

Isothermal storage of solar energy in building construction

Dariusz Heim*

Department of Building Physics and Building Materials, Technical University of Lodz, Al. Politechniki 6, 90-924 Lodz, Poland

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ABSTRACT

The role of advanced isothermal heat storage systems in buildings is discussed. A storage system encapsulated with phase change materials in which energy is absorbed in the hot period and released in the cold period is analyzed. The thermal behaviour of isothermal heat storage composites is examined using numerical techniques.

Two methods of heat transfer with latent heat storage are described in the first part. Based on the initial results, the “effective heat capacity” method was selected and implemented into ESP-r. Numerical studies on the effect of isothermal storage of solar energy in specific building material components are discussed in the second part. Numerical simulations were conducted for two cases of multi-zone, highly glazed and naturally ventilated passive solar buildings. PCM-impregnated gypsum plasterboard was used as an internal room lining in the first case study and transparent insulation material combined with PCM was applied for the external south-oriented wall in the second case study. The behaviour of a TIM-PCM wall and its influence on the internal surface temperature are estimated. Air, surface and resultant temperatures are compared with a “no-PCM” case for both case studies and the diurnal and the seasonal latent heat storage effect is analyzed.

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1. Introduction

Solar gains in buildings are divided into direct and indirect. While direct gains are usually assigned to cover heating requirements at once, indirect gains absorbed and stored in the buffer space are used to decrease temperature differences between the heated zone and the external environment. Three general types of problems can occur in solar thermal energy storage systems: usually insufficient thermal mass which can be increased by an additional form of energy storage, considerable temperature changes of the storage medium and problems related to the phase shift between energy gain and demand periods. They can be solved or attenuated by modifying thermal properties towards their latent heat storage potential.

Most solar energy storage systems are obtained by sensible heating of heavy components with no phase or chemical changes taking place within the system. However, storage over long periods requires a fairly large volume of conventional materials, which is at times neither practical nor available.

In passive solar technology, heat capacity of construction elements is one of the prime features. Traditional storage systems

not only use exclusively the sensible heat capacity, but also give rise to several problems, including high cost, excessive mass and undesirable temperature fluctuations. If, however, traditional building constructions (sensible heat) are combined with phase change material – PCM (latent heat of phase change), additional latent heat is used to increase thermal capacity of the building components [1]. Additionally, the phase change is usually almost isothermal, thus providing an excellent means of temperature control. Heat energy storage and release can also be easily set.

2. Composites with heightened heat accumulation

Thermal energy is stored as either specific or latent heat. In the former case, the temperature of the medium changes during storage charge or discharge, whereas in the latter case the temperature of the medium remains more or less constant since it undergoes a phase transformation. Benard et al. [2] have presented an experimental comparison of latent and specific heat within thermal walls. Traditional storage systems, such as a rock-bed, a massive wall, etc., not only use an exclusively specific heat capacity, but also give rise to several problems including high cost, excessive mass and undesirable temperature fluctuations. If, however, traditional building constructions are combined with phase change material (PCM), additional latent heat of the phase change is used to increase thermal capacity of the material [3].

* Tel./fax: +48 42 6313556.

E-mail address: dariusz.heim@p.lodz.pl

Nomenclature

T	temperature [$^{\circ}\text{C}$]
ρ	density [kg/m^3]
h	enthalpy [J/kg]
λ	conductivity [$\text{W}/\text{m K}$]
g_s	specific heat generation rate
g_l	latent heat generation rate
C_{eff}	effective heat capacity [$\text{J}/\text{kg } ^{\circ}\text{C}$]
C_s	heat capacity in solid phase [$\text{J}/\text{kg } ^{\circ}\text{C}$]
C_l	heat capacity in liquid phase [$\text{J}/\text{kg } ^{\circ}\text{C}$]
T_m	melting temperature [$^{\circ}\text{C}$]
T_s	solidification temperature [$^{\circ}\text{C}$]

Additionally, the phase change is usually almost isothermal, thus providing an excellent means of temperature control [4].

The utilization of PCMs in active and passive solar buildings has been a subject of interest since their first reported application in the 1940s [5]. Any PCM composite will comprise two components: a chemical, organic or inorganic, compound that undergoes a phase transition within a desired operating temperature range, and a porous structure that acts as a containment for the heat storage substance. In the building context, pure organic or inorganic PCMs can be impregnated into the porous structure of traditional construction materials such as gypsum, concrete or ceramic that are normally used as an internal surface lining. The thermal performance of different organic (e.g. paraffins, fatty acids) and inorganic (e.g. salt hydrates) chemical compounds has been analyzed [6–9], with the results demonstrating that organic materials are thermally more stable and easier to encapsulate.

3. Modelling of isothermal storage

The first simulation code for a passive solar structure incorporating phase change materials was proposed at the Oak Ridge National Laboratory in the 1980s [10]. The program for one room modelling allowed PCMs to be incorporated into walls. However, some simplifying assumptions were made: constant infiltration, unstratified room air, no additional internal heat sources. The mathematical model based on the enthalpy method was validated by comparing model results with data from an experimental passive solar structure. The heat transfer through the wall was treated only as one-dimensional. The application of the enthalpy method to solve heat transfer problems with a change phase was investigated by Peippo et al. [11] and further research was conducted at the Concordia University, Canada [12,13]. A 3D wall component model using TRNSYS able to carry out thermal simulations of building structures containing PCMs and combined within a single room model was done by Jokisalo et al. [14]. The ESP-r system [15] was refined by Heim and Clarke [16] by incorporating isothermal storage modelling based on the “effective heat capacity” method. Finally Pedersen [17] developed an implicit finite difference thermal model of building elements containing PCMs that was incorporated into EnergyPlus. A general review of two different types of models with experimental validation was offered by Verma and Singal [18] in 2008.

4. Numerical solution: a comparison of two methods

Numerical solution methods of heat transfer with phase change have been discussed by Fox [19], Fuzzeland [20], Crank [21], Voller and Cross [22] and Pham [23]. Two preferred methods of finite difference solution are enthalpy and temperature methods. The

first is characterized by a highly non-linear temperature–enthalpy dependence and the explicit scheme is usually unstable. The second is represented by a small and narrow peak of the capacity (temperature function). The calculation may in some cases “jump” the phase change temperature range. Two methods are proposed in this paper: an “effective heat capacity” method which does not suffer from the above drawback and an “additional heat source” method which requires a relatively short time step to avoid change-phase jumping and allows for a stable numerical solution.

In the early 1990s, investigations into organic phase change materials that could be incorporated into traditional building materials, gypsum or ceramic, were launched at the Department of Building Physics and Building Materials, Technical University of Lodz. Experimental analyses and examinations were conducted using a differential scanning microcalorimeter [8,9] and the results showed a considerable thermal energy storage potential. In 2001, first attempts to integrate PCM modelling into whole building dynamic simulations were conducted in cooperation with the Energy System Research Unit, University of Strathclyde. So-called “effective heat capacity” and “additional heat source” methods were used and compared using numerical analysis. Several subsequent numerical studies showed the energy saving potential and a reduction in the surface and resultant temperatures as well as in temperature fluctuations inside building components. The potential of PCMs to reduce heating energy in buildings was reported in the studies by Heim and Klemm [24] and Heim and Clarke [16]. A reduction in temperature fluctuations in transparently insulated storage walls was estimated by Heim [25].

In the so-called effective heat capacity method, heat capacity is treated as a function of temperature in the phase change temperature range (between melting and solidification). The calculation process is controlled for phase change materials by both temperature and total latent energy. The material is fully discharged below the melting temperature and additional energy is stored as specific heat. During the phase change temperature range, temperature fluctuations of the material are limited by almost isothermal melting or solidification processes. Temperature equal to or over the solidification temperature is possible only for a fully loaded state. Therefore, the material can be out of the phase change temperature range only in two cases: when it is fully charged or discharged (Fig. 1).

In the so-called “additional heat source” method it assumed that some internal heat flux corresponding to latent heat is stored or released by the material. This flux is temperature dependent in the phase change temperature range and is negative when the material stores the heat or positive when the material releases energy. The latent heat flux equals 0 when the material is out of the phase

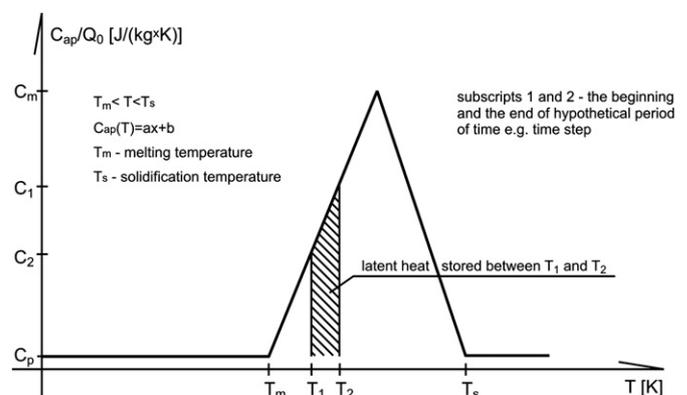


Fig. 1. Graphical representation of “effective heat capacity method”.

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