source based enthalpy model. The consistent linearization of the discretized source is a highlighted feature in this study. In using enthalpy method the conductivity and the density is considered to be temperature dependent. The key feature of the outcomes of the above studies is eliminating the need of accurately track the phase change boundary.

The enthalpy method used in this study includes subsets of both apparent heat capacity and source based methods. TRNSYS Type-241 , PCM Express – ESP-r , and EnergyPlus utilizes different versions of the enthalpy method. These applications indicate the applicability of the enthalpy model to approximate PCM behavior. Günther et al discusses the ability of enthalpy method to correctly account for the subcooling effect. Numerical Models: In building energy modeling platforms

Building energy modeling programs include numerical solutions for building envelope with PCMs. However, most of these programs consider convenience over accuracy and therefore, make assumptions to simplify the algorithm when implemented in the models . A PCM study which uses COMSOL to simulate PCMs and discusses how the 3D/2D model. Several studies use in-house whole building energy models implementing numerical solutions for PCM inclusions which are verified with existing numerical solutions or validated with experimental data .However, the commercial whole building energy modeling platforms are more comprehensive and are updated frequently with more effective PCM models. Therefore, the PCMs modeling algorithms require frequent validation.Commercially available building simulation platforms are useful in evaluating annual energy simulations for PCM included building models . The following software is among mostly referenced and have some type of PCM mod

- ESP-r: Tool developed by University of Strathclyde and commonly used in Europe that has couple of PCM models . PCMs are introduced as special materials and defined as active building elements that have the ability to change their thermo-physical properties. Fallahi et al. Proposes a numerical solution for ESP-r. The solution is based on a finite difference method. The program simulates and predicts temperature profiles and heat fluxes for different configurations of PCM inclusion. ESP-r is used by Kośny et al. due to its built in ability to model PCM sub-cooling effect.
- TRNSYS: Tool Developed by University of Wisconsin-Madison. Earlier TRNSYS models use enthalpy method and solved using explicit schemes . However, later TRNSYS models do not use enthalpy method and use heat capacity/ heat source methods . Castellón, et al. compares, but does not offer proper validation results. There are other TRNSYS PCM models for building wall PCM applications . Implements TRNSYS Type-1270 PCM model which assumes that the PCM undergoes its phase transition at a constant temperature and the specific heat capacity of the two phases are constant. TRNSYS Type-285 uses the boundary temperature concept through a massless dummy layer with a small resistance . Validation is done in small scale tests.

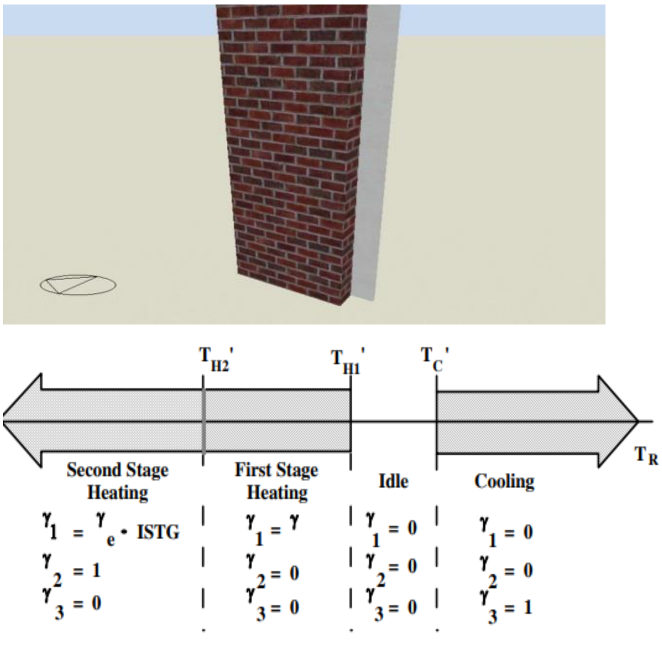


Figure 4: The multi-zone building of Trnsys

10. Mathematical Description

When the regular wall with pcm on if

$\gamma o = 1$ If $\gamma \iota = 1$ and $\Delta tL > (th-tl)$, $\gamma o = 0$ $\gamma i = 1$ and $\Delta tL \leq (th - tl$

IF THE REGULAR CONTROLLER ABOUT THE WALL WITH PCM MODEL Of

$\gamma i = 0$ and $\Delta th \leq (th - tl)$, $\gamma o = 1$

The heating and air conditioning (on/off) Temperature $th1' = th1 + (\gamma 1 \cdot \Delta Tdb) - (\gamma set \cdot \Delta Tset)$.

2 heat source $thl2' = th2 + \gamma 2 \cdot (\Delta Tdb - (\gamma set \cdot \Delta Tset))$.

Conditioning source : $tc' = tc - (\gamma 3 \cdot \Delta Tdb)$. And ySet [any] Setpoint for the controlled variable.

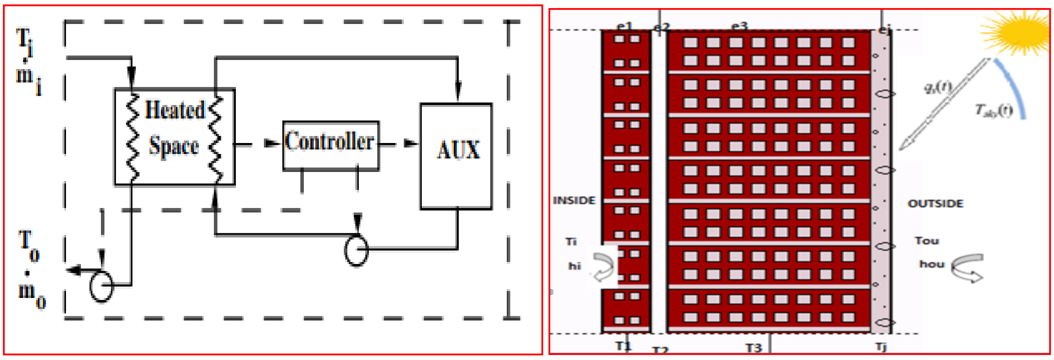


Figure 5: Mode 1 (parallel auxiliary)

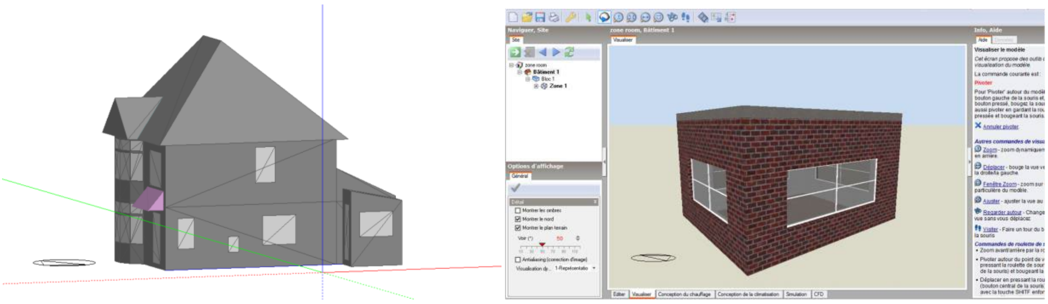


Figure 6: 3D outlook zone.

$$\rho \frac{c_i^n \; \Delta x}{\Delta t}\left(T_i^{n+1} - T_i^n\right) = T_{i-1}^{n+1}\left(\frac{1}{\frac{\Delta x}{2\lambda_{i-1}^n}+\frac{\Delta x}{2\lambda_i^n}}\right) + T_i^{n+1}\left(\frac{1}{\frac{\Delta x}{2\lambda_{i-1}^n}+\frac{\Delta x}{2\lambda_i^n}} - \frac{1}{\frac{\Delta x}{2\lambda_i^n}+\frac{\Delta x}{2\lambda_{i+1}^n}}\right) \quad + T_{i+1}^{n+1}\left(\frac{1}{\frac{\Delta x}{2\lambda_i^n}+\frac{\Delta x}{2\lambda_{i+1}^n}}\right)$$

The Energy rate mhCp and temperature ti **qL = [ua (tb- ta) - qgain]** are applicator in the controller pcm **wall if > 0 qt = ql if qL ≤ εcmin(ti-tb) Equal 0**
if qL ≤ ε cmin(ti - tb) 0 otherwise q aux = 0 if ql ≤ ε cmin (ti - tb) ql or to = ti - qt/mhCp if qt > 0 t i otherwise.
lhr = latent load ACHRAESregalement (latent)/(sensible) ratios of about 0.3, o 0.23. The general total and latent air conditioning loads are calculated as

qcool = qsens /(1lhr)
qlat = qcool - qsens dt = γ ε Cmin ti - tb + qgain - ua (tb - ta + qaux - qsens).
where, γ = 1 if mi > 0 0 otherwise qsens = (1 - lhr) . qcool This differential equation is solved for the final building temperature for each time step, trf and tr using
qt = γ . ε * cmin (ti - tR).
ql= ua (tr - ta) - qgain qlat = qcondito – qsens

cmin Minimum capacitance rate of the building construction heat exchanger. cp: the capitance heat of the flow.

lhr: Ratio of latent heating .
qaux :The auxiliary energy qconditio: air conditioning rate of cooling. qgain: heat gains .
qsens rate at which air conditioning input is used to minimize the building structure internal temperature.

Materials	**Tickness (cm)**	**Density (kg/m3)**	**Resistance (mk/w)**	**Heat capacity (J/(kg•K))**	**Heat conductivity coefficient (W/(m•K))**
Brick layer	25	1800	0.337	1000	0.88
Air gap	4	1000	0.278	1200	0.09
Brick layer	7	1800	0.079	1000	0.88
PCM layer	5	850	0.106	2200	0.47

Table 1: Thermophysical properties of materials

Energy consumption estimation is highly important when designing sustainable and high efficiency buildings. Therefore, engineers, architects, and researchers seek robust, fast, and accurate whole building modeling techniques that can simulate state-of-the art technologies. Hence, this chapter looks into existing PCM modeling techniques and software. Building energy modeling is conducted in district, building, and envelope scale. The current research focuses on the building scale, and the envelope scale heat transfer modeling. Figure 3-1 shows different scales of heat transfer modeling considered in this work and where PCM modeling algorithms apply.

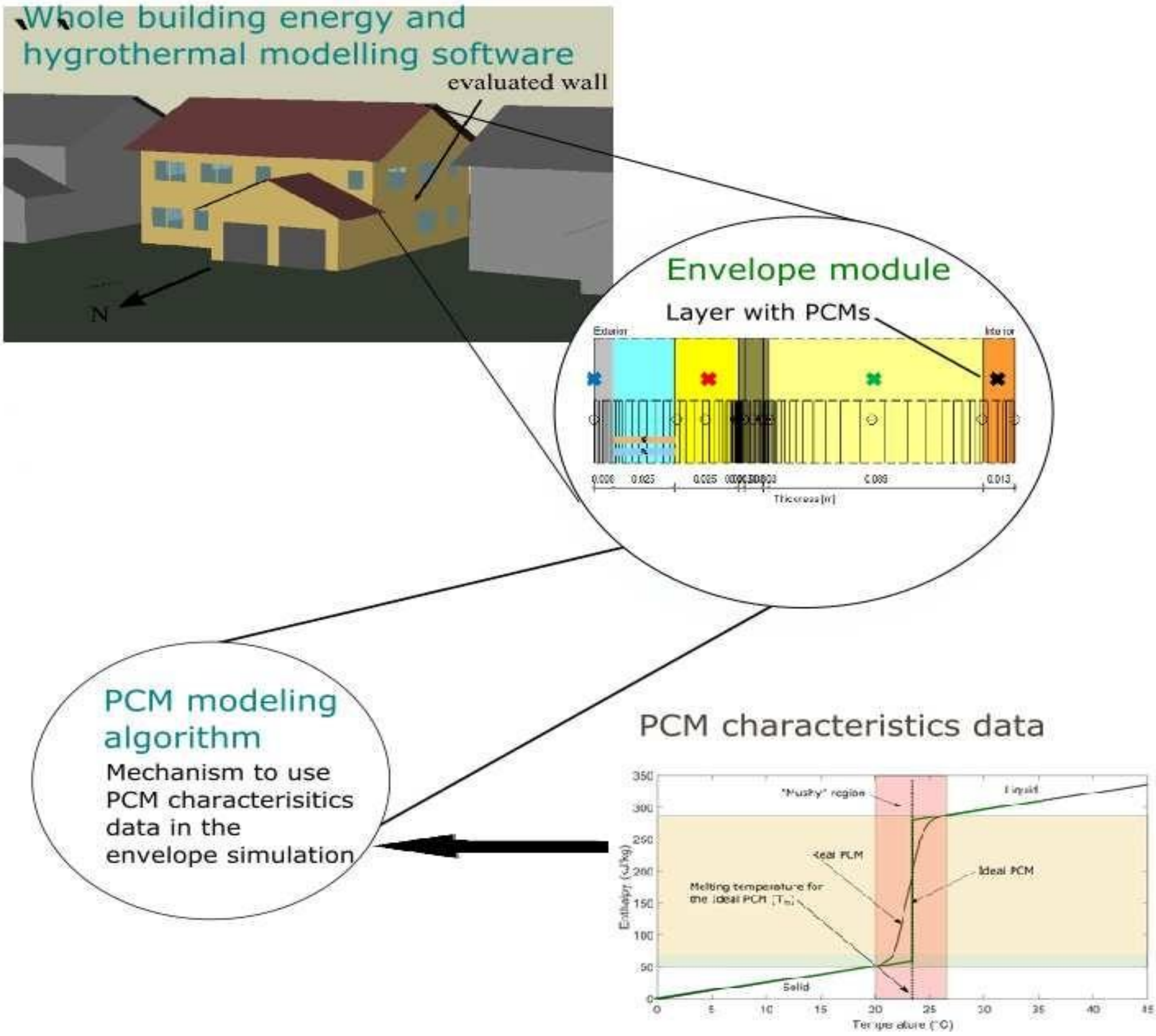


Figure 7: Different scales of building energy modeling considered in the current study are at building scale, envelope scale. The PCM modeling algorithm incorporates PCM characteristics in the envelope modeling algorithm

Energy _Surface= - (dq wall) dt + qcomo-qcomi + qt_rgain_i +qt_rgain_w - qt_al .

(dqwall) dt: change of surface and internal energy.

qcomi : exchange heat flux to inside zone.(Equipment , people)

qcomo : exchange heat flux to outside zone (going to outside-; going into wall +) .

qtrgain_i : the total radiative gains for internal surface .

Input of Walls: The parameters and proprieties about the wall . the input of zone represent the information about the wall , the user can be allow the box in the upper provides an overview of all parameters walls and add, delete or edit the walls of a zone, of clicking on a wall within this overview box .

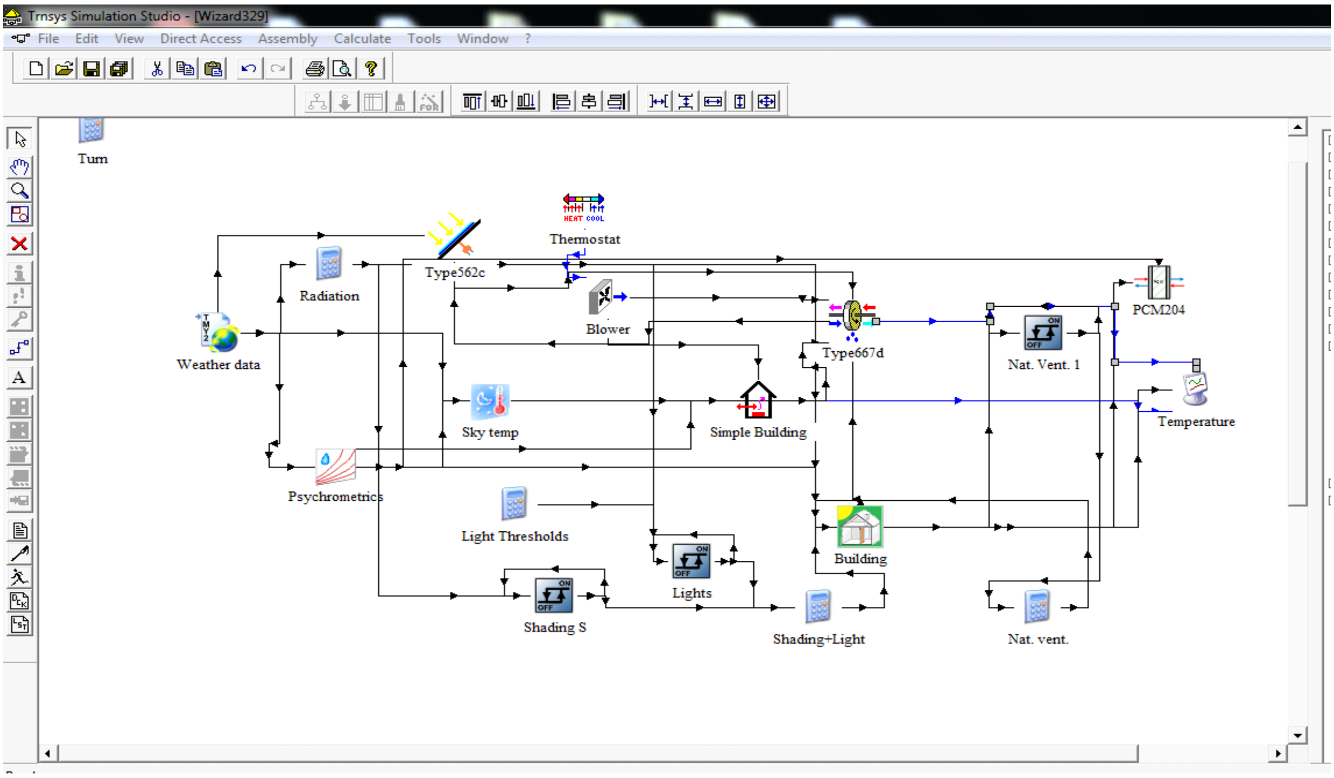


Figure 8: The TRNSYS program

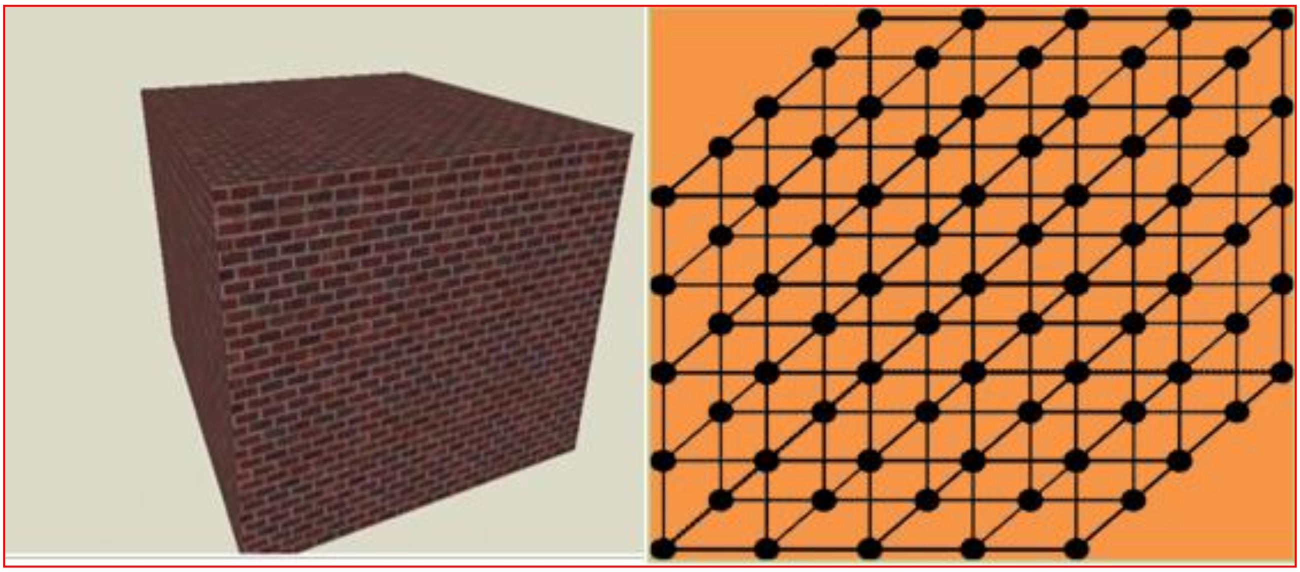


Figure 9: The 3-dimensional 3D wall component.

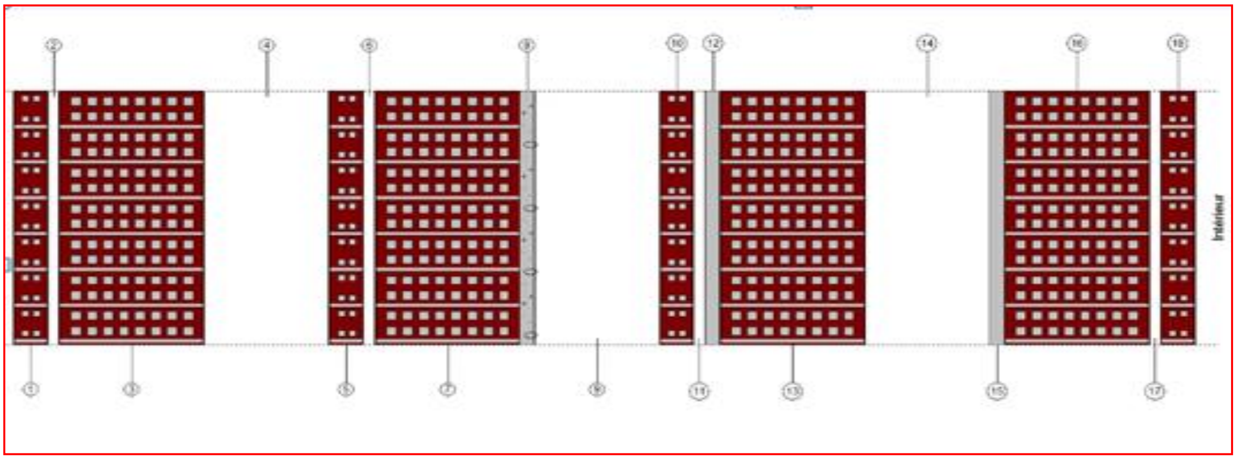
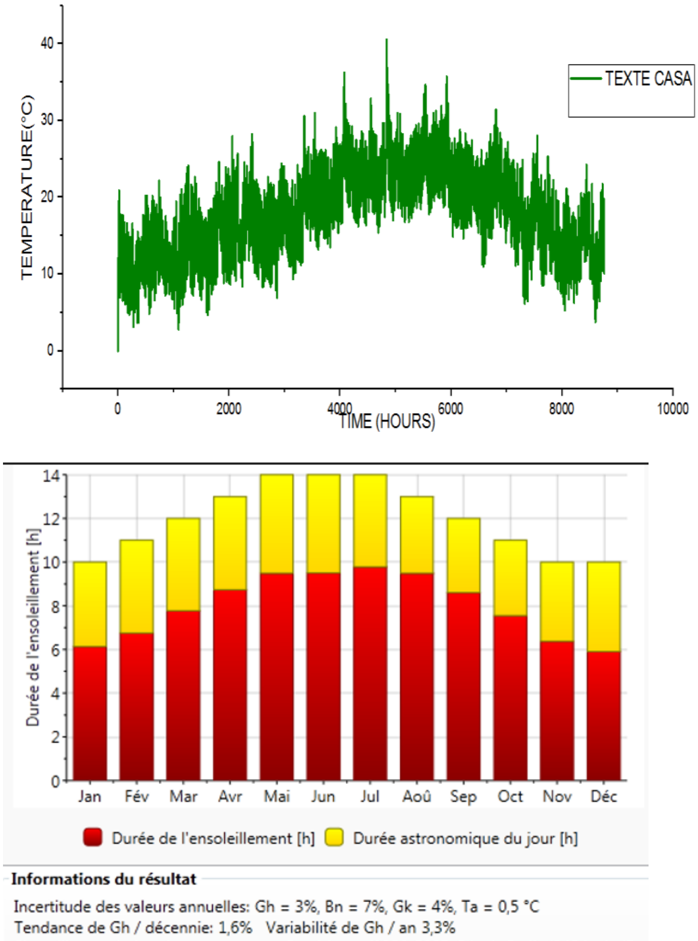


Figure 10: The composition of the 4 scenarios

10. Results and Discussion



Informations du résultat

Incertitude des valeurs annuelles: Gh = 3%, Bn = 7%, Gk = 4%, Ta = 0,5 °C
Tendance de Gh / décennie: 1,6% Variabilité de Gh / an 3,3%

Figure 11: The external temperature in CASABLANCA

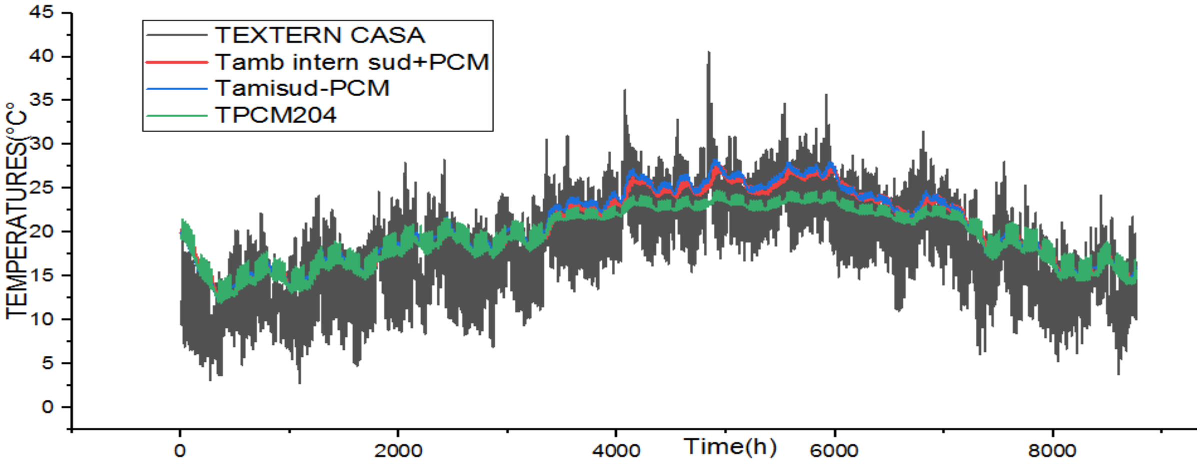


Figure 12: Annual evolution of the external and internal temperature without and with pcm

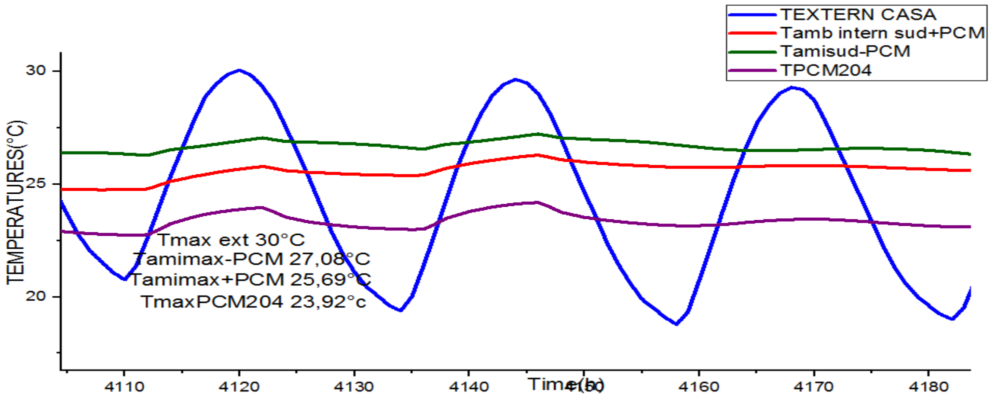


Figure 13: The external and internal temperature without and withpcm in summer

Figure show the minimum and maximum magnitude of the internal ambient temperature without phase change materials and with phase change materials and external temperature. The building envelope with phase change materials debilitate the temperature of 3.19 °C in comparison to the building without pcm. The pcm phase change materials can attenuate the internal temperature to 11.4% of thermal debilitate reduction. The employment of phase changematerial increases the internal temperature of the building envelope .So the internal temperature in the building envelope has inferior to than the ambient temperature extern , which is close by the restrict of thermal comfort space.

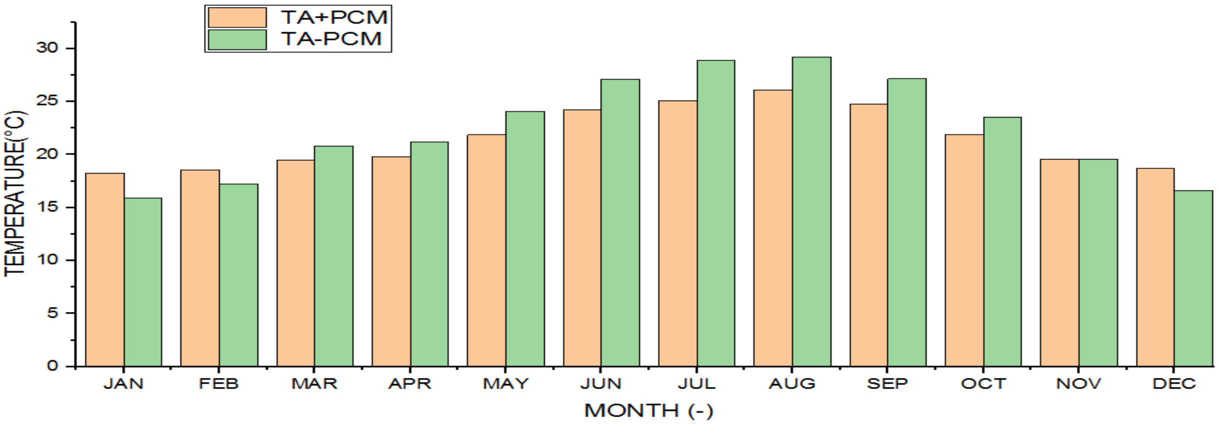


Figure 14: Comparison of the air temperature without and with PCM

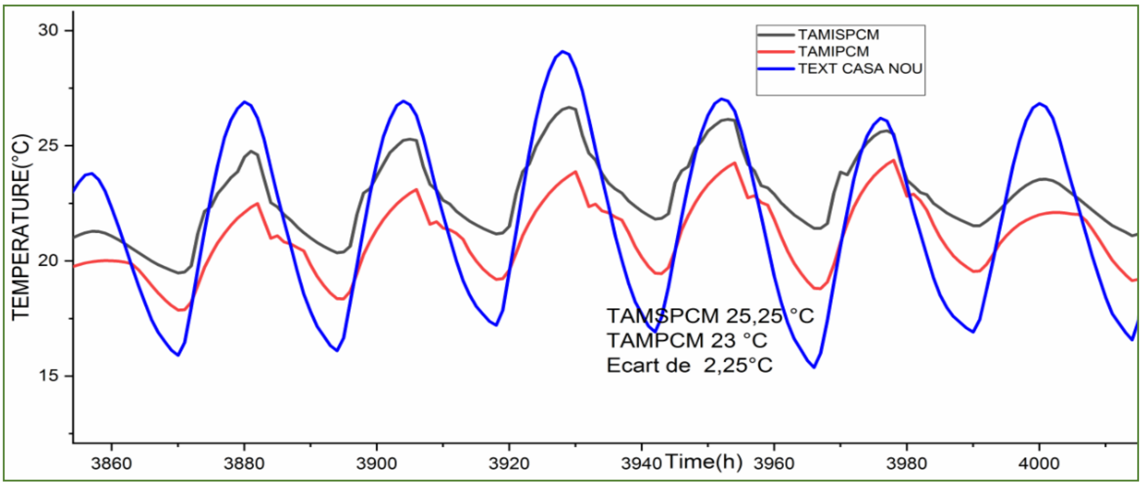


Figure 15: Growth rate of the external and internal temperature without and with pcm in summer

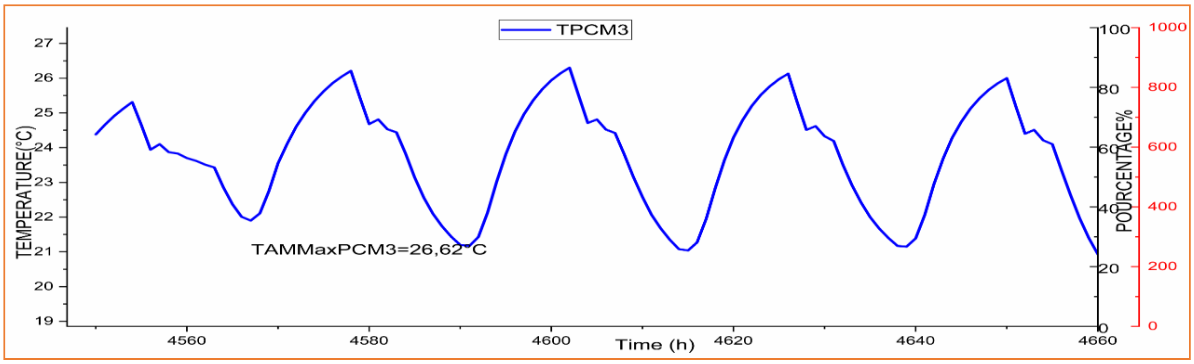


Figure 16: Evolution of the internal temperature with pcm3 in summer

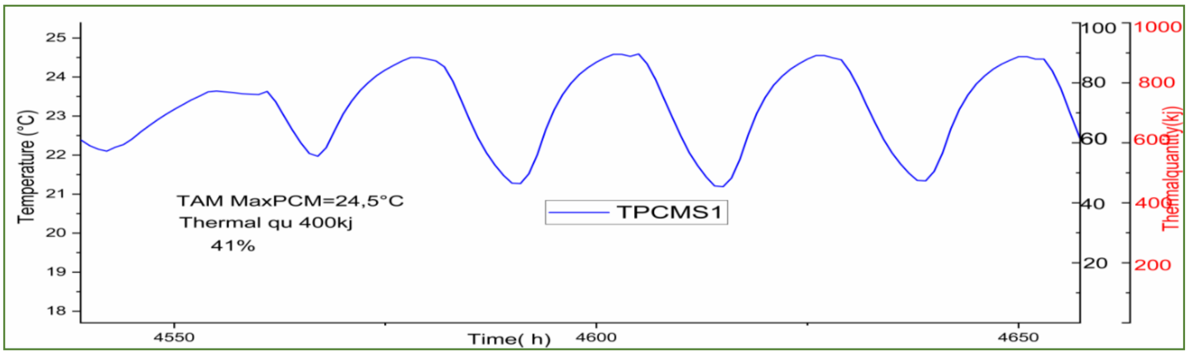


Figure 17: Evolution of the internal temperature with pcm 1 in summer

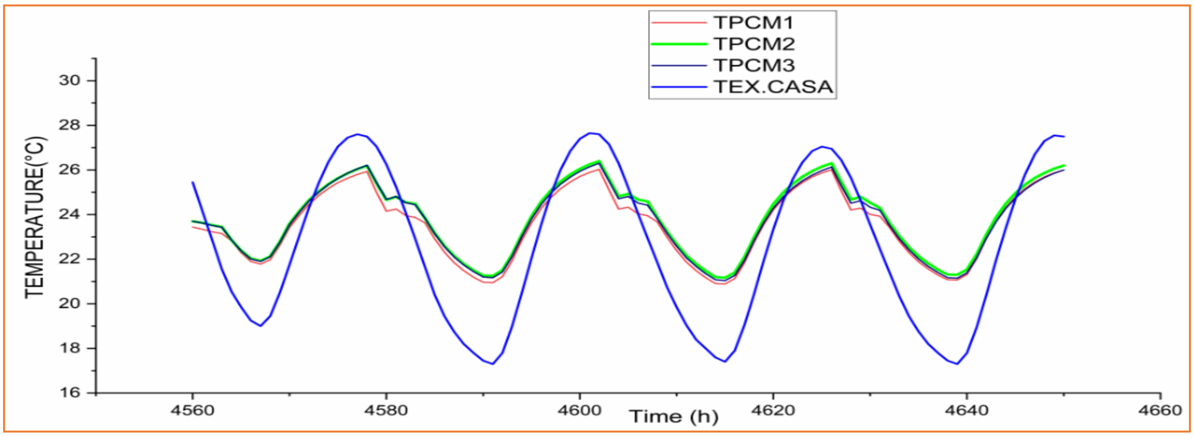


Figure 18: The internal temperature with pcm1.2.3

Figs. 18.shows the comparison about the internal wall ambient temperature during charging and discharging withotand with pcm 1.2.3 in summer , the results obtained in the indoor wall temperature of PCM 1 25.7°C and PCM2 26.4°C ,PCM 3, 26.68°C and without PCM is 28.08 °C and a maximum peak temperature of 2.4 °C.

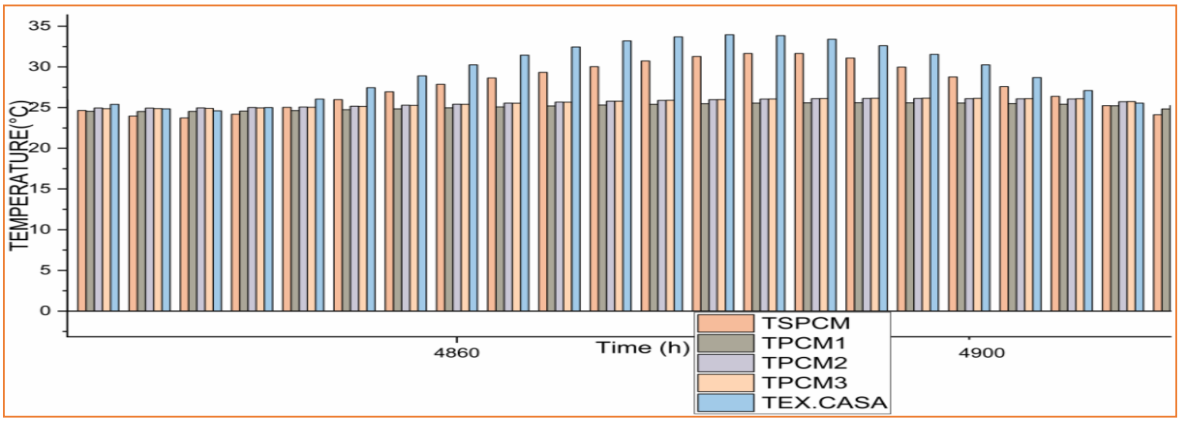


Figure 19: The internal and external temperature with pcm1.2.3 and without pcm

11. The effect of PCM Density

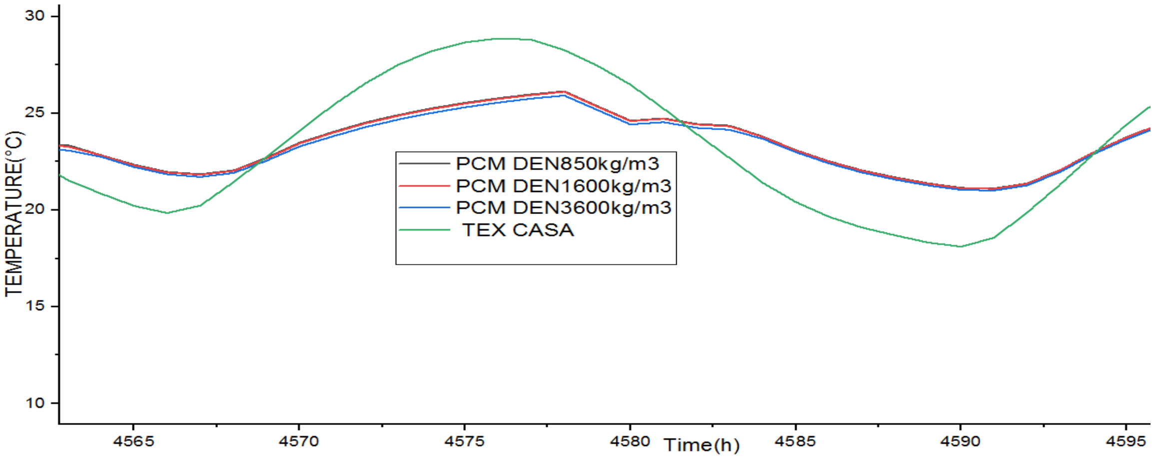


Figure 20: Presentation of the pcm density in summer

Figure 20present the density of pcm in summer ; so when the density parameter is increased,the internal ambient temperature with pcm decreases if the temperature increases, the molecules of the fluid move apart and the density decrease if the temperature decreases, the opposite occurs. So the pcm can storage more energy and the integration the pcm into the building envelope can storage more the energy and minimize the heating and cooling consumption.

12. Influence of PCM Thickness

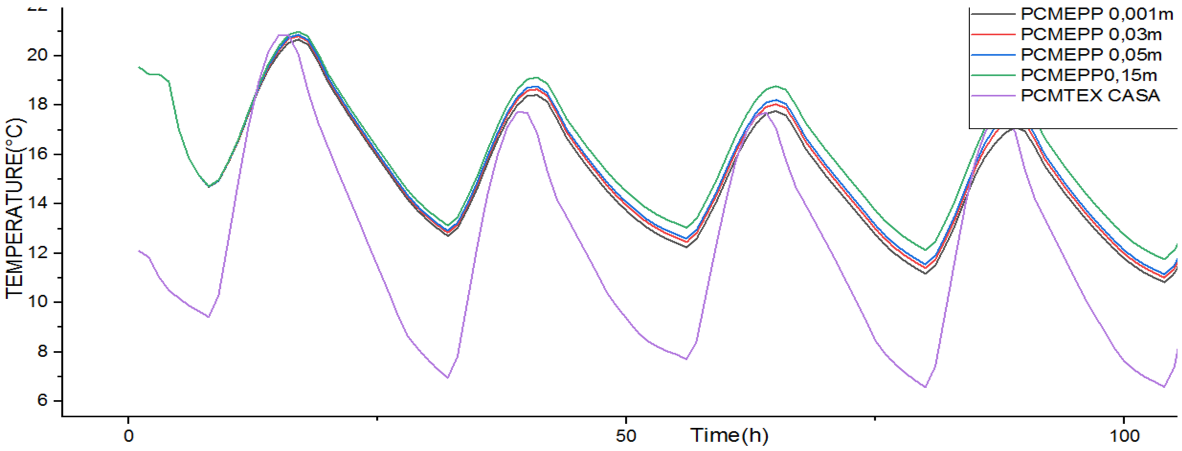


Figure 21: Evolution of pcm thickness parameter in winter

Figure 21: present the growth up of pcm parameter thickness wall in winter,when we growth up the thickness of the wall with PCM the internal ambient temperature also graduate so this condition is good in winter, not in summer so we take the optimum thickness of PCM between 0.01 m and 0.05m.

13. Relative Humidity (RH)

The results conveyed that the building with phase air gap and phasechange materials not only had the reaction on the heat flow transfer and temperature and exchange transfer convection ,conduction and radiative transfer in the wall, but also had reaction on the ratio relative humidity and moisture transfer in the wall. The apex relative ratio humidity and the moisture flux of the wall with phase change materials were both small. Compared with external relative ratio humidity and the relativeratio humidity of the wall without phase change materials . The reduction of the relative humidity of the pcm wall is 28.6 % with the external relative ratio humidity and the relative humidity percentage range of the wall without pcm was 13 %. Although the apex diminution of the relative humidity was small, it is concluded that the risk of crystallization , condensation and infiltration of the wall could be diminish .

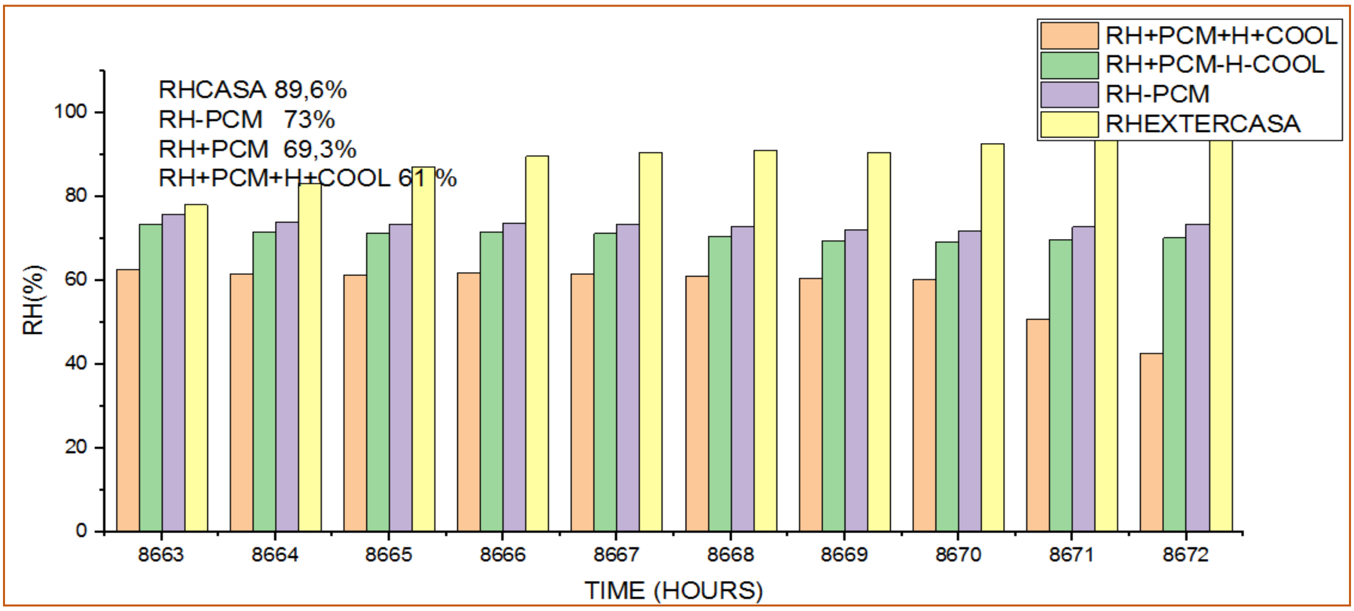


Figure 22: Evolution of the external RH and internal relative humidity with and without PCM

14. Thermal Comfort

The "PMV" index (Fig 37.38)gives the average vote of the individuals surveyed which indicates opinions on their average thermal sensations according to the ASHRAE scale1 which varies from (-3) to (+3) where each number expresses a thermal sensation

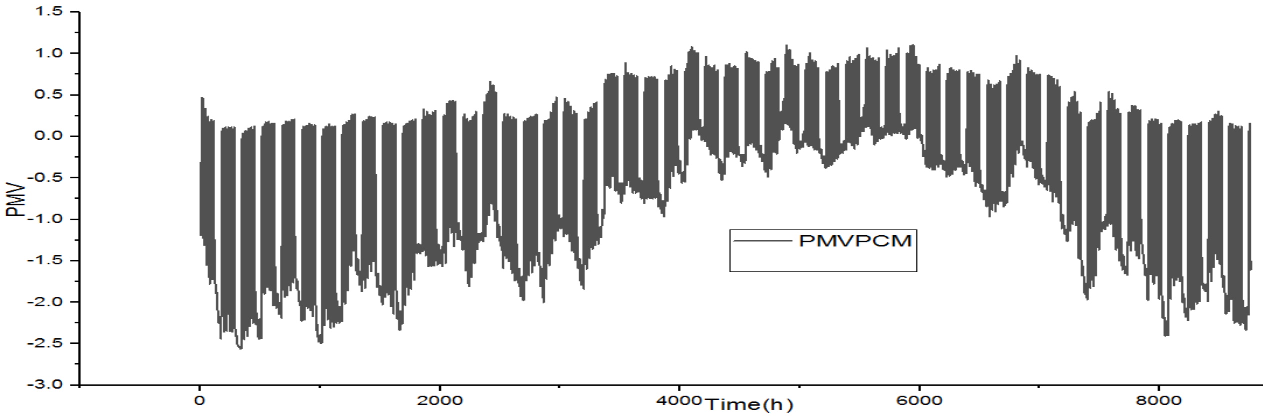


Figure 23: The "PMV" index simulated during one year with PCM

In our case the value of PMV with PCM varies between 1 and -1 in the summer period. The negative values express very low temperatures and the positive values indicate very high temperatures. The thermal comfort zone is between (-1) and (+1). An index of the PMV equal to (0) expresses an optimal feeling of thermal comfort.

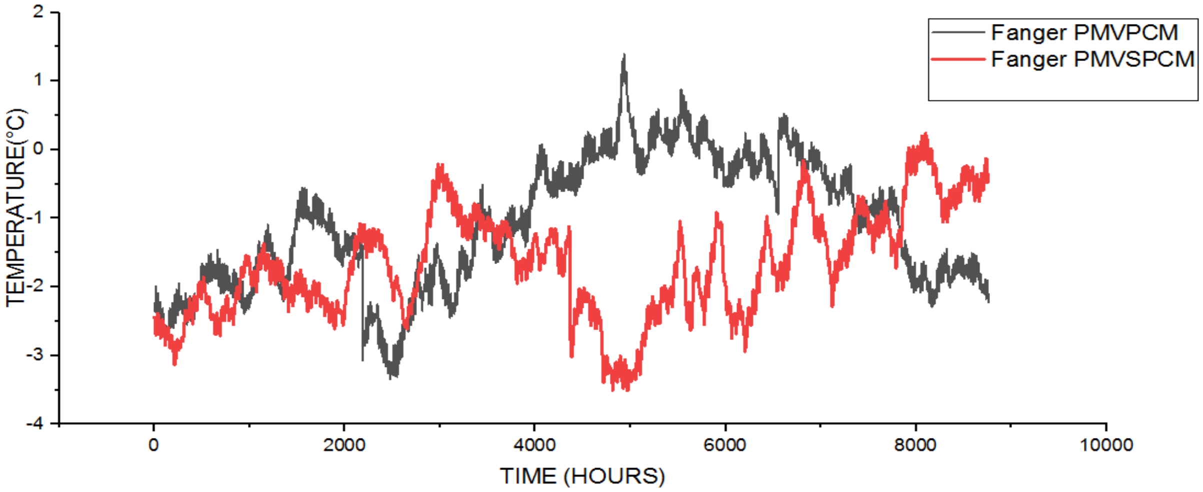


Figure 24: The Annual evolution the "PMV" and "PPD" index simulated with PCM and witout PCM

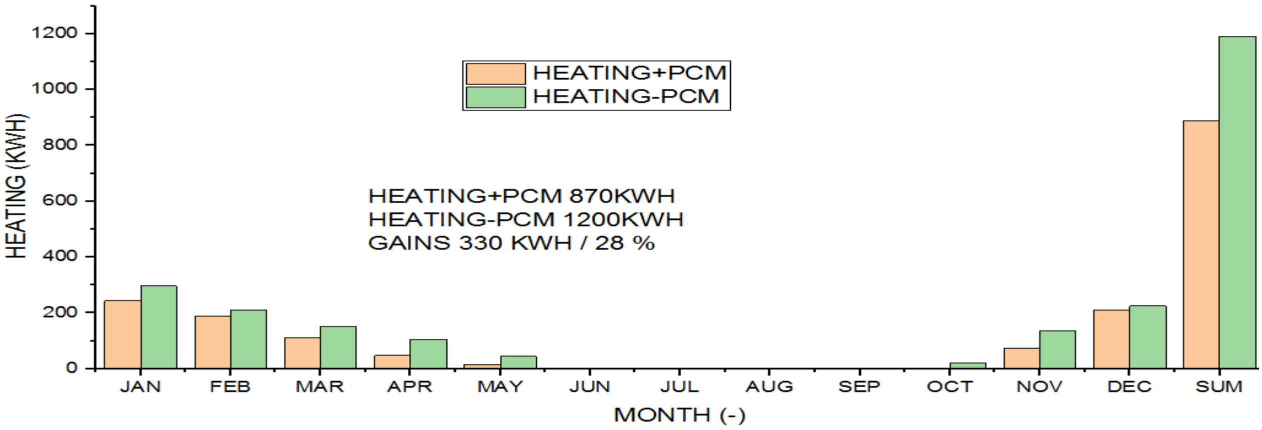


Figure 25: Annal consumption of HEATING

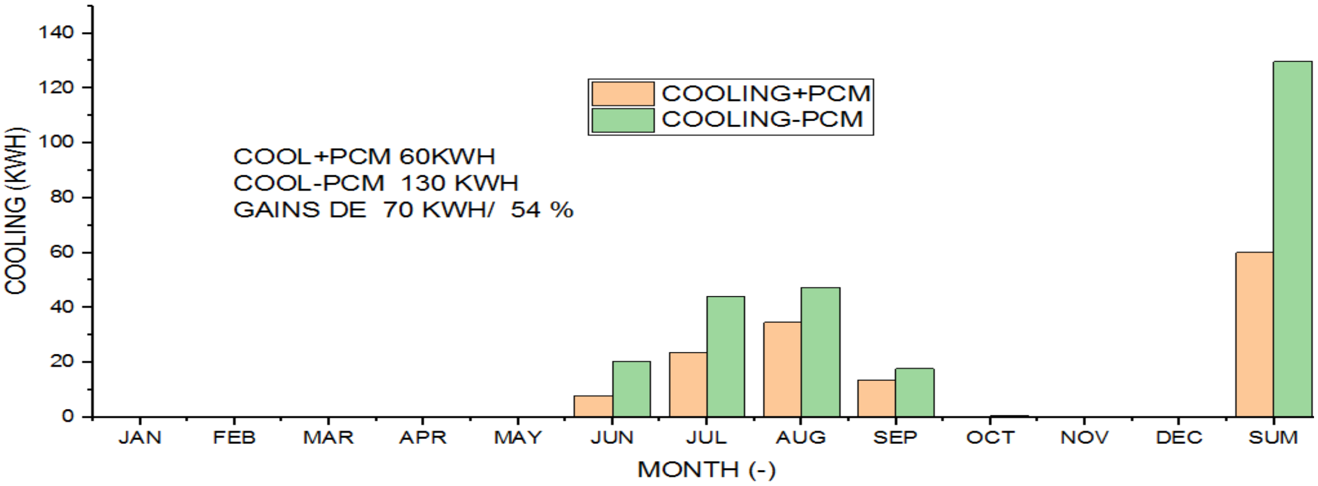


Figure 26: Annal consumption of COOLING

Figures 25.26 summarizes the annual heating and air conditioning loads .The total thermal and electrical energy cnsumption for heating and air conditioning equipments shows that the building with PCM minimize the energy for the tow loads compared to a building without PCM , the energy need for the PCM wall is 1125KJ and without PCM 1348KJ difference of 226 KJ . SO the building envelope with phase changematerials maintain the thermal and electrical energy consumption17%. The energy consumption with pcm in August was 33 Kwh and without pcm51 Kwh. The some results convey that the presence of the phase change material in the building envelope maintain the annual consumption and demand for heating and cooling and achieved energy savings by diminishing the cold period retaining the heat solar charging during the phase change can storage the solar energy and heat transfer and minimize the period of air conditioning maximally avoiding overheating due to solar gains and internal gains and control the heat flux and thermal comfort in the interior wall for the building envelope . The annual needs for consumption air conditioning and heating are according to the NOUSSEUR climate zone 1 (AGADIR), these annual needs are 25 kWh/m²/year for residential buildings [RTCM, 2014]. The results clearly convey that the charge needs are about 13.31 kWh/m²/year. These percentage needs represent 48.76% of the needs set by the MOROCCAN regulation (RTCM.2014.).

15. Convective Heat Flow

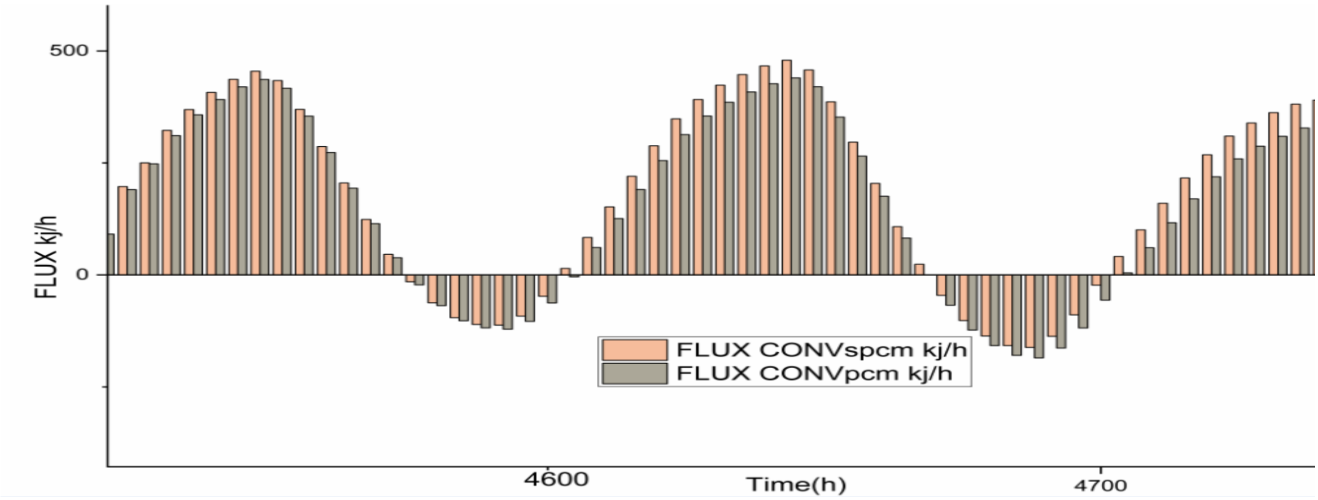


Figure 27: Evolution of convective heat flow without PCM and with PCM in summer

The comparison of the convective solar heat flow asserts that the phase change materials has a effect influence on the reduction ofenergy solar heat gains transmitted in the interior of the building envelope , which directly affects the heat transfer convection conduction and radiative transfers , the air temperature variations and the thermal comfort and the relative humidity of the building as well as its improving the energy performance.

The improvement of the wall through the reduction of the thermal transmission also influences in a positive way the internal ambient temperature ,the creation of thermal comfort inside the building and present the best inertia for the all wall the building envelope.

Fig. 28 shows the results of the growth of the internal surface temperature without and with pcm phasechange materials in summer and the outside surface temperature without and with phase change materials. The internal surface temperature of phase change materials is 23°C and without pcm 25.3 °C , within a fluctuation range of 2.06 °C. The outside surface temperature of phase change materials is 29°C and without PCM 34.42 °C within a fluctuation range of 5.36 °C .so the phase change materials acts the control for the external and intern surface temperature and thermal and electrical energy and thermal and fresh comfort zone

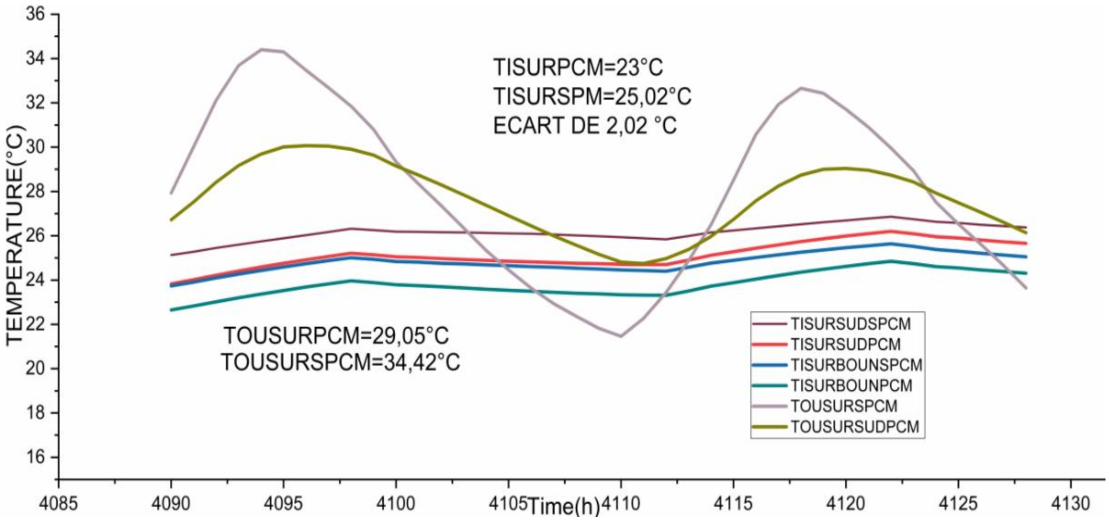


Figure 28: Growth rate of the external and internal surface temperature with and without phase change materials

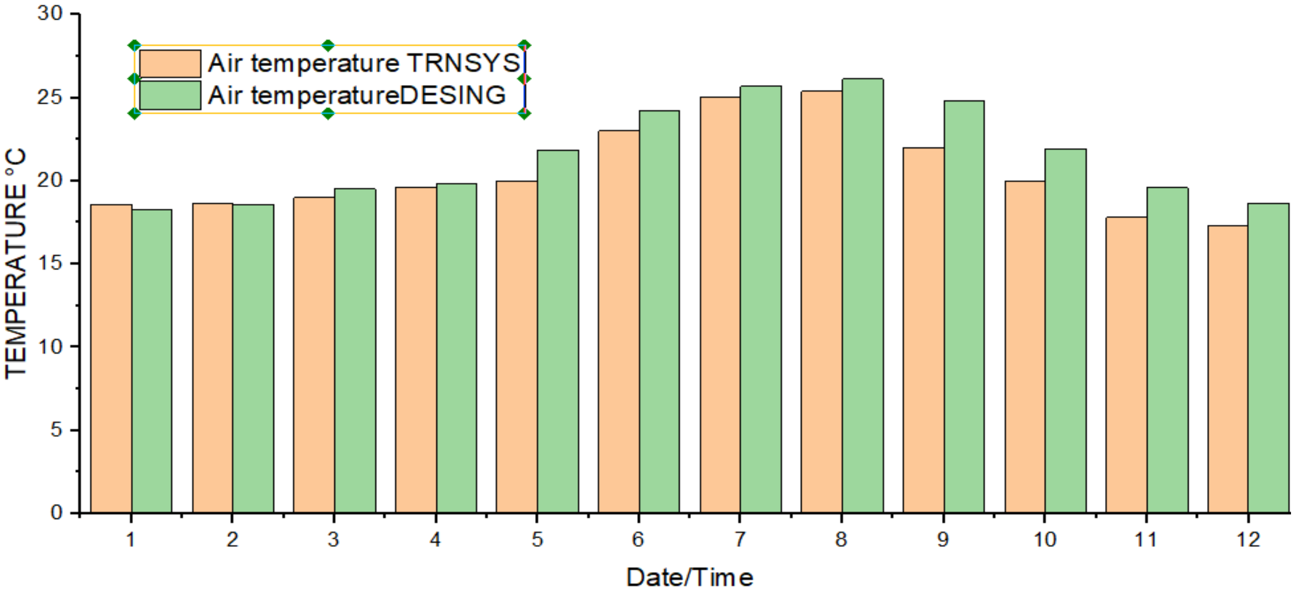


Figure 29: Growh rate the internal ambient air temperature with PCM in energy plus and TRNSYS

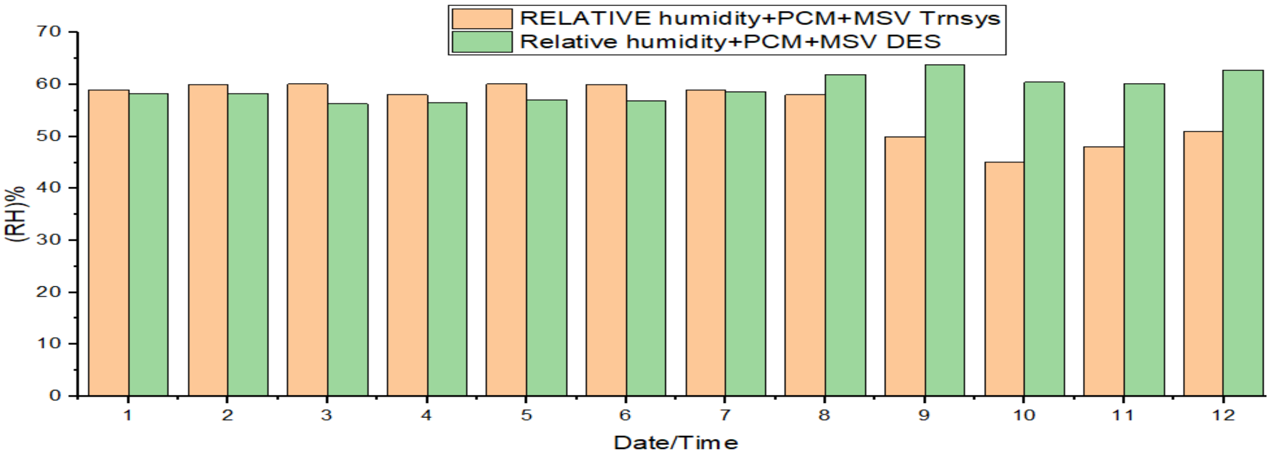


Figure 30: Growth rate of the relative ratio humidity in TRNSYS and Energy plus

Figure 29.30 present the growth rate of the ambient temperature and relative ratio humidity of the two software TRNSYS and Energy plus. The results of the simulation similar in the regalement RTCM ;so it is according to a comfort interval (19°C to 26°C) .The difference of the ambient internal air temperature is 2.6°C and 17 % the difference about relative ratio humidity.So the difference between TRNSYS and Energy plus conclude that TRNSYS is it , expert software for dynamic temperature and thermal ans electrical energy simulation.

- EnergyPlus: Tool developed by Department of Energythat has a finite difference algorithm (CondFD) method coupled with an enthalpy temperature function to simulate PCM that has been verified and validated.
- WUFI: Tool developed by the Fraunhofer IBP, Holzkirc.hen, Germany presents numerical tools for modeling the heat and moisture transfer within building structures. WUFI, which in German stands for “Wärme und Feuchte instationär”. WUFI can perform coupled transient heat and moisture transport simulations user-defined time steps using Finite-volume method and is able to simulate PCMs as illustrated by previous studies.

TABLE 2 summarizes Latent heat methods, discretization and time integration computation methods used in this study with different PCM modelling software. PCM modeling modules used in whole building energy modeling software and studies which have added corrections to the existing methods and added techniques to address the complex PCM behaviors are shown in Appendix B. Based on this analysis we select the enthalpy method to model latent heat, finite difference method for discretization, and fully implicit method for time integral computations in the 1D heat transfer modelling algorithm to model building walls with PCM presented in this thesis. This heat transfer modelling algorithm is modeled using MATLAB modelling language.

Software	Latent heat method	Discretization	Time integration computations
COMSOL	Enthalpy	Finite element	Implicit
ESP-r	Effective heat capacity	Finite volume	Explicit
EnergyPlus	Enthalpy	Finite difference	Implicit
TRNSYS	Effective heat capacity or Enthalpy	Finite difference /Finite element	Implicit: Crank–Nicholson
WUFI	Enthalpy	Finite volume	Implicit

Table 2: Latent heat methods, discretization and time integration computation methods used in this study with different PCM modelling software

16. Conclusion

The application the composite phase change materials (PCM) into the building envelope results in an increase in the electrical and thermal energy storage capacity, providing an effective and reliable means of improving the energy efficiency of buildings. It is concluded that composites incorporatingphase change materials are capable of diminish the thermal and electrical energy costs, about air conditioning and heating demands of the building. Also we can contribute to diminish the CO2 emissions associated withair conditioning and heating equipment. The thermal and electrical energy performance of a building located in (CASABLANCA NOUASSEUR) were addressed. First, a dynamic thermal simulation of the building using TRNSYS TYPE 204 software was according and its results were successfully validated against the experimental results obtained from the monitoring. In this study, the effects of the location of the incorporating the phase change materials on the thermal and electrical performance of the multi-layer wall3D is studied numerically under the climatic conditions of (CASABLANCA NOUASSEUR).

The simulation also convey that the use of phase change materials in brick walls diminish overheating in the summer period, losing the ambient indoor air temperature by 3.4°C in summer, require the annual percentage about the electrical and internal energy for heating and air conditioning by 31%. These percentage needs represent 48.76% of the needs set by the MOROCCAN regulation (RTCM.2014.). So the total results convey that the presence of the phase change material in the building envelope maintain the annual consumption and demand for heating and cooling and achieved energy savings by diminishing the cold period retaining the heat solar charging during the phase change can storage the solar energy and heat transfer and minimize the period of air conditioning maximally avoiding overheating due to solar gains and internal gains and control the heat flux and thermal comfort in the interior wall .In summer, a high thermal capacity prevents the indoor air temperature from rising, minimizes the cooling load or eliminates it altogether and minimizes the investment costs of the necessary cooling equipment. It is concluded that the efficiency of the PCM can be improved if the building can be properly ventilated so for that in the next article we will deal with the integration of mechanic solar ventilation with the phase change material to increase the thermal and electrical energy and created the comfort and fresh zone and attenuate the performance energy to achieve a positive building [50-72].

Nomenclature

A : thermal diffusivity (m2/s)
Cp :specific heat capacity (J/kg.K)
Cel : cost of electricity
E : layer thickness (m)
H : heat transfer coefficient (W/m2.K), specific enthalpy(J/kg)
i :inflation rate (%)kwh
k :thermal conductivity (W/m.K)
n :lifetime of building (years)
N : number of layers of the composite wall
Qc :yearly cooling transmission loads (J/m2)
Qh :yearly heating transmission loads (J/m2)
Qtot :total yearly transmission loads (Qtot ¼ Qh þ Qc) (J/m2) t
: time (s)
T : temperature (°C)
Ta :ambient air temperature (°C)
Tc : cooling set-point temperature (°C)
Tsky :sky temperature (K)
x :coordinate direction normal to the wall (m)
Greek Symbols
ε :emissivity f :time lag (h)
h :reduction rate of annual energy consumption (%)
hs: efficiency of the heating system
c :onvective
i :inside, node number
j :layer number o: outside
r: radiative
S :surface, solar
Qi Net heat gains W
Q surf Convective gains from interior walls W
Q inf Infiltration gains W
Q wind Ventilation gains W
Q g,c Internal convective gains (from occupants, equipment, lighting, etc.) W
Q cplg Convective gains due to airflow between zones W
Q ISHCCI Solar radiation absorbed by internal shading devices in the zone, which is directly transferred as convective gain to the indoor air W
Q r,wi Radiative gains through the wall surface node W
Q g,r,wi Internal radiative gains received by the wall W
Q ground,wi Solar gains received by the wall via the windows W
Q long,wi Gains through radiant heat exchange between a wall and other walls in the zone W
QH Heating load kWh/(m^2.y) QC Cooling load kWh/(m^2.y)
Q Total heat load kWh/(m^2.y) RH Relative air humidity %.

Acknowledgements
The technical inputs of Fhcc organism and I sincerely thank of Mr Mouhib Taoufiq and Bendriaa Farida of Physical Engineering Department are acknowledged and HassanI First University of Settat, (ENSA) Ecole Nationale des Sciences Appliquées, LISA Laboratory and CNRST organismof Physical Engineering Department are acknowledged and Hassan I First University of Settat, Ecole Nationale des Sciences Appliquées, LISA Laboratory.and CNRST organism.

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