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Study on the optimum PCM melting temperature for energy savings in residential buildings worldwide

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Abstract. To maintain comfort conditions in residential buildings along a full year period, the use of active systems is generally required to either supply heating or cooling. The heating and cooling demands strongly depend on the climatic conditions, type of building and occupants' behaviour. The overall annual energy consumption of the building can be reduced by the use of renewable energy sources and/or passive systems. The use of phase change materials (PCM) as passive systems in buildings enhances the thermal mass of the envelope, and reduces the indoor temperature fluctuations. As a consequence, the overall energy consumption of the building is generally lower as compared to the case when no PCM systems are used. The selection of the PCM melting temperature is a key issue to reduce the energy consumption of the buildings. The main focus of this study is to determine the optimum PCM melting temperature for passive heating and cooling according to different weather conditions. To achieve that, numerical simulations were carried out using EnergyPlus v8.4 coupled with GenOpt® v3.1.1 (a generic optimization software). A multi-family residential apartment was selected from ASHRAE Standard 90.1- 2013 prototype building model, and different climate conditions were considered to determine the optimum melting temperature (in the range from 20ºC to 26ºC) of the PCM contained in gypsum panels. The results confirm that the optimum melting temperature of the PCM strongly depends on the climatic conditions. In general, in cooling dominant climates the optimum PCM temperature is around 26ºC, while in heating dominant climates it is around 20ºC. Furthermore, the results show that an adequate selection of the PCM as passive system in building envelope can provide important energy savings for both heating dominant and cooling dominant regions.

1. Introduction

More than one-third of the overall annual energy consumption of a building is attributed to space heating and cooling, especially in cold climate regions where it may account for more than a half of the overall annual energy consumption [[1]]. Phase change materials (PCM) [[2]] can be used for passive design applications in buildings, since they present high energy density and no volume expansion problems. The use of PCM technology for thermal regulation of buildings has been considered by many researchers [[3],[4]].

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The main goal of this innovative system is to reduce the HVAC demand in buildings by enhancing the thermal mass of the envelope, which leads to a decrease in the indoor temperature fluctuations and a higher comfort for occupants [[5]].

The thermal behaviour of buildings is associated with complex physical phenomena, and building simulation tools are very useful to analyse and evaluate the energy performance and comfort conditions, specifically in buildings with renewable and innovative integrated passive technology, such as the integration of PCM.

Parametric studies can be useful in the early stages of building design. However, they may lead to deviations from the actual results due to non-linear interactions of input variables on simulated results, and they could be very time-consuming and computationally expensive [[6]]. Simulation-based optimization methods may be more appropriate for building performance analysis [[6]]. Currently, little discussion can be found in available literature on energy optimization of PCM-enhanced passive buildings addressing the appropriate PCM melting point temperature taking into account various climate conditions.

In the present study, a single-objective optimization method coupled with an innovative PCM enthalpy-temperature (h-T) function will be presented to find out the optimum PCM melting temperature according to the outdoor boundary conditions. The aim is to show that the use of PCM passive system in the building envelopes with optimized melting temperature in each climate can lead to energy savings, in both heating dominant and cooling dominant climates.

2. Methodology

Simulation-based optimizations were carried out using EnergyPlus whole-building energy simulation coupled with a generic optimization program (GenOpt). Computations were performed on a cluster with 32×6 core Intel(R) Xeon(R) processors at 2.00GHz with 48 Gigabyte memory running EnergyPlus 8.4.0 under CentOS release 6.3 - 2.6.32 x86_64 GNU/Linux.

A suitable building model was selected to carry out the simulation in different weather conditions. On this basis, a multi-family residential apartment was selected from ASHRAE Standard 90.1- 2013 prototype building models and slightly modified [[7]]. These building prototypes are simulated in different climate zones and maybe mapped to other climate locations for international use [[8]]. The mid-rise apartment building is a 3100 m^2 four-story building (Figure 1).

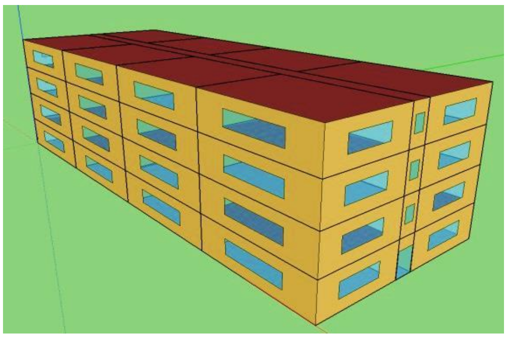

Figure 1. Reference building (mid-rise apartment).

To integrate the PCM into the building, the building envelope is slightly modified and PCM gypsum boards were installed on the inner surface of the exterior walls and roof. Table 1 and Table 2 show external vertical walls and roof construction properties with inclusion of PCM. Further information regarding the baseline building simulated in EnergyPlus, including building envelope components, building internal loads and infiltration could be found in references [[8]] and [[9]].

Table 1. Exterior walls construction.

Material	d [m]	λ [W/m·K]	ρ [kg/m³]	C_p [J/kg·K]	R [W/m²·K]
Stucco	0.0254	0.72	1856	840	-
Gypsum board	0.0159	0.16	800	1090	-
Insulation	-	-	-	-	1.036
PCM	0,0125	0.20	800	1200	-
Gypsum board	0.0159	0.16	800	1090	-

Table 2. Roof construction.

Material	d [m]	λ [W/m·K]	ρ [kg/m³]	C_p [J/kg·K]	R [W/m²·K]
Built-up roofing	0.0095	0.16	1120	1460	-
Insulation	-	-	-	-	4.318
PCM	0.0125	0.20	800	1200	-
Metal surface	0.0008	45.28	7824	500	-

Commercially available plasterboard, suitable for drywall construction applications with about 30 wt.% of microencapsulated paraffinic PCM was selected. The latent heat capacity of 12-mm-thick of such product is around 90 Wh/m², which is available in two different melting points: 23ºC and 26ºC [[10]]. In order to simulate the PCM impact on the building energy consumption, the h-T curve of the selected PCM was introduced to EnergyPlus. Accordingly, the enthalpy method was used based on an equation proposed by Feustel (see eq.1) [[11],[12]] to construct the h-T curve of the PCM, introducing physical properties of Knauf® smartboard (Table 3).

$$h(T) = c_{p,const}T + \frac{h_2 - h_1}{2} \times \left\{1 + \tanh\left[\frac{2\beta}{\tau}(T - T_m)\right]\right\} \quad (1)$$

where C_p is specific heat [kJ/kg·K], T is temperature [ºC], h_1 is specific enthalpy at melting temperature [kJ/kg], h_2 is specific enthalpy at solidification temperature [kJ/kg] β is inclination [−], τ is width of the melting zone [K], and T_m is melting temperature [ºC]. In the eq.1 β was set to 1.4 according to reference [12], and τ was set to 4.

Table 3. Physical properties of the Knauf® smartboard containing PCM [[10]].

Physical property	Value
Specific heat	1.2 kJ/kg·K
Thermal conductivity at 20ºC	0.20 W/m·K
Thermal conductivity at 35ºC	0.19 W/m·K
Melting point	23ºC
Enthalpy of fusion of the PCM	110 J/g
Latent heat capacity ΔH	330 kJ/m²

To study a wider range of PCM melting temperature, hypothetical PCM melting temperatures were considered from 20ºC to 26ºC with reference temperature at -20ºC and melting range of 4ºC. Density change due to phase change was negligible. In current literature, for optimizing the PCM melting point temperature, different PCM h-T curves are created and introduced to the simulation software each time a new temperature is analysed. In the present study, a new methodology is used to iteratively select PCM h-T curve, which reduces the time-consuming process of h-T curve selection at the beginning of each simulation with different PCM melting points.

A packaged terminal heat pump (PTHP) with constant volume fan control, direct expansion (DX) cooling coil and electric heat pump according to baseline building HVAC system types recommendations of ANSI/ASHRAE/IES Standard 90.1-2013 [[13]] was selected. The thermostat control was set to 20ºC for heating and 26ºC for cooling, as recommended for residential buildings and living spaces.

A set of numerical simulation were performed using EnergyPlus v8.4. The numerical model was coupled to a generic optimization program (GenOpt v3.1.1) [[14]], which was chosen because of its capabilities in solving optimization problems corresponding to the building energy performance, where parametric analysis is not feasible or efficient. The algorithm is able to perform optimization of a user-defined cost function such as annual energy consumption, thermal comfort, etc., using various numerical optimization algorithms that could be chosen by the user. In the case of this study the optimization algorithm minimizes annual energy consumption for heating and cooling.

In the present study, the updated Köppen-Geiger [[15]] main climates classification is used to reference different climate zones (Figure 2). Three different cities of each climate were selected and analyzed in this study.

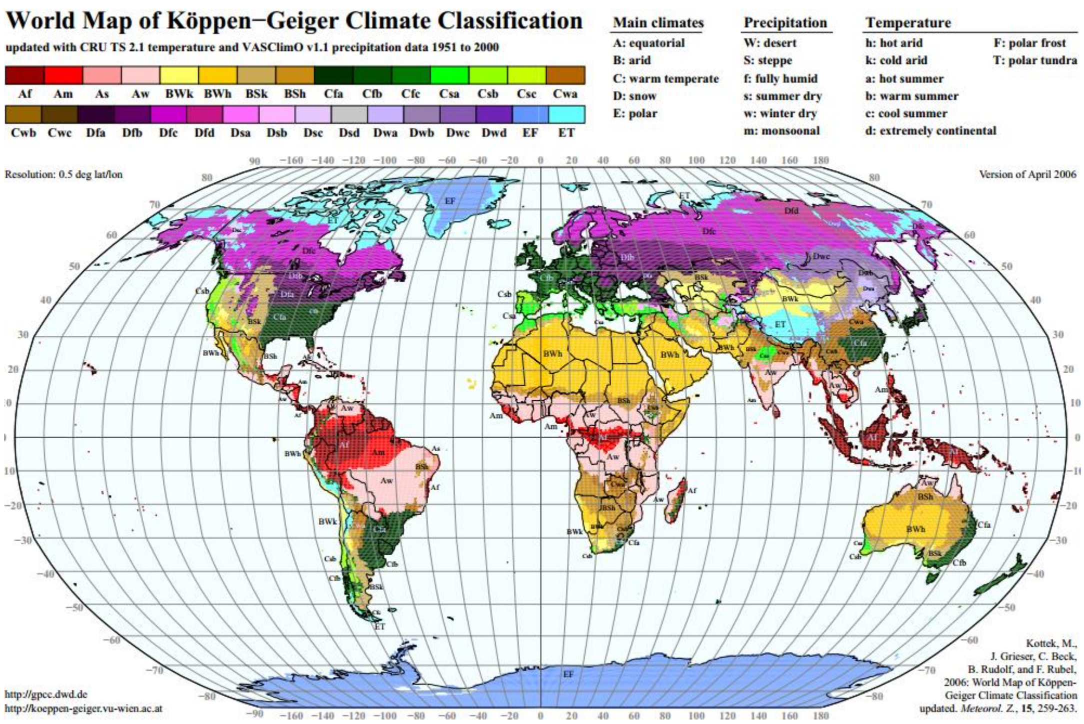

Figure 2. World Map of Köppen–Geiger climate classification [[15]].

3. Results

Table 4 presents the optimization results of PCM melting temperature for the annual total heating and cooling energy consumption. It can be seen that the optimum melting temperature of the PCM highly depends on the climate conditions and the altitude of the region.

In general, in cooling dominant climates (Köppen-Geiger classifications A and B) the optimum PCM melting temperature is closer to the maximum of 26ºC (melting range of 24ºC-28ºC), whereas in heating dominant climates (C and D) the optimum PCM melting is closer to the minimum of 20ºC (melting range of 18ºC-22ºC), with some exceptions such as Johannesburg (25ºC) and Seville (26ºC), which could be because of elevation, solar radiation, and wind profile as explained by Saffari et al. [16]. As it can be seen in Table 4, in equatorial-monsoonal climate zones (Am) the use of PCM is not beneficial since it leads to an increase of the annual energy consumption.

Table 4. Optimum PCM melting for total annual cooling and heating energy consumption.

Climate zones	Cities	Melting point for heating & cooling [ºC]	Total heating & cooling savings [kWh]	[%]	Climate zones	Cities	Melting point for heating & cooling [ºC]	Total heating & cooling savings [kWh]	[%]
Am	Manaus	26.00	-3984	-9.0%	Csb	Antofagasta	20.00	133	5.1%
	Freetown	26.00	-1924	-4.3%		Ankara	20.00	1813	2.0%
	Colombo	22.44	-32	-0.1%		San Francisco	20.06	760	3.8%
Aw	Brasília	25.88	1376	17.5%	Csa	Tehran	20.00	922	2.0%
	Bangui	25.94	589	1.5%		Seville	26.00	811	3.5%
	Kolkata	26.00	685	1.4%		Cagliari	24.44	450	1.7%
As	Fortaleza	24.13	113	0.2%	Cwa	Rangpur	25.50	554	1.4%
	Indore	26.00	1023	3.3%		Hong Kong	20.13	343	1.3%
	Malindi	25.81	157	0.4%		Ankang	25.19	1013	2.3%
Af	Kuala Lumpur	25.38	171	0.4%	Cwb	Huili	20.00	836	4.3%
	Singapore	25.50	213	0.4%		Jiulong	20.00	1705	2.2%
	Puerto Barrios	25.63	3054	8.0%		Addis Abeba	26.00	166	12.0%
BsK	Albuquerque	20.00	1381	2.5%	Dfa	Chicago	25.13	1704	1.4%
	Midland	20.00	1300	3.0%		Omaha	26.00	1952	1.5%
	Ceduna	25.06	987	7.3%		Cleveland	25.63	3492	2.8%
BSh	New Delhi	25.38	619	1.4%	Dfb	Montreal	25.44	3565	1.9%
	Dakar	25.50	561	1.9%		Moscow	24.31	2117	1.2%
	Del Rio	25.63	825	2.4%		Stockholm	21.50	5741	3.3%
BWh	Abu Dhabi	26.00	975	1.8%	Dwa	Beijing	25.63	3099	3.3%
	Jaisalmer	25.94	770	1.4%		Incheon	20.00	883	1.0%
	Phoenix	26.00	1018	2.7%		Pyongyang	25.63	2892	2.6%
BWk	Calama	25.63	317	7.5%	Dfc	Yellowknife	23.75	5537	1.3%
	Las Vegas	26.00	1018	2.6%		Anchorage	23.94	5709	2.5%
	Yumenzhen	26.00	5213	3.3%		Kiruna	20.19	3045	1.0%
Cfa	Brisbane	25.19	656	6.9%	Dwb	Linjiang	25.00	1848	1.0%
	Madrid	20.00	1093	2.6%		Linxi	26.00	3865	1.9%
	Tokyo	20.00	791	1.2%		Pingliang	20.00	2292	2.1%
Cfb	Berlin	24.38	2054	1.7%	---	---	---	---	---
	Johannesburg	25.56	4000	22.7%	---	---	---	---	---
	Paris	24.06	1564	1.9%	---	---	---	---	---

In general, there are interesting correlations between the energy consumption and the optimum PCM melting temperature depending on the climatic conditions. The numerical results demonstrated that the use of passive PCM in building envelopes has high potential for annual energy savings for both heating and cooling. Figure 3 shows the worldwide distribution of optimum PCM melting temperature in different climates according to Köppen-Geiger classification. For example, in Madrid and Seville, despite of being located in a warm temperate climate (C), have different optimum PCM melting temperatures for annual total heating and cooling energy savings. This could be explained by the influence of other factors such as the altitude and the humidity ratio of these regions.

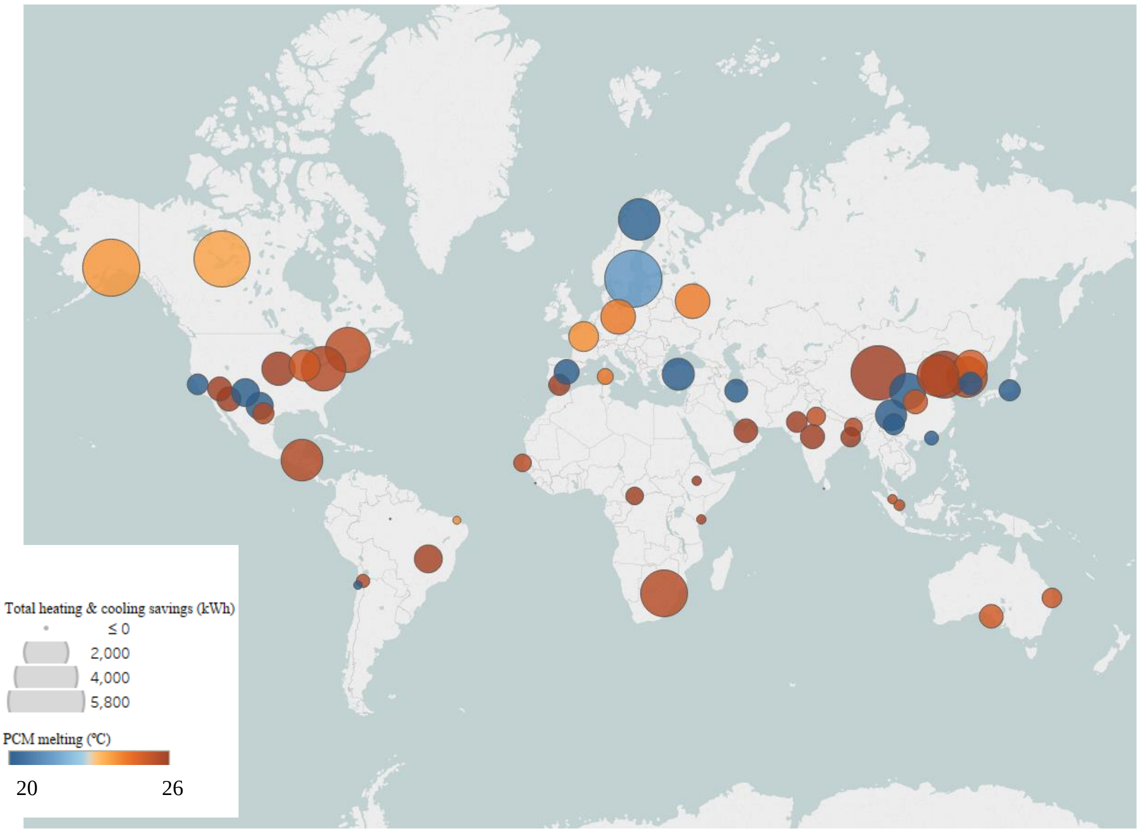

Figure 3. Global energy savings due to use of PCM passive system in building envelopes.

4. Conclusions

In this study, a simulation-based single-objective numerical optimization is presented to determine the optimum PCM melting temperature of a wallboard integrated into a residential building envelope under a wide-range climate zone classifications based on Köppen-Geiger. An innovative h-T function was integrated to the optimization pre-processing step to find out the optimum PCM melting temperature iteratively.

The results show that the proper selection of PCM-enhanced gypsum technology as integrated passive system into the building envelopes can lead to considerable energy savings in many regions in the world, both heating dominant and cooling dominant climates. In cooling dominant climates PCM melting temperature of about 26ºC leads to higher energy savings, while in heating dominant climates the best melting point for the PCM is close to 20ºC. In climates with both heating and cooling energy demands, the optimum PCM melting point could be anywhere in between 20ºC and 26ºC. In addition, the results of the present study show that in almost all high-altitude lands substantial energy savings could be obtained utilizing the passive PCM technology. Also, it should be highlighted that other geographical and climatic factors such as elevation from sea level, solar irradiance, and wind profile notably influence the passive PCM-based design.

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References

[1] International Energy Agency, Technology Roadmap:Energy efficient building envelopes, Oecd. (2013).

[2] Mehling H and Cabeza L F 2008 Heat and cold storage with PCM: an up to date introduction into basics and applications *1st ed Springer* New York

[3] Belz K, Kuznik F, Werner K F, Schmidt T and Ruck W K L 2015 Advances in Thermal Energy Storage Systems *Elsevie*r

[4] Alizadeh M and Sadrameli S M 2016 Development of free cooling based ventilation technology for buildings : Thermal energy storage (TES) unit , performance enhancement techniques and design considerations – A review, Renewable and Sustainable Energy Reviews **58** 619–645

[5] Cabeza L F and de Gracia A 2015 Thermal energy storage (TES) systems for cooling in residential buildings, in: Cabeza L F (Ed.), Advances in Thermal Energy Storage Systems, Elsevier 549–572

[6] Nguyen A T, Reiter S and Rigo P 2014 A review on simulation-based optimization methods applied to building performance analysis *Applied Energy* **113** 1043–1058

[7] ASHRAE 90.1 Prototype Building Models Mid-rise Apartment 2016 https://www.energycodes.gov/901-prototype-building-models-mid-rise-apartment (accessed September 7, 2016).

[8] Thornton B A, Rosenberg M I, Richman E E, Wang W, Xie Y, Zhang J, Cho H, Mendon V V, Athalye R A and Liu B 2011 Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010

[9] Goel S, Rosenberg M, Athalye R, Xie Y, Wang W, Hart R, Zhang J and Mendon V 2014 Enhancements to ASHRAE Standard 90 . 1 Prototype Building Modelshttps://www.energycodes.gov/sites/default/files/documents/PrototypeModelEnhancements_2014_0.pdf.

[10] Kośny J 2015 PCM-Enhanced Building Components - An application of Phase Change Materials in Building Envelopes and Internal Structures, Springer International Publishing, Switzerland

[11] Egolf P W and Manz H 1994 Theory and modeling of phase change materials with and without mushy regions, International Journal of Heat and Mass Transfer **37** 2917–2924

[12] Feustel H E 1995 Simplified Numerical Description of Latent Storage Characteristics for Phase Change Wallboard, Indoor Environment Program,Energy and Environment Division,Lawrence Berkeley Laboratory,University of California, California

[13] R and A C E 2013 American Society of Heating, Standard 90.1-2013. Energy Standard for Buildings Except Low-Rise Residential Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2013 278

[14] Wetter M 2000 Design Optimization with GenOpt, Building Energy Simulation User News. 21 200. http://simulationresearch.lbl.gov/wetter/download/userNews-2000.pdf.

[15] Kottek M, Grieser J, Beck C, Rudolf B and Rubel F 2006 World map of the Köppen-Geiger climate classification updated, *Meteorologische Zeitschrift* **15** 259–263

[16] Saffari M, de Gracia A, Fernandez C and Cabeza L F 2017 (in press) Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings, *Applied Energy*