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Renewable and Sustainable Energy Reviews

Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review

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Abstract

The increasing share of intermittent renewable energy on the grid encourages researchers to develop demand-side management strategies. Passive heat storage in the indoor space is a promising solution to improve the building energy flexibility. It relies on an accurate control of the transient building temperature. However, many of the current numerical models for building energy systems assume empty rooms and do not account entirely for the internal thermal inertia of objects like furniture. This review article points out that such assumption is not valid for dynamic calculations. The furnishing elements and other internal content can have a significant impact on the indoor thermal dynamics and on the occupants' comfort. There is a clear lack of guidance and studies about the thermo-physical properties of this internal mass. Therefore, this paper suggests representative values for the furniture/indoor thermal mass parameters and presents the different available modelling technics. In addition, the large exposed surface area of furniture pieces offers a good potential for the integration of phase change materials. It can highly increase the effective thermal inertia of light frame buildings without any construction work.

Keywords: Furniture, thermal mass, indoor thermal dynamics, thermal energy storage, phase change material, building energy flexibility.

1. Introduction

Climate change, pollution and fossil fuel shortage have been designated by many as some of the most important challenges of the 21st century. To prevent major energy crisis and reduce CO2 emissions, significant efforts are required in increasing the renewable energy production while enhancing the energy efficiency of buildings [1]. With about 40% of the total final energy use in Europe, buildings are indeed the largest end-use energy sector, followed by transportation with 33%. Similar repartitions can be observed in the rest of the world [2]. On the production side, a significant expansion of wind and photovoltaic power is planned in many European countries [3]. In Denmark, for example, the energy mix is characterized by a large share of wind power which is expected to reach 50% on an annual basis in 2020. The energy development strategy of countries like Denmark relies on the implementation of a smart grid with high number of wind turbines coupled with district heating for buildings in cities, heat pumps outside urban areas and extensive use of electric cars [4] and [5].

Studies suggest that flexible technologies and demand-side management can improve the integration of renewable energies and facilitate operation of a smart grid system with high intermittent power penetration [6]. Indoor space heating accounts for 75% of the energy demand of a building in Europe [2]. Analyses showed that individual heat pumps and district heating form the best heat supply solutions in relation to costs, fuel consumption and CO2 emissions [7]. This thermal energy can be stored efficiently in the building indoor environment or in heat accumulation water tanks. It can thereby decouple the energy need from the intermittent availability of renewable energies, reduce excess wind electricity production and allow optimum use of the free internal and solar gains [8].

Low temperature, water-based radiant heating systems can accumulate heat in buildings with noticeable flexibility. They can be controlled according to a price signal and contribute to shaving of load peaks on the grid without affecting indoor comfort. A research indicated that passive heat storage in the indoor space can be more efficient for the reduction of excess electricity production and fuel consumption compared to heat accumulation water tanks [9]. Passive thermal energy storage (TES) aims to accumulate a maximum amount of heat in the building thermal mass and indoor volume. The operative temperature in the building increases when the electricity is available and cheap, and decreases when the power production is too low. However, the temperature must be kept within the limits of occupants' thermal comfort.

The study, implementation and optimization of such strategy for energy flexible buildings need accurate dynamic thermal building models. Nevertheless, many of the current numerical models take into account solely the thermal inertia of the envelope, the floors and the internal walls. The indoor thermal zone is considered as an empty space filled with air only. Furniture and additional mass present in a real occupied building are not included. This assumption is reasonable for classic design and energy analysis of buildings based on steady state or simplified long-term calculations. However, it could lead to noticeable errors for short-term transient temperature prediction, especially in residential buildings with light structure and a lot of furnishing, appliances or objects. This model simplification is thus worth investigating to quantify the role of furniture/indoor thermal mass and develop passive TES with optimum predictive control.

The large surface area of the furniture exposed to the indoor environment can be ingeniously used for latent heat thermal energy storage (LHTES) with the integration of phase change materials (PCMs). Their appreciable energy storage density is an interesting asset for increasing the thermal inertia of light structure buildings and for extending the applicability of the TES strategy. PCM furniture could allow integration of LHTES in low thermal inertia dwellings without the need for building renovation.

This paper aims to review the different scientific studies dealing with the influence of the indoor mass on the building thermal dynamics and emphasises the opportunities for coupling with the PCM technology. The article will first define the thermal mass in buildings. This is followed by a review on the interaction between the internal elements and the indoor environment. Representative thermo-physical characteristics for indoor content will be suggested based on published data and a simple building survey in Denmark. The article will then present different internal element modelling technics. The two last parts of this paper will discuss the different kinds of PCMs and the potential for their integration in furniture. The paper closes with conclusions and proposal for further investigations.

2. Definition

From the thermodynamics point of view, a building is usually considered as an assembly of sub-systems or thermal zones. Each of them is composed of elements with specific conductance and thermal inertia **Error! Reference source not found.**. This section suggests distribution of these thermal inertia elements into three categories: thermal zone envelope, indoor air volume and furniture/indoor thermal mass. Construction parts such as external walls, floors, ceilings, roofs or partition walls form the envelope of the thermal zones. They often integrate heavy materials from the building's structure and have a significant thermal inertia [11]. The external thermal mass of the building envelope is exposed to the outdoor and indoor environment. It is not isothermal and its internal energy varies slowly. On another hand, the air volume contained inside a thermal zone is usually considered as one single node with homogenous temperature. The indoor air temperature can vary quickly because of its limited thermal inertia **Error! Reference source not found.**.

If many numerical models only account for the indoor air volume and the zones' envelope thermal mass, the real occupied buildings are actually not empty spaces. The additional furniture/indoor thermal mass of a building is defined as all the matter in a room with the following characteristics:

- It is not defined in the construction elements of the building envelope, floor, ceilings or partition walls.
- It is permanent in the thermal zone. It can move inside the same zone, but it does not leave it.
- It does not emit noticeable heat.
- Its temperature is driven by convection heat exchange with the indoor air and long-wave radiation heat exchange with the envelope inner surfaces, plus the internal heat gains (sun, HVAC systems, equipment and people loads).

According to that definition, the furniture/indoor thermal mass is composed of all the furnishing elements (sofa, bed, table, chair, desk, cupboard, closet, shelves and boards), the finishing parts or accessories that are not directly integrated in the envelope or walls and the aggregate of the other objects present in a room (plants, books, clothes, paper and small appliances). It excludes the body of living beings, movable objects, which enter and leave the zone several times a day, HVAC terminals (radiators, air handling units) and all equipment emitting heat energy (computer, ventilator, engines, lighting, lamps).

3. Influence of furniture and internal mass on the indoor environment

The furniture/indoor thermal mass elements present a large surface area for interaction with the indoor environment.

They exchange heat and moisture by convection with the indoor air and by diffusion with direct contact surfaces such as floors or walls. They also exchange heat by long wave radiation with the surrounding surfaces and can cover and hinder heating or cooling radiant systems. They can change air flow pattern in the room and affect ventilation efficiency and convection heat transfer. They can also reflect, diffuse and absorb solar radiation or internal gain and release it quickly to the surrounding air.

The furniture/indoor thermal mass is thus highly activated and coupled to the other elements. It is legitimate to wonder if this additional internal mass can be neglected in numerical models. This simplification could lead to significant errors especially for light structure houses or radiant systems. Some researchers have investigated this question. Most of the building related publications about internal mass and furniture study the chemical compounds emission of the different materials of furnishing parts and its impact on the indoor air quality [12]. Building numerical analysis including details of interior partitions and furniture has pointed out that they have a significant impact on daylight conditions [13]. However, the following discussion will only focus on the indoor thermal comfort and the thermal dynamics issues.

3.1. Micro-climate, indoor humidity and local discomfort

Mortensen et al. [14] investigated the local micro-climate created by furnishing elements close to cold walls. A piece of furniture placed near a poorly insulated external wall can lead to condensation on the inner side of the building envelope. The authors used particle image velocimetry to perform a two-dimensional experimental analysis of the airflow pattern in a small air gap between a chilled wall and a closet placed next to it. Two air gap widths were tested: 25 and 50 mm. Length of legs of the furniture varied from 0 to 200 mm. The study indicated that vertical flow dominates with similar behaviour as in between vertical plates heated asymmetrically. The flow in the air gap was not fully developed and maximum velocities were found near the cold wall. Finally, the flow rate increased when the gap was expanded or if the furniture was elevated from the floor.

The humidity buffering effect of materials located in the thermal zone can reduce humidity variation. It improves thermal comfort and decreases energy consumption of the mechanical systems for humidification or dehumidification. Yang et al. [15] conducted full-scale experiments on moisture buffering capacity of interior surface materials and impact of the presence of furniture in the interior space. The results showed that the indoor humidity variation decreased by up to 12% and the total moisture buffering potential of the room increased by up to 54.6% for a fully furnished case. The authors explained that furnishing elements present much more surface area for moisture exchange and buffering than envelope inner surfaces. Furniture materials can also hold more water vapour than interior surface ones. In addition, the variation of moisture contents of walls screened by furnishing is not always the same as in an empty room. The results also indicated that a bookshelf with books and a bed with mattress present higher moisture buffering capacity than tables, chairs and curtains.

In [16], Horikiri et al. used computational fluid dynamics (CFD) to assess the effect of room occupancy and furniture arrangement with and without heat generation in terms of local thermal comfort. Three different configurations of furniture and occupants were compared with the empty room case. The study pointed out that addition of non-heat generating furnishing in the ventilated room can induce complicated flow re-circulations and high local air velocities around edges of the furniture. However, it has little influence on room temperature and airflow buoyancy strength, compared with that of unfurnished room case. Finally, the heat generation from the TV did not have important impact on the thermal comfort and heat transfer.

Another CFD analysis [17] looked into the interaction of ventilation and air-conditioning emitters with furniture in a bedroom. It concluded that the location of air-conditioner unit should take into account the existence of the room's furniture to avoid cold air re-circulation and local draft. Furniture obstruction can indeed lead to the air jet to not fully develop and bounce directly to the occupants.

These different publications emphasised that the existence of furniture in the indoor environment can have a significant impact on the internal air dynamics, local and global humidity conditions and comfort.

3.2. Impact of indoor elements on HVAC systems performance

Furnishing, carpets and interior decoration elements are often laid directly on the rooms' internal surfaces. They produce sensitive changes in radiative and convective heat exchange processes and impact the performance of heating and cooling radiant systems. It is therefore stated in the REHVA Guidebook [18] that additional surface thermal resistance should be applied in order to account for carpets and finishing layers covering radiant floor systems.

Zhao et al. [19] performed detailed calculations and field tests, which emphasised the effect of chairs and benches on the performance of radiant floor cooling systems, exposed to high solar load in a large building. These furnishing elements can overshadow the cooling surface and produce local lower surface temperatures. The floor surface under the benches was 3.8 to 7.5 °C colder than the unsheltered one. Consequently, the cooling effect of the covered radiant floor was decreased by 83%. The risks of moisture condensation on these cold shaded zones are also much higher. This should be taken into account for the system's design to insure that the lowest surface temperature is kept higher than the dew point of the local surrounding air.

Corcione et al. [20] published numerical studies showing a non-negligible decrease in the heat transfer from radiant surface systems to the furnished indoor space in comparison to an empty room case. The air and mean radiant temperature were also impacted. Fontana [21] extended this work with experimental investigations using a small-scale test setup to look at the impact of furniture pieces with different surface areas, locations and distance from the floor. The author concluded that 40% of floor covering with different kinds of furniture can reduce the heat flux from the radiant floor to the room by 25% to 30%.

Pomianowski et al. [22] conducted a full-scale experiment concerning the influence of an internal obstacle on the overall heat transfer in a room when using displacement night time ventilation. The presence of a table changed the average convective heat transfer coefficient in the test chamber and the mean heat flux at the ceiling by 3.96% and 9.84% respectively, when applying an air change rate of 6.6 h^{-1}. The only noticeable drops in the temperature efficiency caused by the presence of the table were observed at low air change rates.

The studies presented above pointed out that the influence of furniture cannot be neglected when designing a radiant floor system. Surprisingly, it has been found that Fontana [21] was the only one to publish the results of an experiment investigating the impact of furniture on radiant systems. As mentioned by Le Dréau [23], further experimental researches are required to quantify the effect of furniture on the effectiveness of radiant systems.

3.3. Building thermal dynamics

The transient thermal behaviour of buildings mainly depends on the heat load admission rate and the activated thermal capacity. The building effective thermal capacitance quantifies its practical energy storage potential. It can considerably differ from the apparent thermal capacitance, which is the sum of specific heat capacities of the building elements [24]. Many different studies looked into the impact of the thermal inertia on the building dynamics, the reduction of temperature swings and cooling peak shaving with night time ventilation strategies [25], [26], [27] and [28]. However, most of them only consider the thermal mass of the building envelope and partition walls.

Antonopoulos and Koronaki [24], [29] and [30] characterized the thermal capacitance, time constant and thermal delay of typical Greek detached houses with a one-dimensional finite-difference model. The authors took into account the presence of furniture thermal mass and modelled it as an equivalent one-side wooden slab of 6 m^2 per m^2 of floor area and a thickness of 5 cm, which gives an internal mass density of about 180 kg per m^2 of floor area. No justification was given for the choice of this value. Solar load and internal heat gains were applied to the air node only. The results showed that the envelope, partition walls and furniture represented 78.1%, 14.5% and 7.4% respectively, of the total effective building thermal capacitance. The authors concluded that furniture/indoor mass can increase the building time constant and thermal delay by up to 40% (25% for interior wall partitions and 15% for the furnishings).

Yam et al. [31] developed a simplified building model with adiabatic envelope and no internal sun load to inspect the nonlinear coupling between internal thermal mass and natural ventilation. They found that a maximum indoor temperature phase shift of 6 hours can be achieved if the fresh air is directly supplied from the outdoor environment, presenting periodic temperature variations. The authors suggested that an appropriate amount of thermal mass should be used in building passive design because further increase above an optimum point does not change the phase shift of the system. Zhou et al. [32] extended the aforementioned study by adding the envelope thermal mass into consideration. The results showed that increasing the internal thermal mass of a building with a large time constant to adjust the indoor air temperature is not an effective solution.

Wolisz et al. [8] carried out a numerical analysis on the impact of modelling furniture and floor covering in thermal building simulations with temperature set point modulation control. The study cases were a massive building and a light frame building, both with very good insulation levels and under-floor heating systems. The furniture element was represented by an equivalent horizontal board of wood or metal. Long-wave radiation heat exchanges were modelled by coupling inner surfaces to a fictive massless black body node in a star network scheme [33]. One internal wall had 50% of its surface area covered by furniture. It was found that after 4 hours of increased set point, an empty massive room was 1.2 °C warmer than the one with flooring and furniture. A fully equipped massive room can have a time delay of more than 7 hours to raise its temperature by 5 °C, compared to an empty room. Furnishing and floor covers can change cool-down times by up to 2 hours in the case of periodic set point control. The floor covering presented more significant effect on the heating time than the furniture element because the under-floor radiant system was used as a heating source. However, the effect of furniture became more important for the lightweight room with periodic set point scenario. The authors concluded that both the furniture and the floor covering of a room have a distinct and significant impact on the indoor temperature for dynamic set point control.

If the influence of furniture is negligible in the case of steady state building thermal calculation, it is clearly not the case for the evaluation of dynamic strategies such as night time ventilation cooling or passive TES. The previously reviewed publications showed that the empty thermal zone assumption will necessarily lead to a noticeable under-estimation of the building thermal capacitance and thus higher internal temperature swing. Consequently, such simplification can produce deviation of few degrees in the calculation of dynamic indoor temperature, which is significant for set point modulation control and TES in the indoor space.

3.4. Impact of internal mass on building energy needs

Only one publication focusing on the effect of furnishing on the building energy need has been found. Raftery et al. [34] performed a sensitivity analysis on the influence of furniture on the peak cooling load of a large open space multi-story office building located in San Francisco. The authors used the Energy Plus software and varied multiple parameters such as type of HVAC system, building orientation, window to wall ratio, envelope thermal inertia and amount and surface area of the internal mass element. Two different furniture models were tested: a simplified non-geometric furniture element, which is not taken into account for solar radiation and long-wave heat exchange and a new model with a geometric representation of an equivalent furniture slab located in the centre of the room, 0.5 m above the floor. With the latter, direct and diffuse solar radiation repartition can be executed accordingly with shading effect of the planar element on the floor. Long-wave radiation heat exchange can also be calculated with correct view factors. Results were presented using the median value following by the lower and upper quartiles in parentheses. The study found that internal mass can change peak cooling load by −2.28% (−5.45%, −0.67%). The geometric modelling changed peak cooling load by −0.25% (−1.02%, +0.23%) when compared to the non-geometric model. This geometric modelling had a larger effect in cases with high direct solar radiation and almost no effect for low solar loads. The impact was also found more important for HVAC radiant systems, which yield a surface temperature asymmetry. The thickness of the internal mass element had a relatively large impact on results. Very thin elements with a small time constant convert the solar load into a convective load quickly and can thus increase the peak cooling load. The authors concluded that the choice of modelling method is not significant compared to the uncertainty on the internal mass characteristics such as surface area, material properties, weight and thickness.

4. Internal thermal mass characteristics

As pointed in [34], there has not been found any survey, study or clear guidance concerning reasonable or typical values for furnishing/indoor mass parameter in buildings. This section treats this issue by presenting the results of a simple survey performed on residential and single office buildings in Denmark. Since the total amount of internal mass in each room and building can vary significantly from case to case, only a survey with a large sampling could pretend to provide statistically representative data. Therefore, the following study only intends to suggest reasonable boundaries for the internal mass and furniture parameters.

4.1. Internal mass materials

Multiple sources such as international standards, software documentation, industrial technical reports and scientific publications have been combined [35], [36], [37], **Error! Reference source not found.**, [39], [40], [41] and [42] to assess the thermal properties variation span of common building materials.

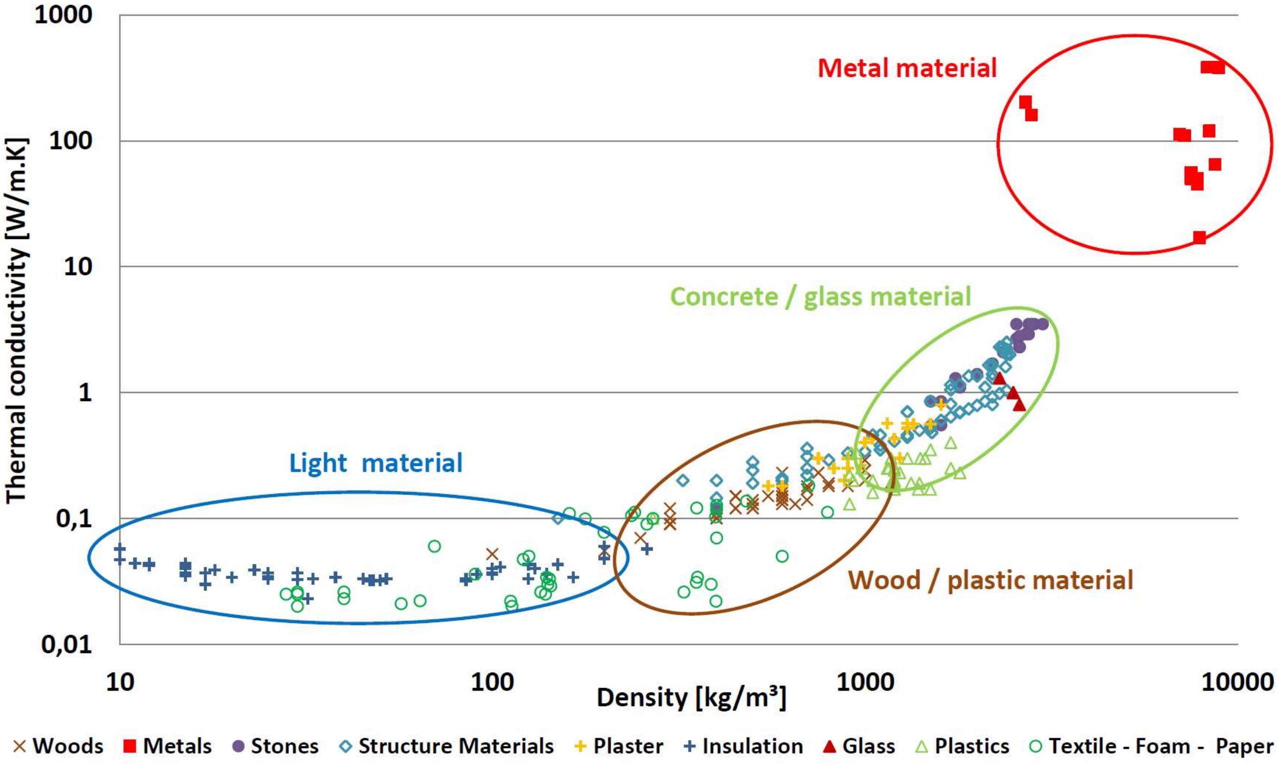


Fig. 1. *Thermal conductivity of building materials in function of density.*

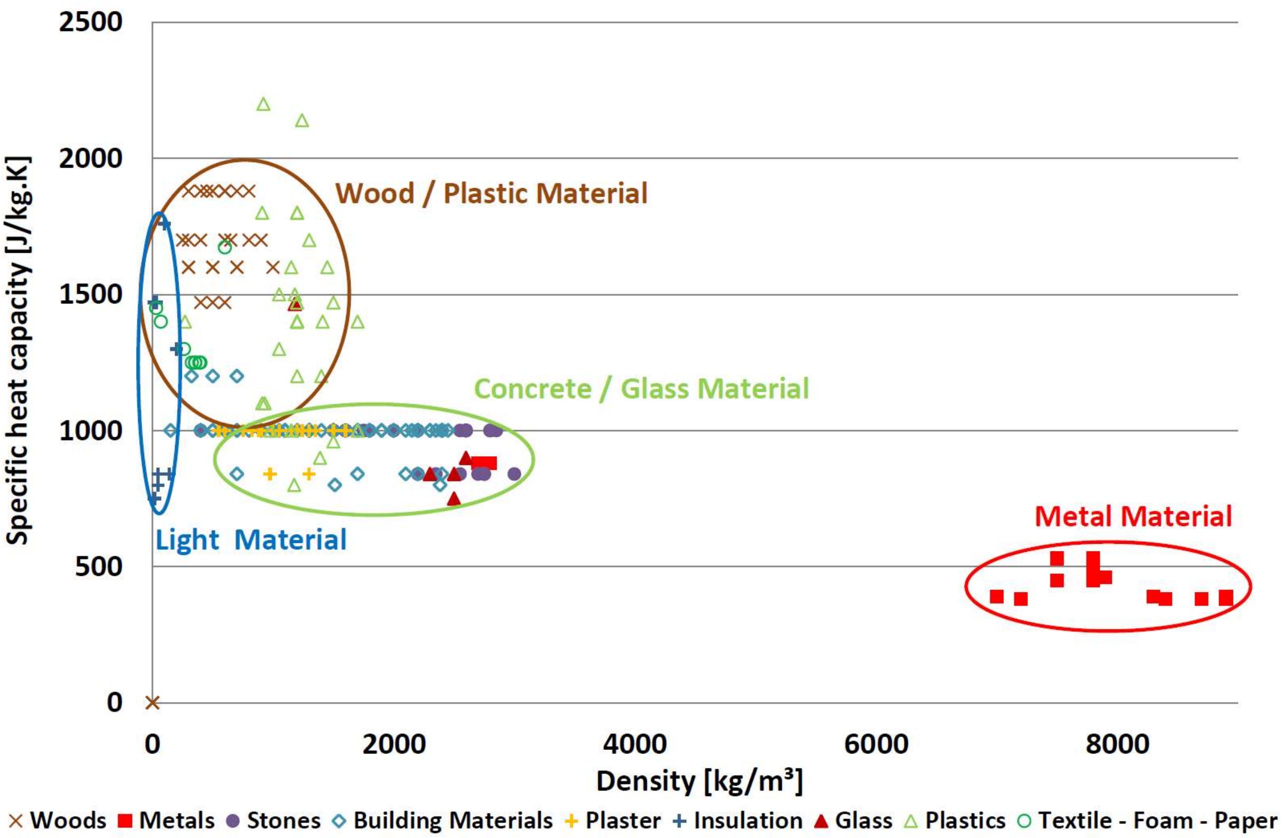
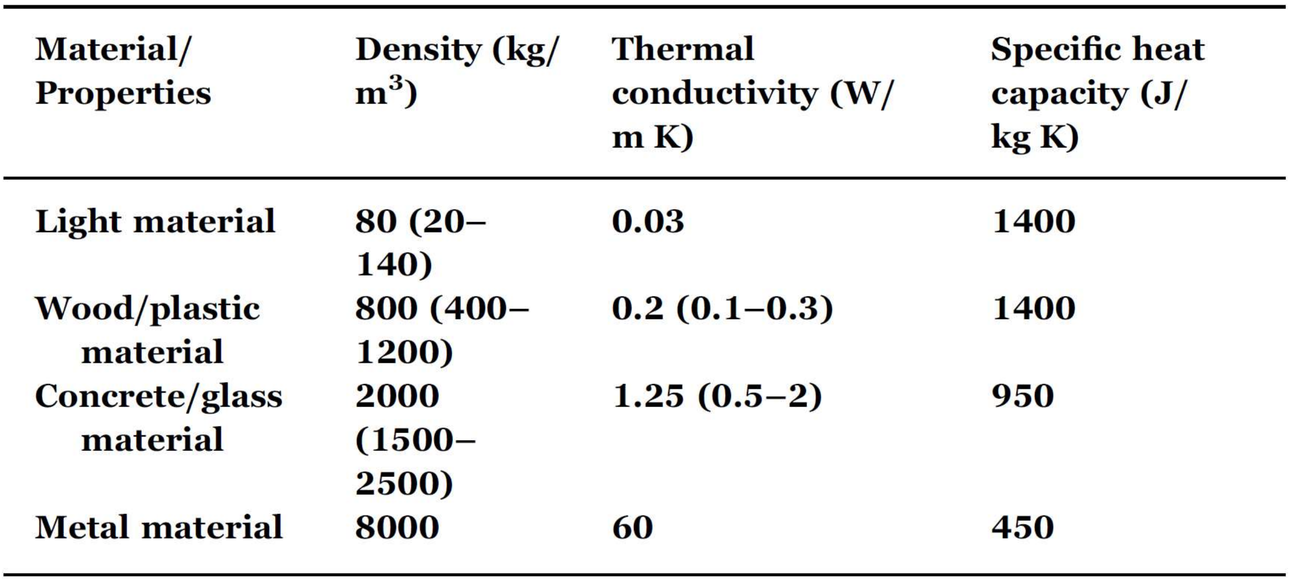


Fig. 2. *Specific heat capacity of building materials in function of density.*

Density and thermal conductivity are two parameters, which are relatively easy to measure precisely. They are well defined in different catalogues. In **Fig. 1,** one can see a clear correlation between material density and thermal conductivity. Several researchers have already studied this point [43], [44], [45], [46], [47] and [48]. Apart from metal, most of the building materials are porous media and compound of plastic, natural cellulose fibres or minerals. Their thermal conductivity is mainly determined by the air and water content, which is directly related to their porosity and, therefore, to their density. On the other hand, the specific heat capacity of the material is more difficult to assess. It has been noted that the same value is often given for the whole class of a material in the sources. As shown in **Fig. 2**, there is no clear relation between the density and the specific heat capacity of construction materials.

The mass and volume of objects are rather simple parameters to estimate. Therefore, it is suggested to classify the different materials in function of their density and deduct the thermal conductivity and specific heat capacity from this first characteristic. One can see this simple classification and representative thermal properties in **Table 1**.

Table 1. *Representative building material categories and their characteristics. The average value is followed by the lower and upper range limits in parentheses.*



Material/ Properties	Density (kg/ m^3)	Thermal conductivity (W/ m K)	Specific heat capacity (J/ kg K)
Light material	**80 (20–140)**	**0.03**	**1400**
Wood/plastic material	**800 (400–1200)**	**0.2 (0.1–0.3)**	**1400**
Concrete/glass material	**2000 (1500–2500)**	**1.25 (0.5–2)**	**950**
Metal material	**8000**	**60**	**450**

4.2. Element thickness

Most of the building and internal mass elements have a planar shape. It is, therefore, possible to measure their thickness and surface area systematically. The simple survey on the Danish buildings showed that the surface weighted average thickness of indoor wood elements is 1.8 cm. Minimum and maximum thicknesses are 1 and 5 cm respectively. Metallic elements have a thickness between 1 and 3 mm. Ceramic and glass pieces have a thickness between 0.2 and 2 cm. Light material elements have a thickness from 0.5 to 24 cm.

4.3. Quantification of the internal thermal mass

The total amount of internal mass in a building is not a trivial parameter to find. Unfortunately, professional removal companies do not estimate nor measure it. In [34], it is stated that the Californian non-residential alternative calculation method manual (2005) prescribes the value of 391 kg/m² of total floor area. It corresponds to about 470 kg/m² of net floor area. This value is very high because it probably takes into account the total amount of thermal mass including the envelope and the partition walls. The US benchmark commercial buildings from the PPNL (2013) and the DOE (2010) models use an amount of internal mass corresponding to 177 kg/m² of wood spread over twice the floor area. In the parametric study of Raftery et al. [34], the internal mass is varied from 0 up to 300 kg/m² of floor area. Antonopoulos et al. [30] used around 180 kg of wood per m² of floor area. In order to assess which of these values are realistic, the mass and dimensions of each piece of internal elements have been measured in 6 different bedrooms, 3 living rooms and 3 single office rooms in buildings located in Denmark. **Fig. 3** presents the results of this simple survey.

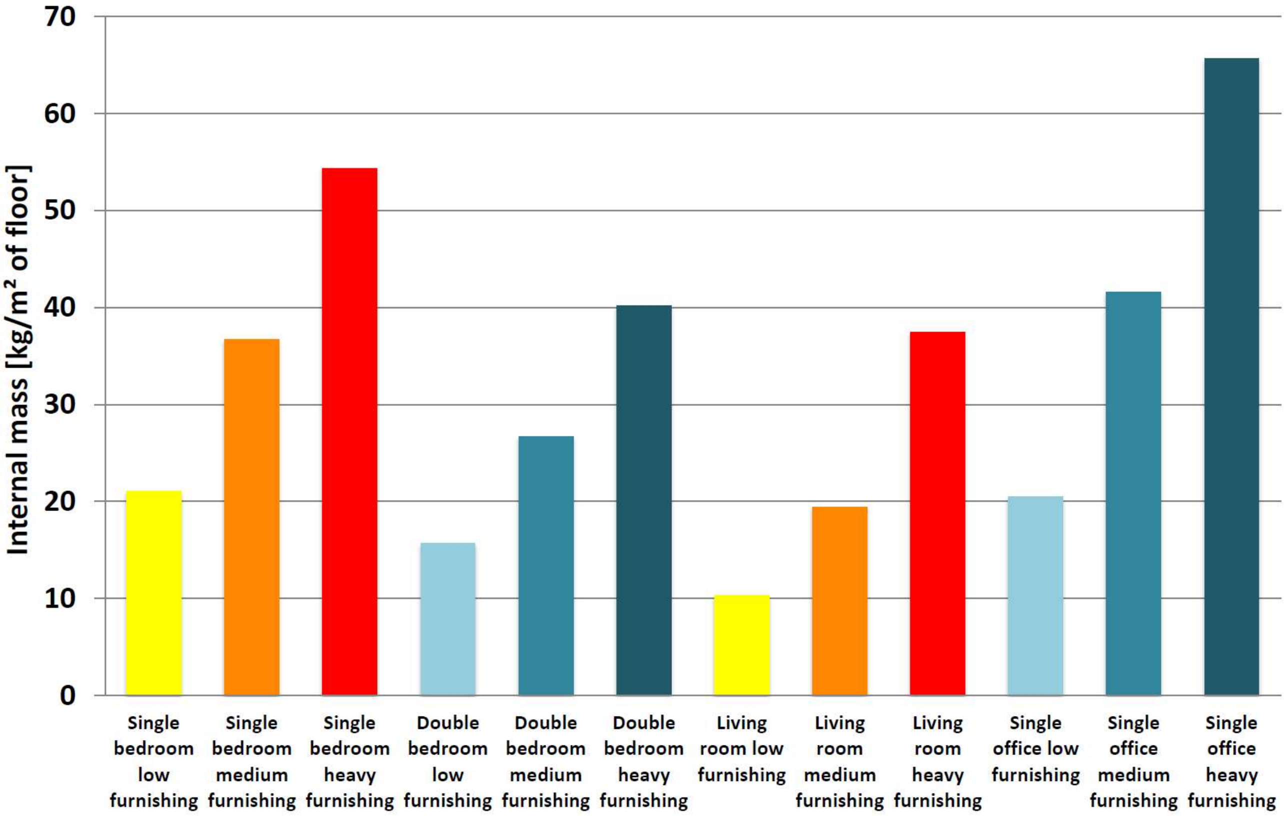


Fig. 3. *Internal mass of the building survey.*

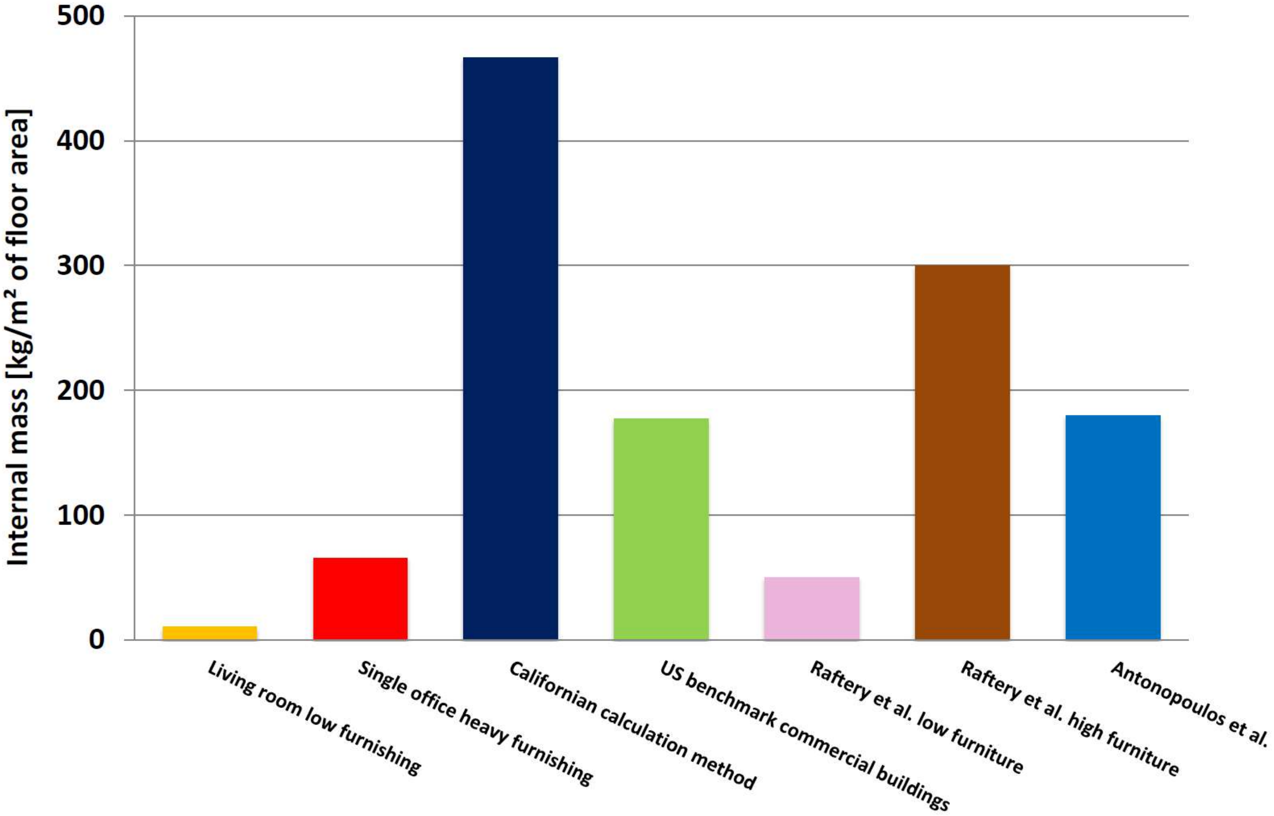


Fig. 4. *Comparison between results of the survey and other published values from Antonopoulos et al. [29] and Raftery et al. [34].*

As seen in **Fig. 4**, the total internal mass is often over-estimated. It is suggested that a reasonable range for the internal mass density in office and residential buildings would be 10 to 100 kg/m² of the net floor surface area.

4.4. Internal mass effective heat capacity

The thermal inertia of the different building elements can also be evaluated according to their effective heat capacity. It can be represented as the thermal storage capacity of a system subject to variable boundary conditions. It is chosen to use 24-hour period sinusoidal variations to assess the effective heat capacity of a building in the case of daily indoor TES. It can be calculated with a one-dimensional numerical model such as finite control volume method or with a matrix calculation procedure defined in international standards [49]. However, such calculation requires a detailed description of every element present in the indoor space, which is rarely the case. To overcome this problem, Wang et al. [50] modelled the internal mass of a thermal zone as a lumped thermal capacitance and identified this parameter from the HVAC operation data with a genetic algorithm estimator.

It is stated in the French energy building regulation that the effective daily heat storage capacity of furniture is 20 kJ/K.m² of floor area [11]. Antonopoulos et al. calculated a value of 45 kJ/K.m² for a typical Greek residential house [30]. In [23] and [51], the indoor air volume thermal capacitance is multiplied by 5 and 8 respectively, in order to account for the furniture thermal mass. This is equivalent to about 17 and 27 kJ/K.m² respectively. Based on the detailed description of the internal mass survey in Danish buildings, the effective daily heat capacity of each construction and internal element is calculated with the matrix calculation method [49]. Furniture elements, metal pieces, lightweight material, clothes, books, paper, appliances and other objects are aggregated in different equivalent planar elements with appropriate material thermal properties. The same constant surface resistance of 0.13 K.m²/W is assumed on both sides of the equivalent planar elements. Internal radiation gains are not taken into account.

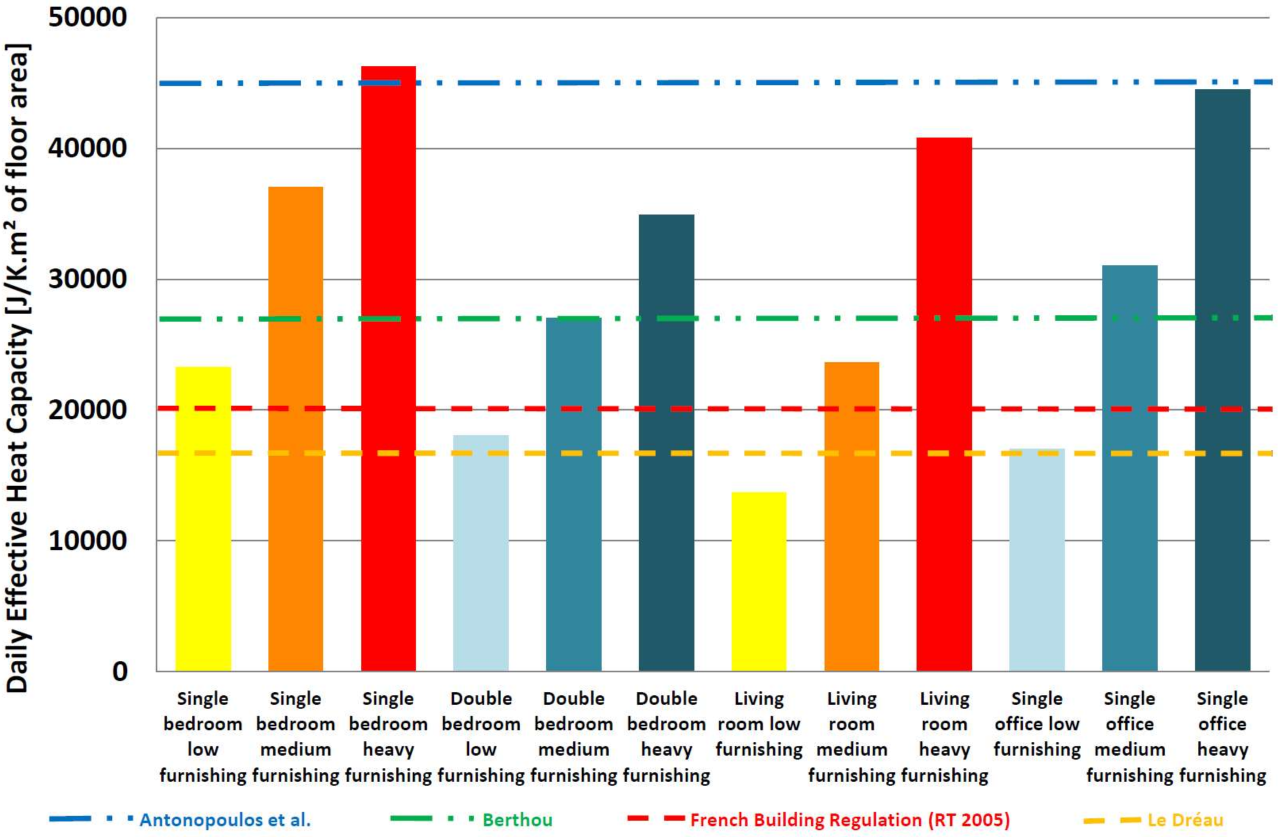


Fig. 5. *Daily effective heat capacity of internal thermal mass in buildings. Comparison with published values from Le Dréau [23], Antonopoulos et al. [29], French building regulation (RT 2005) [11] and Berthou [51].*

The results from the survey presented in **Fig. 5** are in good agreement with the other sources. The same matrix method is then used to calculate the daily effective thermal capacitance of the inner surfaces of the rooms for buildings with different class of envelope thermal mass.

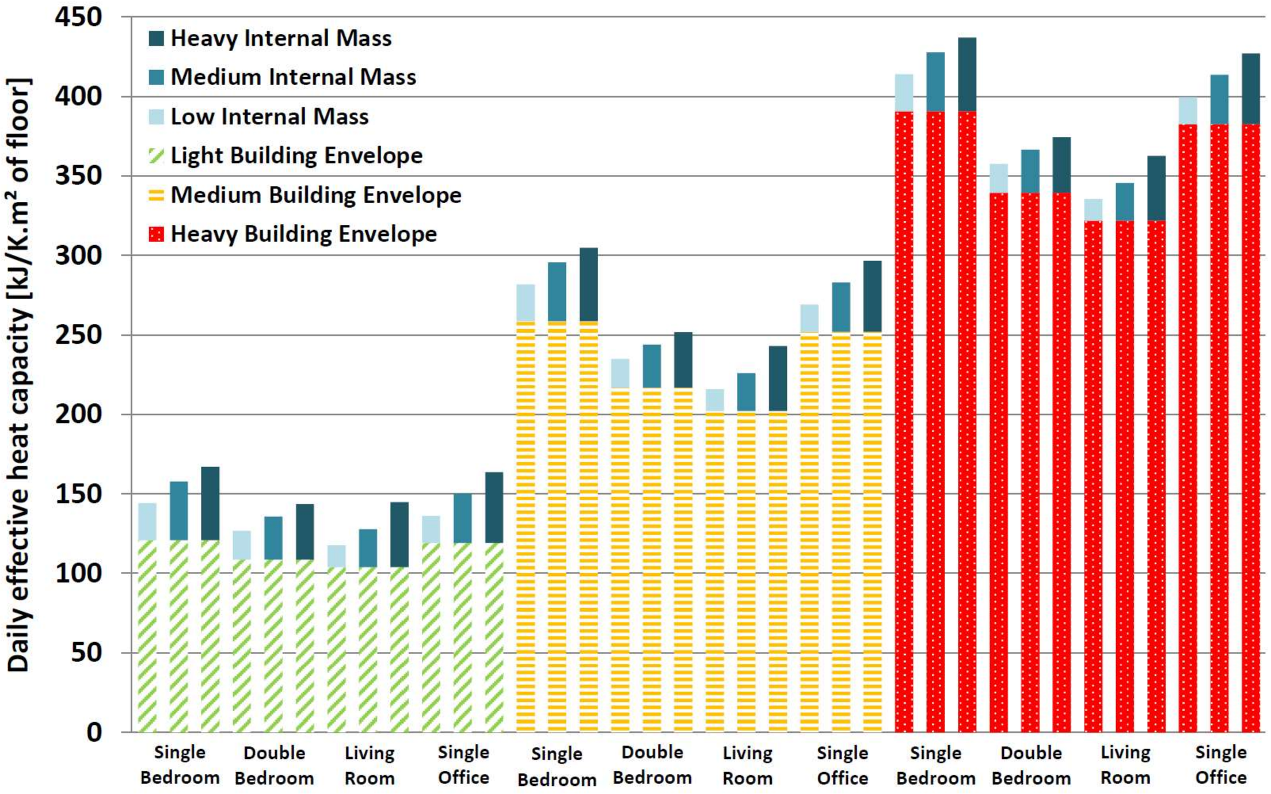


Fig. 6. *Total daily effective heat capacity of buildings.*

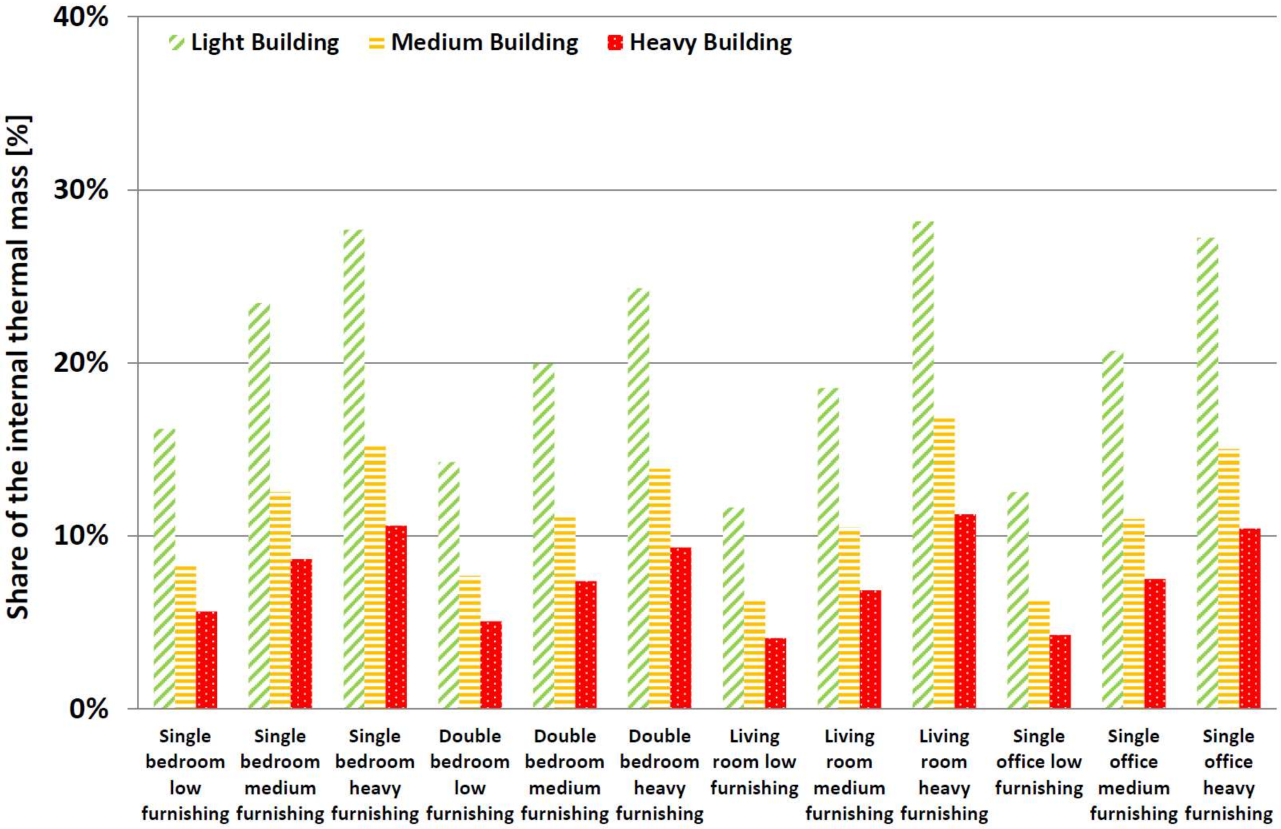


Fig. 7. *Share of the internal thermal mass in the total daily effective heat capacity of the building.*

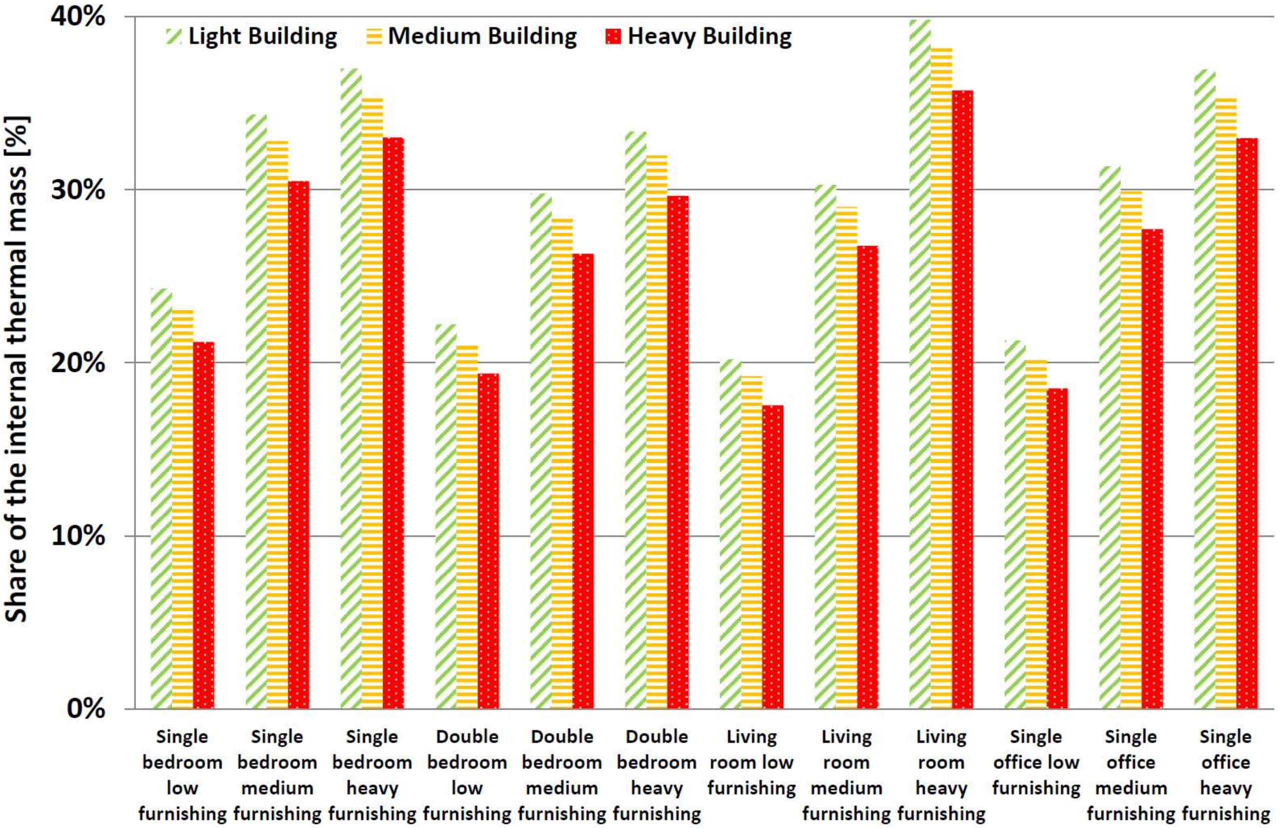


Fig. 8. *Share of the internal thermal mass in the total hourly effective heat capacity of the building.*

As seen in **Fig. 6** and **Fig. 7**, the daily effective heat capacity of the internal mass holds a significant share of the total room thermal inertia. It is particularly important in the case of lightweight structure buildings. Because the internal mass is quickly activated, the impact on the total inertia is even more visible when considering the hourly effective thermal capacity (see **Fig. 8**).

4.5. Impact of internal mass properties on daily effective heat capacity

A simple parametric sensitivity analysis of the daily effective heat capacity is performed for four different materials with the matrix calculation method. Density, heat conductivity and surface thermal resistance are varied within reasonable limits. The daily thermal mass activation percentage (ratio of effective heat capacity on apparent heat capacity) is calculated in function of the element thickness.

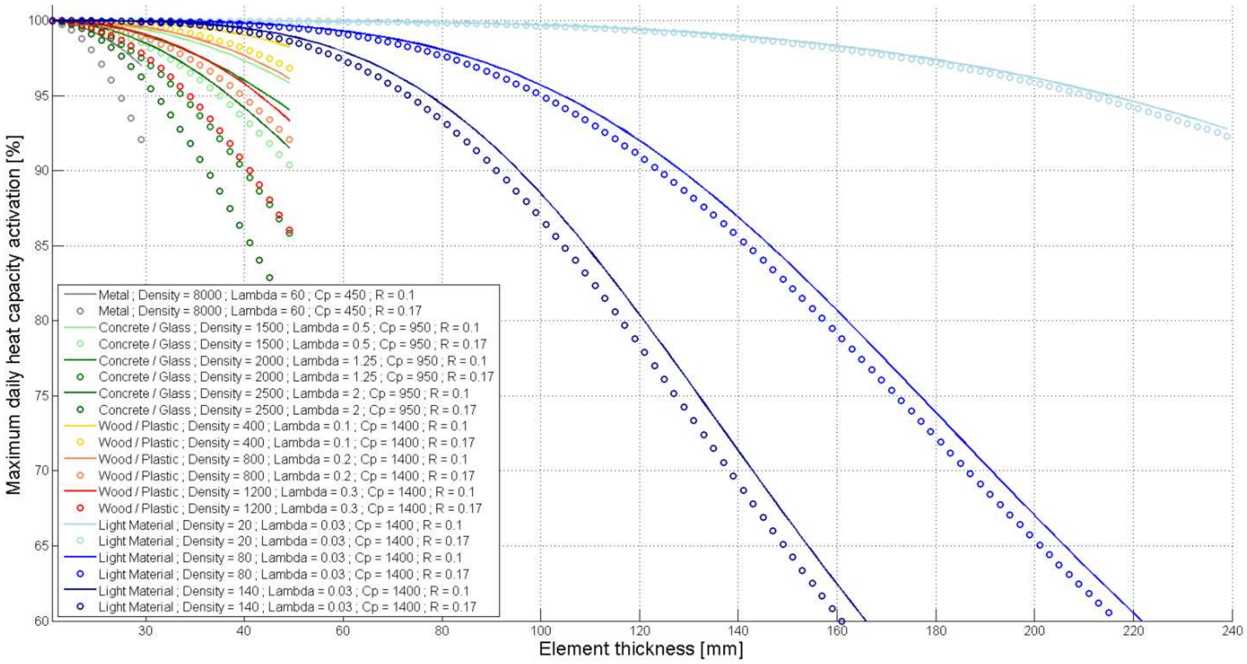


Fig. 9. *Daily activation of the equivalent material elements thermal mass.*

As shown in **Fig. 9**, all parameters of the equivalent planar elements have a significant impact on their effective thermal capacity. However, in the case of daily boundary condition variations, the slab elements are almost totally activated, meaning that their effective thermal capacitance is very close to their apparent maximum thermal capacitance. However, this is not the case for light material elements thicker than 10 cm with density higher than 80 kg/m³. Lightweight elements thicker than 10 cm are generally mattresses and cushions. According to retailer documentation, their density is always lower than 60 kg/m³. It is, therefore, reasonable for a simple calculation to assume that the daily effective thermal capacity of the indoor mass is equal to its apparent thermal capacity.

5. Internal mass modelling

The furniture/indoor thermal mass forms a set of complicated geometries with various materials. It is necessary to simplify such complex system in a proper way so that it grasps the dominant aspects of the indoor physics. This section reviews different approaches found in publications and software documentation.

5.1. First order thermal network

Simplified thermal network or resistance – capacitance (RC) models with the *xR1C* configuration aggregate all the effective thermal inertia of the thermal zone (indoor air, interior walls, furniture and building envelope) in a single capacitance [52]. It is assumed that this thermal mass is perfectly isothermal with homogenous equivalent properties. An example of such model in described by a *5R1C* scheme in the ISO 13790:2008 standard [53].

5.2. Higher degree thermal network

In order to refine the dynamic response of building models, the thermal mass elements with dissimilar thermal diffusivities are segregated into different lumped capacitances. Two clearly distinct thermal masses are the indoor air volume and the construction elements. In *xR2C* schemes and higher degree models, the indoor air temperature is coupled to the air volume heat capacitance. The building envelope temperature is coupled to an equivalent wall capacitance [51]. The question is thus to decide where to include the furniture and other indoor items.

One way is to assume that objects in the indoor zone are perfectly isothermal and always in thermal equilibrium with the indoor air node. In this situation, all the indoor content capacitance is added to the one of the air. This configuration can be found in TRNSYS multi-zone building model (type 56) [54] or in the *xR2C* schemes described in ref [51]. The air capacitance is simply multiplied by a constant value to account for the additional furniture inertia. Nevertheless, no requirement or indication concerning this parameter has been found. The TRNSYS software uses a default value of 1.2 times the air volume heat capacitance, but some guided examples advise using a value of 3 [54]. In ref [23] and [51] the coefficient is set to 5 and 8 respectively. Another solution, presented in the *6R3C* model of ref [51], is to couple the furniture thermal capacitance to the inner surface envelope temperature node. It is also possible to aggregate interior walls, furniture and other indoor mass into a lumped capacitance which is distinct from air and external walls one [52]. This internal mass sub-system can be expended into a *2R2C* scheme to account for the temperature gradient in the equivalent element [50].

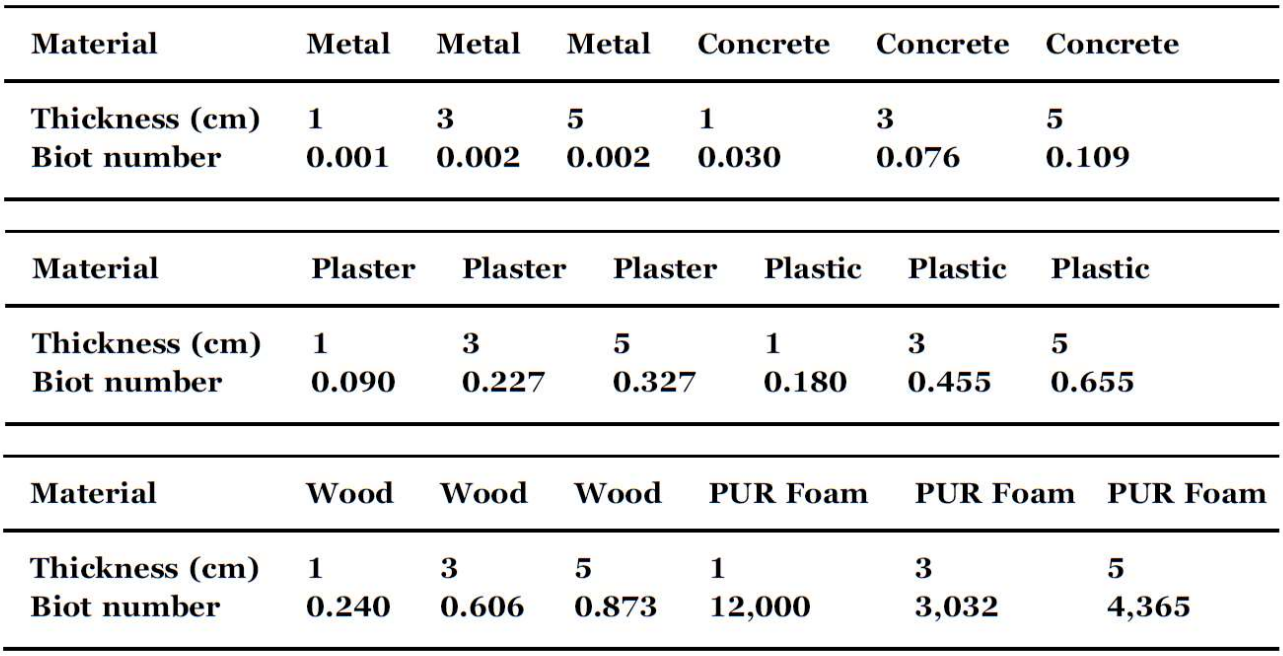
5.3. Distinct internal mass capacitance

One could consider that the thickness, thermal diffusivity and heat exchanges of internal mass elements differ significantly from the ones of the air volume and wall inner surfaces. The temperature difference between the furniture node and the other elements would justify an indoor mass modelling with its own lumped capacitance. The TRNSYS Type 56 model is a non-geometrical heat balance [54]. The room furnishings can easily be included in the star network for radiation and convection heat exchange [33] and [54] as a new lumped capacitance like an ordinary wall element. The location of the internal mass is not required, but a proper representative surface area must be specified [55]. The effective thermal mass area is defined in international standards [53] as $A_m = {C_m}^2 / \sum(A_i \times {\kappa_i}^2)$. Where C_m, A_i, κ_i represent total effective heat capacity of the zone [J/K], area of the *i* element [m²], areal effective heat capacity of the *i* element [J/K.m²], respectively.

5.4. Virtual sphere model

In models presented before where an element is represented by a single node, the temperature distribution is assumed to be uniform. The element is isothermal, and heat exchanges are treated as quasi-static processes. This assumption is acceptable if the thermal diffusion within the thermal mass is much faster than the heat transfer at the volume surface. It is the case when the *Biot* number is smaller than 0.1. For wooden plate element, this condition would be fulfilled if the thickness is smaller than 2 mm. However, most of the internal mass and furniture elements are thicker than 2 mm. Therefore, the lumped method should not be used to model the interior thermal mass [56]. The *Biot* number calculations for planar elements with different materials presented in **Table 2** clearly show that only metal elements can be modelled realistically with the lumped method.

Table 2. *Biot number of different material elements.*



Material	Metal	Metal	Metal	Concrete	Concrete	Concrete
Thickness (cm)	1	3	5	1	3	5
Biot number	0.001	0.002	0.002	0.030	0.076	0.109

Material	Plaster	Plaster	Plaster	Plastic	Plastic	Plastic
Thickness (cm)	1	3	5	1	3	5
Biot number	0.090	0.227	0.327	0.180	0.455	0.655

Material	Wood	Wood	Wood	PUR Foam	PUR Foam	PUR Foam
Thickness (cm)	1	3	5	1	3	5
Biot number	0.240	0.606	0.873	12,000	3,032	4,365

In order to overcome this problem, Zhou et al. [57] presented a building model where the effect of intern mass is calculated by the virtual sphere method. The latter was first proposed by Gao et al. [58]. It aggregates different shapes of solid body into a single sphere with a radius equal to the characteristic length of the element. It is appropriate for systems with *Biot* number in the range of 0 to 20, which is typically the case for internal building content. Zhou et al. published a new formulation for unsteady heat transfer of the indoor mass. The total heat capacity for *N* internal thermal mass elements is $C = \sum_{i=1}^{N} M_i C_{m,i}$ [J/K]. The radius of the virtual sphere is $R = 3\sum_{i=1}^{N} V_i \,/\sum_{i=1}^{N} S_i$ [m]. Where M_i, $C_{m,i}$, V_i, S_i represent mass [kg], heat capacity [J/kg.K], volume [m³], area [m²] of *i* internal thermal mass, respectively. The heat balance equation between the virtual sphere and the indoor air is then developed with the external and average temperature of the sphere. The temperature of the solid can be calculated from analytical solution of the heat equation in spherical coordinates. Moreover, an effective convection heat transfer coefficient is introduced to account for the uneven distribution of internal mass temperature. Nevertheless, the current model does not include radiation heat exchanges.

5.5. Virtual equivalent planar element

In the Energy Plus and IDA ICE software, there is a possibility to insert furniture elements as a one-dimensional multi-layer planar element [59], [60] and [61]. The same approach is used in ref [30], [8] and [56]. The energy balance and temperature distribution of this simple system is easy to solve by the mean of numerical methods. However, these internal mass equivalent slab elements do not have a geometric representation in the thermal zone. This means that the presence of the planar elements in the room is not taken into account for the internal solar distribution or the long-wave heat exchanges in between inner surfaces. The equivalent furniture element only interacts with the air node by convection.

5.6. Geometric equivalent planar element

As mentioned before, Raftery et al. [34] developed and implemented into Energy Plus an internal mass equivalent planar element model with a geometric representation and location inside the thermal zone. This object is thus fully taken into account for the computation of the direct light beam reaching internal surfaces, diffuse solar repartition and radiant mean temperature. The long-wave radiation heat exchange can be calculated by radiosity method with correct view factors affected by the furniture element in the middle of the room. Shading effect on the floor is modelled properly which adds a more realistic physical behaviour to radiant systems.

5.7. Heat balance modelling

The energy balance of an internal mass element depends on the three heat transfer modes. The dynamic conduction in a solid is a well-known problem which is handled by solving the heat equation with numerical methods such as finite difference, finite volume, finite element methods or transfer functions [23]. One-dimensional heat flux with constant thermal properties and homogenous surface temperatures are convenient assumptions, which are reasonable in the case of slabs such as equivalent internal mass elements.

Solar radiation distribution to the internal mass can be modelled in a simple way with the “solar to air factor” or “sol-air coefficient”. It is defined in the standard ISO 15265:2007 [62] as the fraction of the radiation entering through a glazing which is immediately delivered as a convective heat flow to the indoor air. This fraction depends on the presence of internal elements with very small time constant such as carpets or furniture. These thin elements can be illuminated by direct solar radiation and reach thermal equilibrium with the indoor environment within one simulation time step. This coefficient is assumed to be time independent and set to the default value of 10%. However, this factor does not exist in the simplified modelling method described in the ISO 13790:2008 [53]. BSim software documentation **Error! Reference source not found.** advises to fix this factor between 10% and 30%.

If the internal elements have a real geometry in the indoor space, various calculation methods can determine the shadow and direct solar beam trajectory striking internal surfaces with a certain number of reflections and diffuse re-emission. The diffuse sun radiation distribution is performed separately with a simple absorptance weighted area ratios or from view factors between internal surfaces and the windows (Gebhart Method) [54]. The ray tracing method gives very accurate results for the solar repartition of direct and diffuse sun gain on inner surfaces but it is computationally demanding. The values are thus pre-calculated for different positions of the sun in the sky and then interpolated during the actual simulation [23].

Straightforward long-wave radiative exchange models have been developed for simple geometries with 2 or 3 interacting surfaces and infinite reflection [23]. Concave configurations with more surfaces can be transformed in a simplified start network with coupling to a central fictive massless black body node [33] and [54]. The radiosity method gives the exact solution to long-wave radiation heat exchange, but it needs higher computation resources, especially when surface temperatures are unknown [23]. This method is based on the calculation of the view factor matrix. The latter can be determined in a furnished enclosure by the mean of correlations taking into account the obstruction of an object by another one [63] or with the ray tracing method.

The convection is the least well understood and thus the most difficult thermal transfer mode to simulate in building physics. It has not been accurately modelled yet and many simplified models use constant convective or combined convective/radiative indoor heat transfer coefficients ranging from 0.7 to 5 $W/m^2.K$ and from 5.88 to 10 $W/m^2.K$, respectively [64]. However, the review paper of Peeters, Beausoleil-Morrison and Novoselac [65] presents detailed empirical correlations for various indoor configurations and surface orientations.

6. Phase change materials for building energy storage

In recent years, the use of phase change materials to enhance the thermal capacity of the buildings is becoming an attractive solution [66]. Indeed, PCM's latent heat can store 5 to 14 times more thermal energy per unit volume than sensible storage materials such as water or concrete [67]. Moreover, this high storage density can be employed with a small temperature change. This section gives an overview of the state-of-the-art of materials with solid-liquid phase transition which are the most commonly used PCMs for building applications [68].

6.1. PCMs characteristics

A good PCM for building TES should have the following properties:

- Melting temperature in the desired operating range to assure useful heat storage and extraction. Building application temperatures range from 15°C (cold storage) to 70 °C (heat storage).
- High latent heat of phase transition per unit volume to achieve high storage density.
- High specific heat to provide additional sensible heat storage.
- High thermal conductivity of both solid and liquid phases to assist the energy charging and discharging process.
- Small volume change on phase transformation (less than 10%) and small vapour pressure at operating temperature to reduce the containment problem.
- Congruent melting for a constant storage capacity with each freezing/melting cycle.
- Complete reversible freeze/melt cycle. Stable and reproducible phase change over time. No degradation after a large number of freeze/melt cycles.
- High nucleation rate to avoid sub-cooling of the liquid phase and to assure that melting and solidification proceed at the same temperature.
- No corrosiveness to the construction and containment materials.
- Non-toxic, non-flammable and non-explosive material for environmental and safety reasons.
- Abundant, available and cost-effective to be economically competitive with other storage options.

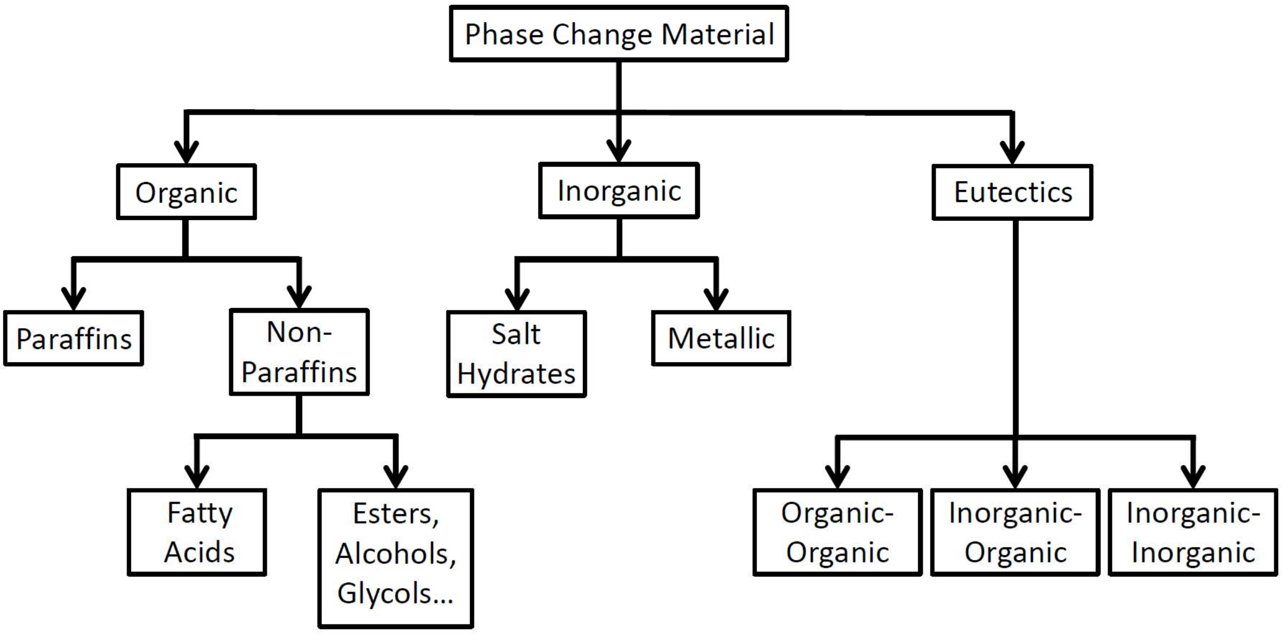


Fig. 10. *General categorization of PCMs [69].*

Relevant PCMs for building TES are paraffin, fatty acids, salt hydrates and their eutectic mixtures. Their price varies from 0.5 to 10 €/kg. Different technics allow change in their chemical composition and combination with other substances in order to tune the melting temperature to a desirable one, improve the thermal conductivity and incorporate them into common construction elements [70].

The paraffins are very popular organic PCMs. They have a wide range of melting temperatures with a density of around 900 kg/m³. Most of commercial products are extracted from oil. They are cheap with good thermal storage densities (around 200 J/g or 180 MJ/m³). They undergo negligible sub-cooling during the freezing process and provide congruent melting. They are non-corrosive, chemically inert and stable with no phase segregation and low vapour pressure. However, their flammability and low heat conductivity (around 0.2 W/m.K) are certain limitations of their effectiveness [71].

Other organic PCMs are generally found in the form of fatty acids. Their melting temperatures vary from 5 to 70 °C. They possess appreciable latent heat ranging from 45 to 210 J/g but usually around 150 J/g (140 MJ/m³). They have the advantages of congruent melting, low sub-cooling and vapour pressure, non-toxicity, good thermal and chemical stability, small volume change, self-nucleating behaviour and biodegradability. They are also capable of thousands of thermal (melting/freezing) cycles without any notable degradation in thermal properties. The raw materials of fatty acids can be obtained from cheap sources such as the fat of animals and vegetables. They are divided into six groups: caprylic, capric, lauric, myristic, palmitic and stearic. They can be combined together in different proportion to form binary and ternary fatty acids eutectic mixture. The phase change temperature of these eutectic mixtures can be tuned to desirable ranges. Their high surface tension improves their capability of integration in a porous material matrix. However, like paraffins, the major drawback of fatty acids is their low thermal conductivity (around 0.17 W/m.K) [71] and [72].

Esterification of fatty acids with alcohols is a common method to shift the phase transition temperature. It enables decreasing the melting point of fatty acids with high thermal capacity. The production of binary and ternary PCMs by mixing fatty acids with fatty alcohols, polyethylene oxide, oleic acid, pentadecane or other products with low melting temperature is another possible tuning technic [72].

Other organic PCMs have received less attention by researchers such as sugar alcohol. Some of the polyalcohols have latent heat almost double than that of the other organic PCMs but their melting point ranges from 90 to 200°C, which is too high for building applications. Among them, erythritol is especially noticeable with a latent heat of fusion of 339.8 J/g at 120 °C.

Bio-based PCMs are organic materials produced from the biomass: soybean oils, coconut oils, palm oils and beef tallow. Like the other organic product, they have an interesting latent heat with good chemical stability and phase transition temperatures ranging from -22.77 to 77.83 °C. Nevertheless, they suffer from the same problems as other organic materials [71].

Inorganic PCMs are classified into two main material groups: hydrated salts and metallic products. Metallic PCMs have too high melting temperatures for building applications. Like previously mentioned PCMs, the salt hydrates possess a significant storage capacity and operate phase transition at ambient temperature. Many studies focused on the calcium chloride hexahydrate, sodium sulphate and magnesium chloride hexahydrate because of their availability, moderate costs and non-flammability. Salt hydrates have a density of around 1700 kg/m³, which is twice higher than for paraffins. With a maximum latent heat of around 200 J/g, their heat storage on a per volume basis is around 350 MJ/m³, which is much higher than organic products. Another significant advantage is their thermal conductivity (around 0.5 W/m.K), which is also higher compared to organic materials. However, these products become chemically instable at high temperature. Heating cycles cause continuous dehydration of the PCM and the heat storage capacity usually degrades over time. Moreover, most salt hydrates melt incongruently with the formation of a lower form product. This irreversible process is an additional drawback for their long term performance. The liquid phase separation and segregation can be prevented by addition of gelling or thickening agents. Sub-cooling is another problem associated with salt hydrates. The phenomenon is characterised by a solidification of the product below its phase transition temperature. It can be reduced by inducing heterogeneous nucleation in the salt hydrates thanks to nucleators or direct contact with an immiscible heat transfer fluid [70].

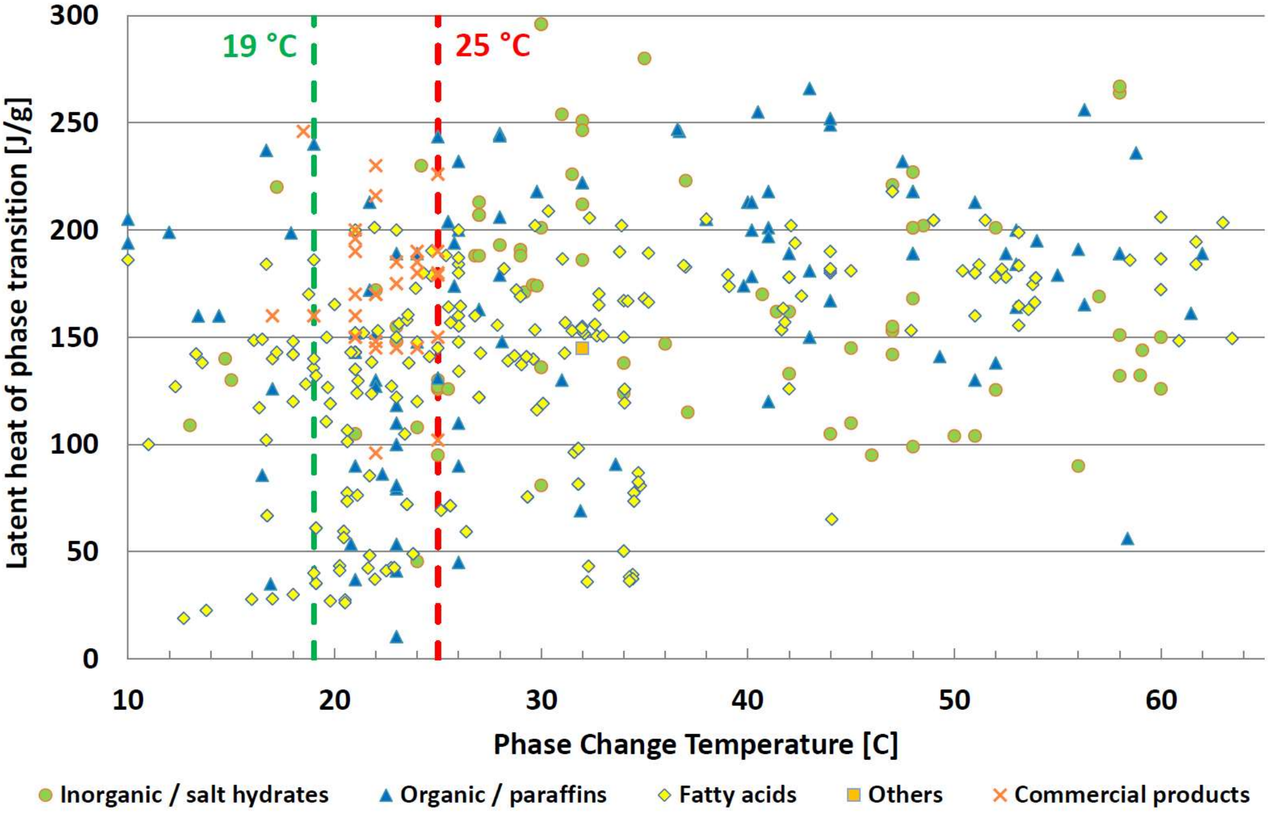


Fig. 11. *Compilation of PCM thermal properties found in the literature [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88]and [89].*

One can see that there is no perfect product for LHTES in the temperature range 19 – 25 °C. **Fig. 11** shows that very few of them present latent heat above 200 J/g. Organic PCMs offer better chemical and thermal stability with congruent melting and they exhibit little or no sub-cooling. On the other hand, inorganic products suffer from cycling instability, require nucleating and thickening agents to minimize sub-cooling and are highly reactive to metal materials. Therefore, the organic PCMs seem to be the most appropriate for low temperature building TES application.

6.2. PCMs containment

For building applications, a PCM should be contained or mechanically stabilized so that the liquid phase cannot flow away. A good integration within passive LHTES system has to prevent direct contact between the product and its environment to avoid deterioration of the PCM by its surrounding and vice versa.

PCMs can be integrated into conventional building materials by direct incorporation or immersion methods. The first method is the simplest and the cheapest. The PCM is directly mixed with construction materials such as gypsum, concrete or plaster during their production. For the immersion method, the porous construction material is immersed into the melted PCM. The porous media absorbs the product by capillarity. However, leakage and incompatibility with building materials may occur in the both cases [66].

PCMs can be encapsulated before incorporation into building elements. The containment should provide strength, flexibility, resistance to corrosion, structural and thermal stability. It should also separate properly the material from its environment but have sufficient surface area for optimum heat transfer [90].

The micro-encapsulation method involves small (less than 1 mm) spherical or rod-shaped PCM particles coated with a thin polymeric film. This film must be compatible with both the PCM and the matrix. This technique improves heat transfer to the surrounding through its large surface-to-volume ratio. It also provides a good cycling stability since phase segregation is restricted to microscopic distances [91]. Even though microencapsulation is a relatively expensive process, micro-encapsulated paraffin is a popular solution such as the commercial product Energain® [92] which contains 60% PCM and presents a latent heat of around 70 J/g [93].

It is also possible to encapsulate PCMs at nano-scale. A study suggested that the nano-capsules are more stable than micro-capsules. Paraffin was successfully encapsulated in 100 nm diameter formaldehyde spheres. With a PCM mass content of 60%, this product showed an appreciable latent heat of 134.61 J/g [94].

Macro-encapsulation is a simple containment method. The PCM placed in bulk storage reservoirs such as tubes, pouches, spheres or panels which are usually larger than 1 cm. The first historical macro-encapsulation systems were too large and suffered from the poor thermal conductivity of most PCMs to insure an efficient energy loading. The product solidifies at the edges of the containers preventing effective heat transfer. The containers can serve directly as heat exchangers to overcome this problem. Aluminium profiles with fins or heat exchanger with finned tubes filled with PCM can thus significantly increase the heat transfer rate and reduce phase segregation [70] and [95].

In recent years, shape-stabilized PCMs were attracting a lot of attention. They have a large apparent heat storage capacity, suitable thermal conductivity, chemical and mechanical long-term stability [95]. Stable form PCMs without any leakage can be obtained by impregnation of porous material matrices. Direct impregnation technic is simple, but the vacuum impregnation method is more effective in loading very fine mesh porous matrix with a maximum amount of product. The latent heat of these compounds increases almost linearly with the PCM fraction mass [96]. For example, a shape-stabilized PCM composed of 80% mass paraffin and 20% styrene-butadiene-styrene can reach 80% of pure paraffin's latent heat [97]. Because of their high surface tension and chemical stability, organic PCMs are the most appropriate for integration in porous matrices [96]. Many researchers tested incorporation, stability and thermal properties of PCMs in various porous materials such as expanded perlite [98], halloysite nanotubes [99], montmorillonite [100], vermiculite [101], expanded graphite [102], porous silica matrix [103], expanded clay aggregate [104] and diatomite [105].

6.3. PCMs thermal transfer enhancement

PCMs are employed to accumulate energy within short periods. Fast loading and unloading capability is therefore a problem for LHTES systems because of their low thermal conductivity. Numerous technics for heat transfer enhancement have been tested in order to increase the activation depth of the material layer and consequently improve the energy storage capacity. High conductivity structures in bulk PCM reservoir such as copper, aluminium, nickel, stainless steel and carbon in various forms of fins, plates, honeycomb, wool, foam, fibres or brush have been employed as thermal conductivity promoters. The presence of metal fins in PCM macro-containers significantly hinders natural convection in the liquid phase but strongly enhances the conduction [106]. The integration of PCMs in highly conductive porous matrices or the dispersion of high conductivity particles (expanded graphite, fibrous materials, macro, micro or nano capsules) has been widely studied as containment and heat transfer enhancement [107]. Direct exposition to solar radiation, high radiation absorptivity of the finishing surface and augmented convective heat transfer can highly improve LHTES capacity as well [110]. The performances of some thermal conductivity enhancement technics are presented in **Table 3**.

Table 3. *Performance of different thermal heat transfer enhancement methods.*

PCM type	Containment	Thermal enhancement method	Performance	Reference
Deionized water	Macro-container	Addition of copper tubes and graphite matrices	Reduce melting time by factor 2.5	[106]
Pure eicosane and commercial wax	Macro-container	Addition of aluminium honeycombs and thin-strip matrices	Reduce solidification time by factor 7	[106]
Paraffin	Macro-container	Addition of 20% volume of lessing rings	Reduce solidification time by factor 9	[106]
Paraffin RT58	Stable form PCM	Integration in copper foam matrix	Increase heat transfer by factor 10	[107]
Eicosane	Stable form PCM	Integration in 95% porosity copper foam matrix	Thermal conductivity from 0.423 to 3.06 W/m K	[102]
Eicosane	Stable form PCM	Integration in 97% porosity nickel foam matrix	Thermal conductivity from 0.423 to 9 W/m K	[102]
Paraffin	Stable form PCM	Integration in compressed expanded graphite matrix	Thermal conductivity from 0.24 to 4 or up to 70 W/m K	[108]
Paraffin	Macro-container	Addition of 0.5% mass of 80 µm aluminium particles	Reduce melting time by 60%	[107]
Fatty acid	Stable form PCM	Addition of 2% mass EG in expended perlite matrix	Thermal conductivity from 0.25 to 0.5 W/m K	[73]
Fatty acid	Stable form PCM	Addition of 7% mass EG in expended perlite matrix	Thermal conductivity from 0.25 to 2.51 W/m K	[73]
Paraffin	Stable form PCM	Addition of 10% mass exfoliated graphite nano-platelet	Increase heat transfer by factor 10	[109]

6.4. Passive latent heat storage applications in buildings

LHTES has found many practical applications from solar energy storage to space satellite thermal regulation or cooling of the electronics. This discussion focuses on low temperature passive LHTES systems in buildings, loaded and unloaded by the only mean of indoor temperature variations and internal radiation.

Macro-encapsulated PCMs were found inadequate to deliver accumulated heat due to their limited surface of exchange. Therefore, most studies focused on PCM integrated into building elements such as walls, ceilings and floors. They offer a larger surface of exchange with the indoor space and thus a greater storage capacity [107]. Wallboards are cheap, commonly used in building construction and thus appropriate for the integration of PCMs. Many numerical and experimental studies assessed the performance of these enhanced wallboards [66]. A full-scale experiment with summer conditions showed that 5 mm PCM wallboard is equivalent to 8 cm of concrete with regards to indoor air temperature fluctuations and overheating. [112]. Comparative in situ studies in a renovated building equipped with similar PCM wallboards concluded that the heat storage capacity of rooms was doubled [113]. A wallboard with 25% mass butyl stearate could reduce heat load by 15% for a building located in Montreal [114]. The energy savings of a sandwich-type PCM / insulating wallboard integrated in a building under continental climate were evaluated at 12.8% for heating and 1% for cooling. Cooling and heating peak loads were reduced by 35.4% [115]. Another experiment demonstrated that PCM insulation wall can decrease daily heat transfer across the envelope by 38% and diminish peak heat flux by up to 62% under summer conditions [116].

Researchers tried to incorporate PCM into concrete for effective heat capacity augmentation. The latest analyses concluded that concrete LHTES was not a suitable solution because the maximum amount of mixed PCM cannot be higher than 5 – 6% by weight. The thermal inertia improvement due to the PCM itself is thus very little. In addition, it significantly deteriorates the thermal conductivity of the concrete and consequently the overall activated thermal mass [107].

The translucent properties of some PCMs can be employed to manufacture translucent bulk containment panel in windows [107]. The product is in direct sun exposure and can be fully activated. The PCM filters out the solar radiation and reduces the amount of heat gains until it is completely melted. The system can provide homogeneous illumination with light transmittances in the range of 0.4 and reduce heat losses by 30%. These PCM panels can be good supplements to conventional windows where there is no need for visual contact to the environment [117]. Internal shutters and solar shadings can also contain PCM and be integrated in window facades. The systems should operate cyclically to enable sun energy storage during the day and release towards the indoor space at night. Tests showed that rooms equipped with PCM interior sun protections had air temperature 1 – 2 °C lower than rooms with conventional blinds [118]. Numerical results indicated that 23% reduction of heat gain through a window can be reached with 3 cm thick PCM shutter with regards to the same shutter made of foam and aluminium [119]. Finally, the introduction of PCMs in Trombe walls could contribute to the development of light and portable systems adapted to the lightweight buildings [66].

7. Integration of phase change materials into furniture

As discussed previously, PCM systems located in the inner surfaces of the indoor space, such as wallboards, offer the best thermal mass enhancement. However, their use is limited to the internal surface area of rooms. Furniture parts are often neglected in energy building investigations, but they also possess a large surface of exchange with the indoor environment. The furnishing can be an interesting location for LHTES which could therefore be installed without the need for extra space or construction works. This section is reviewing the few projects involving furniture and PCMs. A simple calculation is then presented to give an idea of the potential for PCM furniture in terms of TES. Finally, the section will discuss modelling and optimization of LHTES systems.

7.1. PCMs furniture systems

Passive cooling by direct contact with human body such as cooling seats or cooling blankets are the most common products available on the market. "Smart textile" with integrated PCM is also commercialized. However, these solutions are not TES systems and only have a limited effect on occupants' thermal comfort.

Many papers focus on the study or the review of the different PCM applications, but no specific publication was found on the integration of PCM in furniture. Very few articles mention the PCM furnishing option and if they do, they do not provide any concrete examples [120].

Only one publication presented the first PCM active application located in furniture. It consists of an air heat exchanger (electric fan) with macro-encapsulated PCM. The system is placed underneath box-type furniture for living rooms or bedrooms. The concept was proposed for the American Solar Decathlon in 2007, but no further documentation or characteristics could be found [121].

The company EPS Ltd has elaborated the "PlusICE furniture" for office passive cooling. This product is actually not available, and the company only provides bulk containment or stable form PCM to be placed under the furnishing parts [122].

One architecture group suggested the use of paraffin in an aluminium frame to mount various office furniture pieces for the 2012 "adream" competition. A simple performance assessment in office buildings concluded that the cooling and heating energy needs can be decreased by up to 40% and 34%, respectively [123].

A similar solution was presented in the French press by the engineering company Egis in 2015. The PCM is encapsulated and located below a wooden office table. The bottom face of the furniture is covered with an aluminium corrugated sheet in order to increase the heat exchange rate. According to the designers, this PCM table can reduce cooling and heating needs by up to 30% and 60%, respectively [124].

7.2. Potential for furniture PCMs integration

The simple survey on Danish building indoor content provided an estimation of the available furniture, wall, floor and ceiling surface area in direct contact with the air. One can see on **Fig. 12** that the furniture surface, which is available for PCM integration can represent up to 50% of the room's inner surface.

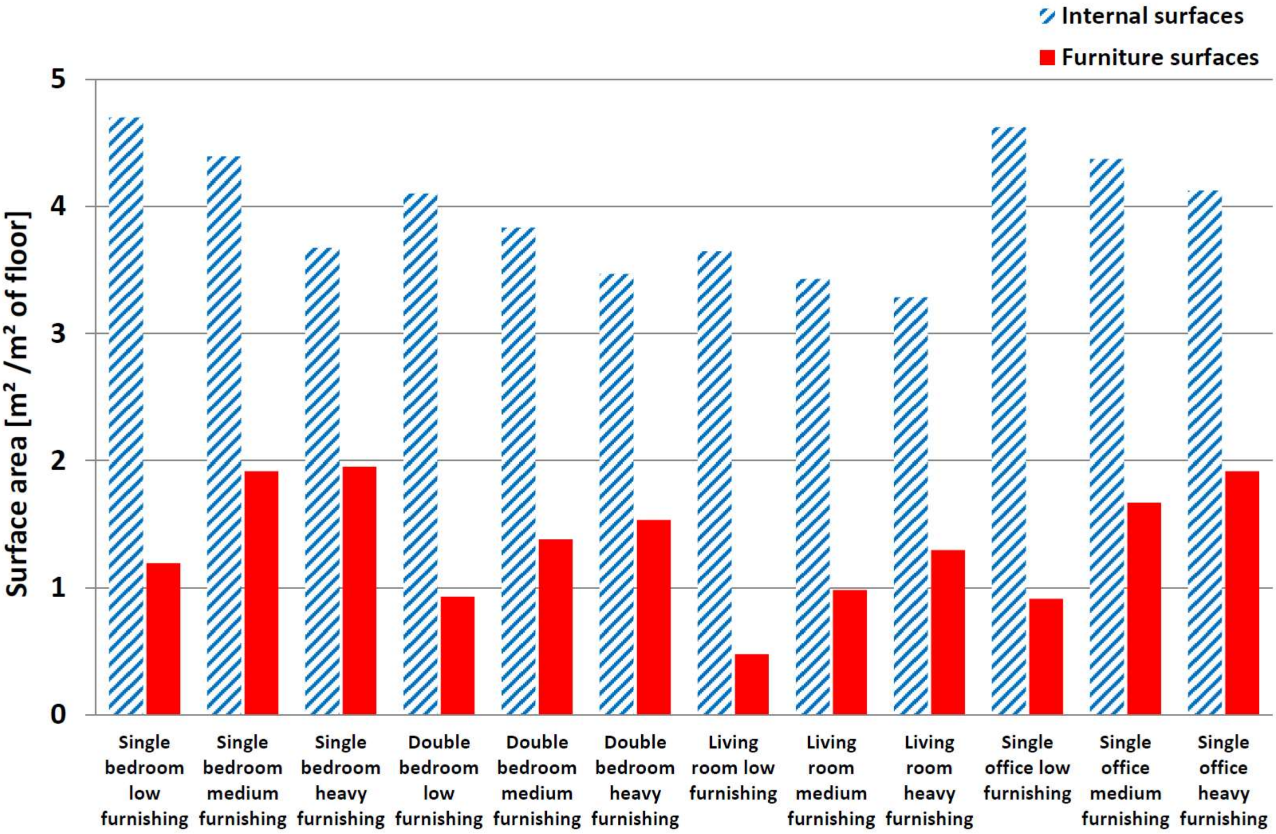


Fig. 12. *Surface area available in buildings for integration of phase change materials.*

An optimization study on a wallboard containing 60% of micro-encapsulated paraffin showed that the optimum daily activated PCM thickness is 1 cm [125]. This value is used to get a simple estimation of the daily effective thermal capacity of internal wall and furniture covered by a layer of PCM. The latent heat of the product is chosen to be 180 MJ/m³. It is assumed that the 1 cm of PCM is fully activated within a 24-hour cycle, which is equivalent to 1.8 MJ/m². The sensible heat of the other building elements is calculated with the daily effective heat capacity of each element and a temperature variation of 4 °C.

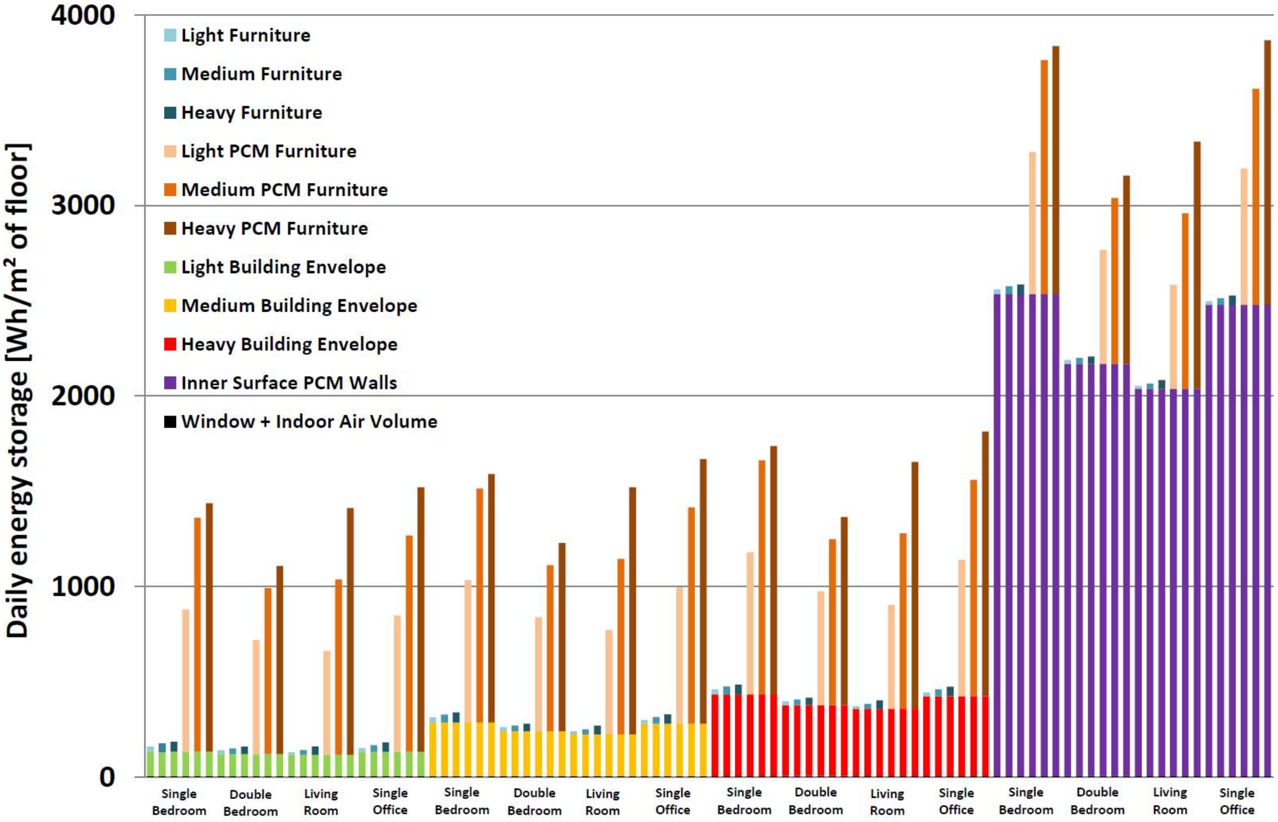


Fig. 13. *Daily thermal storage capacity of building elements.*

As seen on **Fig. 13**, the furnishing elements covered with PCM can significantly improve the daily thermal capacity of a room.

7.3. Modelling and optimization of LHTES systems

PCM mathematical models are needed for the study and optimum design of LHTES systems. In their review paper, Soares et al. [66] discussed the different modelling technics. It is stated that solving a phase change problem numerically is difficult because of the moving boundary on which heat and mass transfer have to be solved. The two phases of the PCM have different thermo-physical properties. Because of this non-linear behaviour, the position of the moving interface cannot be determined a priori. This solid–liquid interface boundary system is named "Stefan problem".

The authors report that most of the current numerical models are based on the first or the second law of thermodynamics and use fixed or adaptive meshing. The first law models do not consider the effect of time duration for heat storage and release nor the temperature at which the heat is supplied. The second law models take these parameters into account. The time variant meshing method offers good accuracy, but it is limited to simple problems and geometries. On the other hand, the fixed mesh approach is much simpler to use for multidimensional problems.

LHTES equations are usually solved with finite difference, finite control volume or finite element methods. The phase transition can be modelled by introducing an equivalent specific heat of the PCM in function of temperature. The material's latent heat of fusion is transformed into a peak on the sensible specific heat capacity curve over the whole phase transition temperature interval. The system is simplified into a non-linear single phase conduction problem. The latent heat of fusion can also be described with an enthalpy formulation. The enthalpy of the system becomes the state variable which has to comply with the energy conservation equation. The temperature is then calculated from the enthalpy and the thermal properties of the PCM.

The performance of passive LHTES systems is highly affected by the indoor environmental conditions such as internal heat loads, ventilation rate, convection heat transfer coefficient, solar radiation and ambient temperature. The type of PCM, its melting temperature, layer thickness, location and orientation should be determined within an optimization process to increase the storage/release capacity using as little material as possible [125]. Charging and discharging time should also be taken into account. The effective energy storage capacity is proportional to the PCM volume, which has melted and solidified during a complete TES cycle. If the material amount is overestimated, the time needed for the heat to penetrate the PCM layer could become larger than the charging period, and the melting process cannot be completed [126]. Similarly, the design of passive LHTES furniture systems should be performed according to a specific TES strategy and account for the difference in radiative and convective conditions on the each side of the elements.

8. Conclusion

This article intended to attract readers' attention on what many consider a negligible detail in the field of energy and buildings. Most of the building models assume empty rooms without furniture or indoor content, but very few people have tried to understand if such simplification is reasonable or not. Some publications emphasised the strong interaction of the furniture/indoor thermal mass with the internal air node and HVAC systems. It can have a significant impact on the local indoor humidity and thermal comfort. Because of its large surface for heat exchange, the internal content is highly activated and can account for up to 40% of the total hourly effective heat capacity of a room, and increase its time constant by several hours. Although it does not play a major role in the energy consumption of buildings with a static controller, several studies showed that indoor mass cannot be ignored when using set point modulation for passive TES or night time cooling.

There is a clear lack of guidance in publications for the assessment of the indoor thermal mass characteristics. This paper suggested a simple classification of these elements with representative thermal properties. In addition, the results of a survey on Danish buildings were presented to give some insight into reasonable variation for the mass and heat capacity of furnishing and items in a room.

Different furniture modelling technics were described in scientific articles and software documentation. Most of them introduce an additional lumped capacitance in a RC network while some use an equivalent fictitious planar or spherical element. Only one model was found with a geometric description of an equivalent slab for proper solar radiation distribution and long-wave radiation heat exchange. Very little methodology was found concerning the way to aggregate internal content with various sizes and thermal properties into equivalent simplified elements.

Furnishing elements offer a large surface area exposed to the indoor environment, which makes them a good candidate for PCM integration. It can be an interesting solution for the implementation of passive LHTES systems without construction work and thereby improving thermal inertia and energy flexibility of light buildings.

Further investigations are needed to assess the complex effects of furniture/indoor thermal mass on building systems. A large survey on occupied buildings would give statistical insight into rooms' content. Full-scale experiments should be performed to measure the impact of internal mass on building's time constant, HVAC systems efficiency, and passive TES potential. Realistic models and aggregation methodologies have to be developed for indoor mass elements. Finally, the integration of PCM in furniture raises new issues concerning their compliance with fire regulation, recycling process and total life cycle analysis.

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