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Passive cooling of buildings with phase change materials using whole-building energy simulation tools: A review

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ABSTRACT

Buildings contribute to climate change by consuming a considerable amount of energy to provide thermal comfort for occupants. Cooling energy demands are expected to increase substantially in the world. On this basis, technologies and techniques providing high energy efficiency in buildings such as passive cooling are highly appreciated. Passive cooling by means of phase change materials (PCM) offers high potential to decrease the cooling energy demand and to improve the indoor comfort condition. However, in order to be appropriately characterized and implemented into the building envelope, the PCM use should be numerically analyzed. Whole-building energy simulation tools can enhance the capability of the engineers and designers to analyze the thermal behavior of PCM-enhanced buildings. In this paper, an extensive review has been made, with regard to whole-building energy simulation for passive cooling, addressing the possibilities of applying different PCM-enhanced components into the building envelope and also the feasibility of PCM passive cooling system under different climate conditions. The application of PCM has not always been as energy beneficial as expected, and actually its effectiveness is highly dependent on the climatic condition, on the PCM melting temperature and on the occupants behavior. Therefore, energy simulation of passive PCM systems is found to be a single-objective or multi-objective optimization problem which requires appropriate mathematical models for energy and comfort assessment which should be further investigated. Moreover, further research is required to analyze the influence of natural night ventilation on the cooling performance of PCM.

1. Introduction

The building sector (both residential and non-residential buildings) is responsible of consuming roughly 32% of the global final energy use (Fig. 1) [1] and emitting roughly 36% of all greenhouse gas emissions [2]. For instance, according to the EU reference scenario trend projection 2016, the share of energy consumption in houses and buildings accounts for about one-third of the final energy consumption in all sectors and it is expected to be increased slightly by 2050. This sector also contributes to the urban heat island (UHI) phenomenon in urban areas which causes higher surface and air temperature in city centers than in outskirts [3].

A substantial upsurge for cooling energy demands is expected by 2050. The estimated increase is roughly 150% worldwide and about 300–600% in developing countries [5]. Fig. 2 shows an outlook of this sharply increasing cooling energy demand in some developing nations (Association of Southeast Asian Nations (ASEAN), Latin America, India, and China) [1].

To overcome this global concern, policy makers are endeavoring to put energy-efficient solutions on the table since the energy efficiency is found to be the most economic and instantly accessible way to diminish carbon emissions [3]. For instance, the Roadmap 2050 long-term policy [6] is seeking pathways to achieve low-carbon economy with a minimum cost in Europe [7]. The improvement of the building envelope is an essential step to achieve this goal, as 20–60% of all energy consumed in buildings is affected by the design and construction of the building envelope [5].

Today, the energy beneficial of the thermal energy storage (TES) is well known. TES is a promising technology to achieve a low-carbon future [8]. It is accounted as an initiative to reduce the energy consumption in buildings [8], to alleviate the UHI effects in cities [3] and to increase the energy efficiency and comfort by creating a balance

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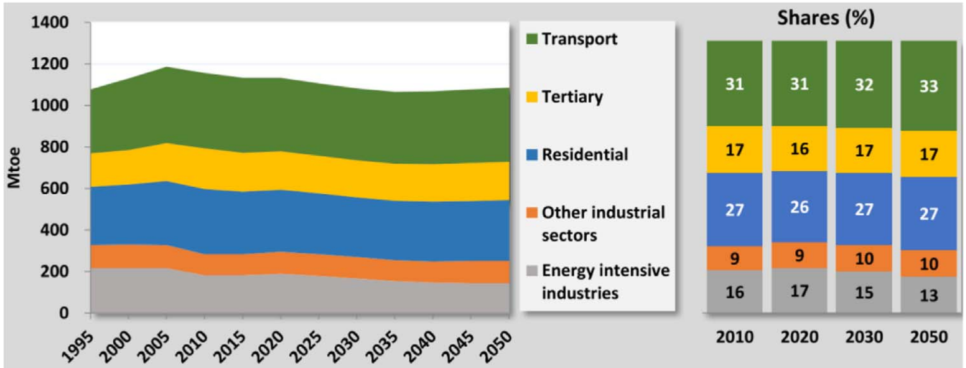

Fig. 1. Final energy consumption by sector in EU countries [4].

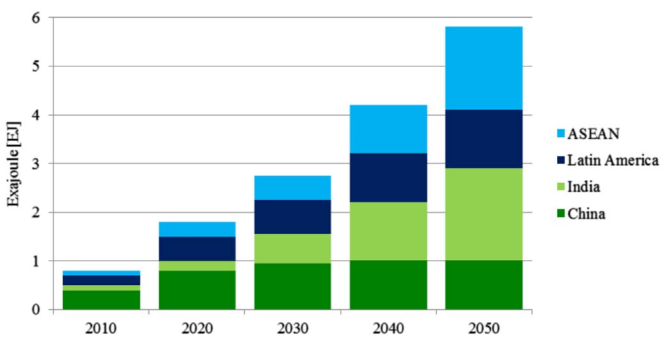

Fig. 2. Perspective of cooling energy demand up to 2050 [1].

between diurnal and nocturnal energy demand [9]. Energy could be stored physically or chemically. In physical processes energy is accumulated as sensible or/and latent heat, on the other hand thermochemical energy storage takes place when a chemical reaction with high heat of reaction happens [10]. For building applications, mostly sensible and latent heat storage are considered, although today thermochemical energy storage is increasing in interest within researchers [11]. For sensible heat TES, massive materials (concrete, stone, etc.) are required to store considerable amounts of heat, however, in latent heat TES higher amounts of energy per volume can be stored. Latent heat storage takes place by phase transition of the storage material. When heat is transferred to the storage material, melting takes place at a specific and quasi constant temperature, storing a large quantity of heat, which is called melting temperature or phase change temperature. After this stage, further increase of heat results in an addition of sensible heat storage. This heat then dissipates by solidification of the storage material. Regularly, for building applications solid-liquid phase change is used since it presents high energy density and no volume expansion problems. Materials with a solid-liquid phase change which are capable to store heat and cold are generally called phase change materials (PCMs) [9,10,12]. Previous researches [13–16] were documented and classified different types of PCM for building applications. These materials can be incorporated in buildings either as passive [17] or active [18] systems. In passive design approach the PCM is incorporated into the building construction and elements as an integrated-design. Enhancing the benefits of sunlight to reduce heating requirements or reducing energy needs for cooling by minimizing heat gains in summer are principal objectives of integrated designs.

An appropriate passive design by means of PCM can provide long-term energy efficiency, thermal comfort, stabilization of indoor air temperature and a reduction of the use and size of the HVAC systems [19,20]. Commonly, in passive design approach for building applications the PCM is incorporated into the building envelope as an integrated material into building walls, roofs, floors, slabs, fenestration, insulation, façade, and shading system [21,22]. However, before applying these innovative materials their performance should be analyzed using validated numerical simulation tools since application of PCM requires special attention to proper materials selection, the location, and the quantity of PCM in the envelope [23].

With the advent of digital computers, mathematical modeling and computer simulation has now become a crucial economical and quickest way to providing a broad understanding of the practical processes involving PCM [24]. Reliable whole-building energy simulation tools can numerically facilitate design, analysis and optimization of the PCM-enhanced building component with no need to set up expensive and time consuming whole-building field experiments [25]. Further on, computer-based simulation tools help designers and engineers to evaluate potential decisions and achieve long-term targets. For example, some researchers developed thermal load predictive models of commercial buildings using building energy simulation software [26]. In another study, whole-building simulation was used for the benchmarking of residential buildings [27]. Additionally, the validated model can always be employed for parametric or optimization studies and has more general applications than an experimental work. Therefore, numerical simulation is a widely-used method for economically and efficiently analyzing complex physical phenomena, such as the modeling of PCM [24].

Accordingly, a considerable amount of literature was published on the building energy simulation pointing out the advantages of using the PCM as a passive cooling or free cooling approach [21]. The current paper presents a holistic review of the numerical simulation of buildings containing PCM for passive cooling purposes using whole building energy simulation tools. The present study is an attempt to address the methods that have been used to evaluate and analyze the effects of passive PCM-based design on the cooling energy performance in buildings through whole building energy simulation software. In this regard, an extensive study was done to address the previous, current and future research trends towards the application of PCM in buildings for passive cooling by means of building energy modeling tools.

2. Whole-building energy simulation for PCM-based passive design

The use of whole-building energy simulation is an essential step to evaluate and analysis the performance of PCM-enhanced buildings. These tools can numerically analyze the dynamic thermal behavior of the building passively enhanced with PCMs. Today, there are many validated whole-building energy simulation programs which are capable of carrying out dynamic energy simulation for different applications [28] but there are few validated whole building energy simulation programs that can analyze energy performance and indoor comfort of PCM-enhanced passive buildings. This section overviews the com-