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Passive thermal control in residential buildings using phase change materials

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ABSTRACT

This paper analyzes the state of the art in R & D on integration of phase change materials into building structures for their passive thermal control. Such perspective phase change materials as paraffins, fatty acids and their blends, as well as fatty acid esters, are considered for passive thermal control of buildings. Gypsum wallboards, concretes, porous and other materials used for building structures forming are discussed. Various technologies of the PCM integration into building structures are described. The characteristics of three laboratory small models of buildings, which were subject of investigations, are presented in this paper. The results of comparative tests on fifteen full size buildings containing elements with PCMs are summarized. Experiments conducted by a number of researchers on passive solar buildings demonstrated that the application of phase change heat storage materials decreases the variation in the air temperature in the rooms; shifts the peak of energy consumption for heating and cooling of lightweight buildings by several hours and decreases energy consumption for maintaining the comfort temperature levels in buildings. Recommendations for further research activities in this field are proposed at the end of this review article.

Contents

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1. Introduction

Continuous growth of greenhouse gas emissions and rising costs of fossil fuels are the major driving force behind intensification of R & D works activities on effective utilization of energy. Commercial and residential buildings consume the most of generated energy. Thus, in 2005 about 39% of all energy consumed in the US was spent for heating or air-conditioning of buildings and their illumination [1]. The similar situation exists in the European Union where buildings consume about 40% of energy used [2]. These numbers highlight the importance of the efficient energy use in buildings.

Deployment of Thermal Energy Storage (TES) is one of the most prospective methods of increasing the efficiency of energy conversion and utilization of various available sources of heat. Thermal energy can be stored using sensible heat of solids or liquids, latent heat of phase change materials (PCMs) or chemical reaction of some chemicals. Among many TES methods quite often the latent heat (or heat of fusion) storage (LHS) is more preferable. LHS has a relatively high density of energy accumulation at the constant temperature or over very narrow temperature range. A wide range of PCMs such as hydrates of salts, paraffins, organic acids, clathrates and their mixtures were studied for different applications including TES. The latter makes it possible [3]:

– To use low cost energy this would otherwise be wasted because its generation timing frequently does not coincide with the thermal demand period. Examples of such low cost energy sources are passive and/or active solar heating; warm infiltrated air; heat generated by building occupants, particularly in classes, public rooms, theaters, restaurants etc.; lighting, cooking, electric and electronic appliances, heat-emitting equipment or exothermic processes.
– To purchase and store energy at a low cost during off-peak periods and discharge this at times when premium rates are applied;
– To reduce the peak in energy demand resulting in reduction of energy costs and in energy conversion equipment.
– To improve the efficiency of burners and chillers by reducing their cycling frequency (this is achieved by rationalization of TES capacity to increase periods for energy accumulation and its discharge).

Results of numerous R & D projects which include the study of PCM properties and designs of phase change TES systems are presented in open literature. The review conducted in this article demonstrates there are at least 1194 papers on properties of PCMs and designs of phase change TES and 1437 articles on applications of PCMs in buildings were published in the leading Elsevier energy journals, see Tables 1 and 2. It can be seen in these tables that during the last ten years the number of publications on the subject of LHS increased by factor of ten. The real number of research papers in the above subject areas, published across a wide spectrum of journals, is substantially greater and a noticeable part of these are review articles. The main topics of review articles, which were printed in the last 30 years on PCMs and systems and their application, are presented in Table 3. It can be seen that PCMs and their applications for heating and cooling of buildings with utilization of solar energy were in the focus of numerous research activities.

The technology of PCM integration into building structure elements, such as gypsum wallboards, walls, floors, ceilings, bricks, concrete blocks, roofs and insulation envelops, and their performances with PCMs were central to a significant number of review articles on the application of PCMs for building heating and cooling. The issues of passive heating and cooling of buildings with integrated PCMs, including the shifting of energy load timing, were discussed in publications listed in Table 3. The aim of this paper is to revise the state of the art in R & D and summarize results obtained in major projects on passive heating and cooling with deployment of small laboratory models and real size test rooms and analyze properties of PCMs used in experiments.

2. Phase change materials for heat storage in buildings

Depending on the application, the working temperature of PCMs during their exploitation can vary over a wide range, namely from −20..−30 °C to 1000 °C. Ideally, residential buildings should provide comfortable living conditions at any regional climatic conditions with annual seasonal changes. In the majority of the countries living conditions are considered to be comfortable if the room temperature is in the range between 18 °C and 25 °C. Therefore melting temperatures of PCMs to be used in building heat storage systems for passive heating and cooling should also vary between 17 °C and 25 °C. In the case of active systems, the melting temperatures of PCMs usually are in the range of 30–40 °C.

The advantage of salt hydrates is their relatively high latent heat. At the same time, they have such shortcoming as the chemical instability, increased tendency to overcooling and they are highly corrosive towards some construction materials. Therefore salt hydrates can be deployed as heat storage materials for buildings if these are in hermetic capsules. Encapsulation of PCMs leads to essential increase in their cost [8,10]. Encapsulated PCMs are usually used in active heating and cooling systems. Organic PCMs do not have specific shortcomings of salt hydrates described above. They can be deployed in passive systems for thermal regulation of buildings. Therefore, in this paper, results of experimental investigations are considered which involved organic materials only for passive heating and cooling systems.

Physical and chemical properties of phase change materials of different grades which are suitable for TES in low, middle, and high temperature applications were summarized in [4–11,18,21,25–29,56]. The numerical simulations conducted by Lund with co-workers [73,74] for climatic conditions of Helsinki, Finland (60°N) and Madison, Wisconsin (43°N) demonstrated that in a direct-gain passive solar house, the direct energy