Engineering Materials and Processes

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PCM-Enhanced Building Components

An Application of Phase Change Materials in Building Envelopes and Internal Structures

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Preface

Thermal mass plays an important role in building energy conservation and in control of internal thermal comfort. It has been observed that it can be also greatly assisted by the incorporation of building components with latent heat storage capabilities. Phase change materials (PCMs) are one of the thermal control means used today in building envelopes and in internal construction components. PCMs in buildings can be utilized for many different purposes including reduction of space conditioning energy consumption, thermal peak load shaving and shifting, local temperature control in building envelope components, or improvement of overall system durability. The scope of this book is to summarize and explain the most important basics of PCM applications in building structures. Despite wide interest in PCM-enhanced building technologies by researchers from industry and academia, engineers, architects, building developers, energy policy makers, code officials, and home owners, there is still a shortage of publications supporting design and analysis in this field. In addition, the industry lacks sufficient technical data and performance information for performance comparisons and development of new technologies. At the same time, industry and government code bodies call for adequate performance testing and rating standards.

Note that there are a large number of engineering and research publications focus on PCMs as a major topic. However, even though PCM-enhanced building materials represent today the major market share for the PCM industry, there is still very little engineering literature dedicated to this subject. Most recent publications treat PCM-enhanced building components more from the material perspective (i.e., PCM types, PCM packaging and encapsulation, PCM manufacturing processes, and experimental analysis of PCMs from the chemical and thermal engineering points of view), rather than focusing on the building component scale. As a result, analysis of the PCM-enhanced building components is most often based on the very basic material scale (only the PCM's performance is examined), or a relatively inaccurate whole building scale analysis is performed without taking into consideration that PCM-enhanced envelopes are distinct building systems with their own properties and performance characteristics.

This work is almost exclusively focused on PCM applications as parts of building envelopes and internal building fabric components. A variety of PCM building products and applications are presented here, followed by subsequent thermal and energy performance data. This publication also presents state-of-the-art testing methods to enable thermal performance analysis of building envelope systems containing PCMs. In addition, numerical methods for dynamic thermal analysis of PCM-enhanced building envelopes and whole buildings containing PCM building envelope components are presented here.

This work was motivated by my desire to further the evolution and widespread application of PCM-based building technologies. Since my goal was to reach a wide audience, I organized this book so that it could be easily understood by advanced undergraduate mechanical engineering students and first-year graduate students of architecture and different engineering disciplines with sufficient thermal/energy analysis and material engineering backgrounds. However, this publication also offers an inclusive collection of references leading to more detailed technology descriptions, performance data, and advanced analytical methods, which may be helpful in research work. In my opinion, this publication is mainly intended for:

- Architects, building designers, home owners, and architectural students, who I trust, will benefit from learning about the history of PCM applications in building envelopes and will be able to study most common material configurations, and PCM locations within a building.
- Building materials and systems developers, engineers, and researchers will find in this book an overview of different types of PCMs, their physical characteristics, commonly used PCM carriers, and a selection of commercially available building products containing PCMs. This group of potential readers may also benefit from the patent list associated with PCM-enhanced building products.
- Researchers, engineers, and code officials will learn from information presented here about performance characteristics of the PCM-based building technologies and descriptions of experimental methods used worldwide for testing of PCMs and PCM-enhanced building products.
- Students, engineers, researchers, product developers, designers, home owners, and finally, energy policy government officials should find the field performance data generated during various whole-system and whole-building field experiments worldwide very helpful.
- Lastly, students, engineers, researchers, and energy modelers should find useful the chapter dedicated to numerical performance analysis of the PCM-enhanced building envelopes and whole buildings utilizing these technologies.

Please bear in mind that publications of this type inevitably reflect the opinions and prejudices of their authors. Hence, some readers may inevitably disagree with my opinions, book structure, and of course the choice of presented material.

In my opinion, such disagreements usually represent healthy reflections coming from the diversity of technology under discussion and are essential for its evolution. Nevertheless, I hope that all future readers will find something of interest here.

Boston Jan Kośny

About the author

Dr. Jan Kośny is a leading building envelope researcher with over 30 years experiences in the building sciences. Dr. Kośny leads Building Enclosure Research Program at Fraunhofer Center for Sustainable Energy Systems (CSE) in Boston, MA, USA. The main objectives of this R&D program are Building Physics, High Performance Thermal Control Materials, and Building Integrated PV Technologies. Dr. Kośny holds a Ph.D. degree in Building Physics from the Polish Academy of Sciences. His doctoral research was in the area of passive solar systems. Prior to joining Fraunhofer CSE, Dr. Kośny spent 18 years at Oak Ridge National Laboratory where he developed several high-performance building envelope and BIPV concepts. Since 1981, he has held a number of faculty positions in Europe and North America and has published more than 120 technical papers and numerous patents related to advanced building concepts. Dr. Kośny actively works for the ASTM C16, ASHRAE TC 4.4 and TC 4.7 committees. He has been representing the United States at many international organizations and standards bodies including the International Energy Agency. Dr. Kośny, is a winner of the 2009 R&D 100 Award for the development of novel phase-change materials.

Contents

Chapter 1
Introduction

Thermal storage plays an important role in energy conservation, which is greatly assisted by the incorporation of latent heat storage in different products. It has been observed that building components, which store heat during peak power operation, can reduce at the same time space-conditioning energy consumption. Phase-change materials (PCMs) are one of the thermal control devices used today in building envelopes. PCMs have been tested as a thermal mass component in buildings for at least six decades. A key goal in low-energy building research is to find ways to manage differences in time between energy sources and energy consumption (i.e., building loads). According to the International Energy Agency (IEA) Annex 24/42 Energy Conservation through Energy Storage/Solar Heating Cooling, thermal energy storage, including PCM technologies, is essential for energy efficiency.[1] PCMs are emerging materials with the potential to dramatically reduce cooling energy consumption and peak cooling demand in buildings, when applied properly.

Published research data have shown that PCMs can notably enhance building energy performance. A large variety of research studies demonstrated that an application of thermal mass in well-insulated structures could generate heating and cooling energy savings between 5 and 30 % in residential buildings (Feustel 1995; Tomlinson et al. 1992; Yamaha 2006; Schossig et al. 2005; Castellón et al. 2007; Kośny et al. 2006, 2012a, b). Considering that new PCM-enhanced building envelope components could be installed in about 10 % of both new and existing US residential homes, the potential for energy savings would be between 0.6×10^{11} and 1.5×10^{11} KWh/year (Kośny et al. 2008).

There is large number of engineering publications focused on PCM as a major subject. However, even though building envelopes represent major PCM applications, there is very little literature dedicated to this topic. Most of recent publications give overviews of PCMs performance, manufacturing processes, and testing from chemical and thermal engineering points of view. Building applications are usually presented more generally as a combination of wall applications,

[1]http://www.iea-eces.org/files/annex_24_extension_work_plan_v6_20120917.pdf.

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space-conditioning systems containing PCMs, active solar heating systems, and the large-scale whole building seasonal thermal storage applications. This publication is focused almost exclusively on PCM applications in building envelope components. A variety of PCM-based building products and PCM blends with building materials and insulations are presented here. Performance data for most major PCM building envelope applications are also described here. Furthermore, this publication presents state-of-the-art testing methods enabling thermal performance analysis of building envelope systems containing PCMs. In addition, numerical methods for dynamic thermal analysis of PCM-enhanced building envelopes and whole buildings containing PCM building envelope components are discussed here.

PCMs in building envelopes can be used for many different purposes including reduction of space-conditioning energy consumption, thermal peak load shaving and shifting, local temperature control in building envelope components, or improvement of overall system durability. This publication mainly discusses several strategies for mitigation of thermal loads generated in residential and commercial buildings. Reduction of the space-conditioning energy consumption can be achieved either by improvements in building thermal shell components (i.e., through increasing the thickness of the insulation), or by adding PCM to the walls, roof, attic floor insulation, floors and ceilings, and fenestration components.

In a traditional, simplified understanding, the thermal performance of insulation is directly proportional to the insulation thickness, when isolating the exterior surface from the rest of the building. However, reported results of field testing, energy simulations, and cost analysis demonstrated that conventional thermal insulations, due to relatively high-cost and diminishing energy benefits, cannot be considered as the only means to achieve improved thermal performance of a building shell in low-energy buildings (Kośny et al. 2012a, b). From the whole system perspective, the impact of thermal insulation thickness on overall energy efficiency is significantly more complex. Thermal analysis becomes more difficult when adding the effects of structural members, local thermal bridging caused by imperfections in insulation installation, air leakage, moisture content impact, deterioration of material properties caused by aging, etc. This shows that taking into account only thickness and thermal conductivity of insulation is not sufficient while analyzing the overall thermal performance of building envelopes. Several alternative building envelope systems have been developed during last decades to assist thermal insulation with control of building thermal loads and in the reduction of the building space-conditioning energy consumption. These systems can be grouped into the following basic areas:

- Exterior radiation control technologies—cool-roof and cool wall coatings (Miller et al. 2008);
- Radiant barriers and foil-faced insulations (Medina 2012);
- Conventional thermal mass and building components utilizing thermal inertia for whole building energy consumption mitigation (Kośny et al. 1998; Kossecka and Kośny 2002);
- Phase-change materials (Mehling and Cabeza 2008);

- Airspaces and naturally ventilated cavities (Sedlbauer and Künzel 1999; Miller et al. 2010);
- Roofs with above the deck inclined airspaces (Miller et al. 2007).

Listed above, recent improvements in building envelope technologies suggest that in the near future, residences can be routinely constructed to operate with very low heating and cooling loads. Optimized design of building envelopes using PCMs can be one of the engineering means to meet low-energy consumption targets in the future. It may result in notable savings in energy consumption, reductions in peak-hour power loads, shifting of building thermal loads, and sometimes, in long-term system durability improvements. An application of PCM thermal mass in buildings has been a main building research topic for the last 60 years. Although the information is quantitatively enormous, it is also spread widely in the literature, and not easy to come across. In general, a material that uses its phase-changing ability for the purposes of heating, cooling, or temperature stabilization is defined as a PCM. PCMs have found applications in many fields, including thermal energy storage, building energy efficiency, cooling of food products, packaging and transportation, spacecraft thermal systems, solar power plants, microelectronics, thermal protection of military installations, waste heat recovery, etc. In most current building applications, PCMs continue to absorb heat without a significant rise in temperature until all the material is transformed into the liquid phase. When PCMs reach the phase transition temperature, they absorb large amounts of heat at an almost constant temperature. Then, when the ambient temperature around a liquid material falls, the PCMs solidify releasing stored latent heat.

Concepts of latent heat and specific heat were discovered by Scottish scientist Joseph Black in the mid-eighteenth century. He was a professor of Medicine and Chemistry at University of Glasgow, UK. Prof. Black assisted James Watt in the development of the steam engine. They also collaborated in a project to manufacture sodium hydroxide.

Ice is the best-known PCM used by humans for food preparation, food conditioning, cold drinks, and space cooling. The knowledge of preserving snow for cooling drinks and preserving food during the summer in warm countries has endured since ancient times. Greeks and Romans bought snow and ice transported on donkey trains from mountains. Most urban residents bought it at snow shops, although few could afford private ice houses. Roman refrigeration techniques involved digging deep pits that were then filled with snow and covered with straw. Ice was also preserved for similar purposes in the northern regions of the world.

For generations, inhabitants of northern arctic regions have been using ice for thermal stabilization of their dwellings. Igloos are the first-known application of the phase-change latent heat in building structures. Derived from "igdlu," the Inuit word for "house," igloos have been the traditional dwellings of the natives of the frozen northern reaches of Europe, Canada, and Greenland for thousands of years (Fig. 1.1). The igloo is an ingenious invention, very effective in keeping arctic people warm. Igloos are relatively easy to construct and made from materials found

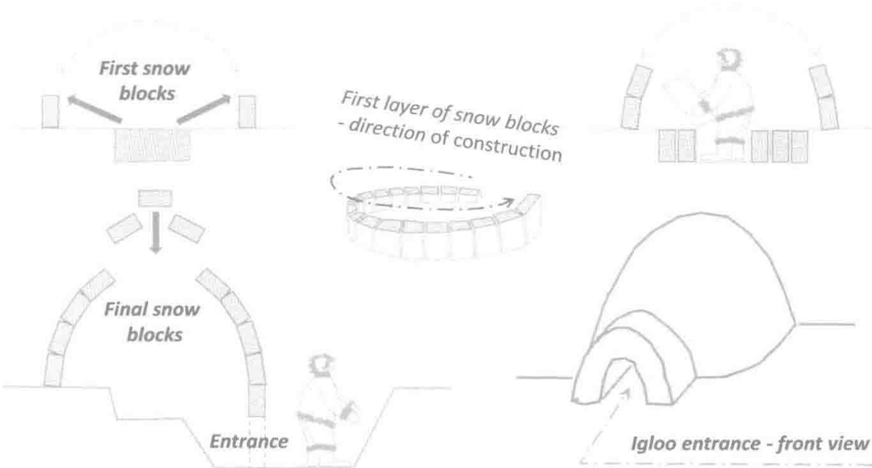

Fig. 1.1 Igloo—a first human construction utilizing PCM—erection details

in abundance: snow and ice which serve simultaneously as building structural components, thermal insulation, thermal radiation shield, and energy storage. Blocks of ice are formed into the dome shape, joined together by snow. To prevent excessive amount of snow and cold wind from coming in, a sunken entrance is typically constructed, along with a raised sleeping platform covered with fur for comfort and warmth.[2] According to González-Espada et al. (2001), internal igloo temperature circulates between 9 and 15 °C, when occupied, even during harsh arctic winters where outside temperatures can drop to −45 °C.

Since the mid-twentieth century, latent heat of ice and a large group of materials with capability of storing heat through the phase transition have been successfully used in buildings. The first documented use of a PCM was by Massachusetts Institute of Technology (MIT) researcher Dr. Maria Telkes in 1948 in a house located in Dover, Massachusetts, USA. In this building, Dr. Telkes followed passive solar wall design, which was first explored by Edward S. Morse and patented by him in 1881.[3] In her house, metal drums filled with Glauber's salt were used as a part of a passive solar heating system. The five-room 135-m^2 house comprised of two bedrooms. Solar energy was collected by the galvanized steel absorber plates, painted black and placed behind the double glazing. Heat generated by this passive solar system passed along a duct via a fan to three heat storage bins situated inside the rooms (see Frysinger and Sliwkowski 1987).

During two and a half winters, in the Northern US coastal climate of Massachusetts, the Dover house was exclusively heated by the sun, before the experiment

[2]http://www.dspace.library.cornell.edu/bitstream/1813/125/2/Igloo.pdf.

[3]http://www.dailykos.com/story/2007/05/17/335503/-Old-Solar-1881#.

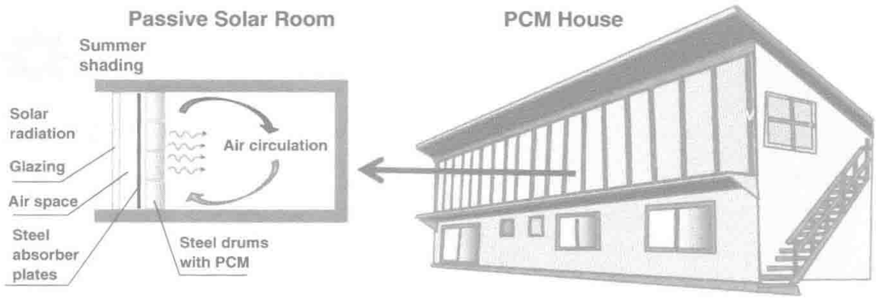

Fig. 1.2 PCM house built in Dover, Massachusetts, USA, by Dr. Maria Telkes and schematic of its passive solar heating operation

ended.[4] On cloudy days, when no solar energy was entering the system, a fan system blew heat from the PCM storage, recrystallizing the salt. Dr. Telkes had analyzed climatic data from the National Weather Bureau and found that, for a period of 65 years, Boston had not gone more than nine days without the sun. She estimated that 21 tons of salt would be enough to heat her house through a 10-day sunless period (see Telkes 1978, 1980) (Fig. 1.2).

A large number of similar residential houses were designed and built in the 1950–1980s worldwide using similar solar design principals to Dr. Maria Telkes approach. One of the first follow-up houses built by Lawrence Gardshire in New Mexico, USA, consisted of a two-story 102-m^2 floor area with collector glazing located in the roof structure (see Ghoneim and Klein 1991). Unlike Telkes' design, comprising of steel barrels with PCM located at the ground floor level; smaller 5-gallon steel storage cans were located within the roof space. The major difference in configuration of the PCM containers was the addition of Borex to the Gluaber's Salts to act as a nucleation enhancing agent. In the 1980s, a large number of solar houses using PCM were built in the USA following very promising field testing results—such as performance data published by Balcomb and McFarland (1978) of Los Alamos National Laboratory, New Mexico, USA, followed with numerous publications describing design principles of passive solar houses using thermal mass components (see Collier and Grimmer 1979; Wilson 1979; Cook 1980; Balcomb et al. 1983; Garg et al. 1985; Neeper 1986), etc. In that time, in experimental passive solar buildings utilizing PCM, different types of hydrated salts were often used for heat storage (see Balcomb and McFarland 1978; Farouk and Guceri 1979; Ghoneim et al. 1991; Crosbie 1997). For example, in late 1970s, Bordeau tested a passive solar collector containing $CaCl_2 \times 6H_2O$, finding that a 8.1-cm-thick PCM wall had an appreciable thermal accumulation (see Bordeau 1980). Unfortunately, these substances frequently created serious durability and corrosion problems, which later affected a number of similar constructions.

[4]http://www.doverhistoricalsociety.org/documents/DoverDays_new/bicentennial/fifties.html.