Experimental evaluation of two low temperature energy storage prototypes based on innovative cementitious material

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HIGHLIGHTS

- An aerated material based on sulfoaluminate cement is used for heat storage.
- A first prototype with an axial metal tube is designed and investigated.
- The thermo-hydric behavior is analyzed during charging/discharging phases.
- Functioning and heat storage performance are improved in a second prototype.

ARTICLE INFO

ABSTRACT

The world's energy consumption has huge environmental and socioeconomic impacts. Heat storage allows the use of renewable energy in buildings to be increased and enhances their energy storage performance. Ettringite material has the advantage of high energy storage density at low temperature (60 °C) compared to existing adsorbent materials such as zeolites (around 200 °C). The objective of this study was to build and improve an experimental prototype of a thermochemical reactor to serve as a proof of concept. A previously modelled cylindrical thermochemical reactor with an axial metal tube was built in the laboratory. It was the first proto-type, with a heat storage yield of 44% or storage capacity of 61 kWh/m^3. To improve the heat storage perfor-mance of the thermochemical reactor, a second prototype without the metal tube was also developed in the laboratory. The storage tests with this second prototype showed a heat storage yield increase from 44% to 71%, with a storage density of 117 kWh/m^3.

1. Introduction

It is becoming essential to use renewable energy systems, as solar energy systems, to enhance the energy performance of buildings and to reduce their environmental impact. However, the problem of using solar energy is its intermittent character: in summer, the solar energy received exceeds the energy needed but, in winter, it is insufficient. It is clear that seasonal thermal energy storage could avoid this phase shift and would increase the use of solar energy in the building sector. There are many heat storage materials that could be used for this purpose.

Sensible heat storage is widely used in such devices as a hot water tanks [1]. Concrete solutions for thermal energy storage are usually based on sensible heat transfer and thermal inertia [2–6]. Compared to other, more expensive, ceramic materials, concrete has already been shown to provide suitable and economically feasible thermal energy storage solutions for sensible heat [7–9]. Thanks to its low cost and good thermal conductivity, concrete block with a piping network has

been used in solar power plants to store sensible heat [10–13]. The disadvantages of sensible heat storage are the low storage density, the space required, the heat losses, and the short duration of heat storage.

The storage density of Phase Change Materials (PCMs) is higher than that of materials storing sensible heat, with a smaller difference between the temperatures at which heat is stored and released [14,15]. PCMs incorporated in concrete walls have been widely investigated in the aim of improving the energy performance of buildings [16–28]. Basically, the three different ways of using PCMs for the heating and cooling of buildings are [29]: (i) PCMs in building walls, (ii) PCMs in building components other than walls, and (iii) PCMs in hot and cold storage units. The incorporation of PCM into different sections of a building, such as wallboards, floors and Trombe walls has promising applications in heating or cooling systems in buildings [23]. However, these materials are not suitable for long-term heat storage. Indeed, some disadvantages of PCMs constrain their use in the building sector [30]: limited storage time, mechanical effect on cementitious material,

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volume instability, and (in some cases) flammability of the PCM.

A seasonal storage system needs to have very low heat loss between summer and winter, and high energy density to reduce its size and cost [31]. Most adsorbent materials (thermochemical storage) are capable of providing seasonal heat storage, but often at high temperature. However, ettringite has the advantage of high energy storage density at a lower temperature (around 60 °C) than many existing adsorbent materials [32,33]. Thermal energy storage by ettringite material is a combination of physical (desorption - adsorption) and chemical (dehydration-hydration process) processes usable in both the short (daily, weekly) and long (seasonal) term. In the charge phase, the heat is stored by heating (endothermic desorption and dehydration) and is not restored as long as the ettringite material is kept dry. In the discharge phase, the heat stored in the ettringite material is released by exothermic reactions of physical adsorption and chemical rehydration in the material. The physical process is related to water vapour desorption-adsorption on ettringite molecules. The connection between ettringite and free water molecules is physical bonding related to the weak intermolecular forces (Van der Waals forces) and hydrogen bonding [34]. The chemical heat storage process is based on the reversible ettringite-metaettringite conversion (dehydration-hydration process) according to Fig. 1 [34,35].

The intermediate phase between charging and discharging generally lasts several months for seasonal storage. One of the key problems of seasonal heat storage is to ensure thermal insulation during this long period. In the case of cementitious material (ettringite), thermal insulation is not necessary during this intermediate phase as the heat from chemical sorption is not restored as long as the material remains isolated from water (liquid or vapour). This may argue in favor of the use of this cementitious material as a seasonal storage material.

Seasonal storage between summer and winter is increasingly being employed to improve the use of solar energy in buildings. The thermochemical reactor prototype (hydrate/water reactive pair) using pure water vapour to humidify the salt is the simplest and most widely employed [36–40], although moist air at atmospheric pressure can also be used [41–43]. The reactor design with moist air instead of pure water vapour is more complex [31] but less expensive to run [44]. Heat storage tests on a large-scale prototype using the $SrBr_2/H_2O$ reactive pair (400 kg of hydrated salt, 105 kWh of storage capacity) have demonstrated the feasibility of the long-term storage system using moist air [31]. Heat storage using ettringite-based material (non-aerated material) has been studied [45] but is hampered by problems of durability, stability and heat storage process.

In a previous work [46], a cementitious material with high ettringite content was developed by sulfoaluminate cement hydration and the durability and stability of the resulting ettringite-based material was investigated (thermal stability, carbonation, and reversibility) [34]. The measured properties of the material were used as input parameters to a two-dimensional heat storage model based on energy and mass balance in the cylindrical thermochemical reactor that was also developed and simulated [35]. Thus, by taking the specificities of the cementitious material into account, the spatiotemporal behaviour of the storage system could be predicted during the charging and discharging phases. The results of this numerical study gave a better understanding of the behaviour of the ettringite material in the cylindrical thermochemical reactor and also helped to predict operating conditions for heat storage [35]. The numerical results were considered as a design study for the construction of a first prototype reactor with ettringite material. A patent application has been filed for this innovative heat storage process [47].

The objective of the present study was to build and improve an experimental prototype of the thermochemical reactor to serve as a proof of concept. The cylindrical thermochemical reactor modelled [35], with an axial metal tube surrounded by ettringite material, was built in the laboratory as the first prototype. The test bed installed in the laboratory, comprising the thermochemical reactor prototype, a heater and a humidifier, was used to carry out complete heat storage tests. For these tests, the reactor prototype was connected first to the heater and then to the humidifier, simulating heat charging and discharging, respectively. The temperature and relative humidity sensors placed in the prototype reactor were used to measure the hydrothermal evolution within the ettringite material during a complete storage cycle (charge and discharge). To improve heat storage performance, a second prototype without the metal tube was built and tested in the laboratory. Instead of water circulating in the axial metal tube, the second prototype used a single gaseous phase in direct contact with the ettringite material (porous network) as the heat transfer fluid in the charging phase and the humidifying gas in the discharging phase.

2. Description and experimental set-up of reactor prototypes

2.1. Heat storage material

The cementitious material used in both thermochemical reactors was developed to satisfy the criteria for a storage material. The ettringite material was first developed by sulfoaluminate cement hydration [46]. The resulting material had a high ettringite content (68%) and dimensional stability. However, its high density reduced the access of water molecules to the ettringite. The porous network of the ettringite system was improved by adding aluminium powder (chemical foaming) to promote exchanges between ettringite (or metaettringite) and water molecules. The ettringite material synthesized and then aerated by the foaming process could be used as a monolithic thermochemical storage material for buildings (Fig. 2). This aerated product satisfied the main criteria for a storage material: high ettringite content (68%) to increase the heat storage density, high permeability ($8.8 \cdot 10^{-14} \, m^2$) to promote the exchange between water and ettringite molecules, and sufficient mechanical strength (2 MPa) to be self-supporting.

2.2. First prototype

2.2.1. Description

The thermochemical reactor modelled in a previous work [35] consisted of a thin metal tube (inside radius, $R_1 = 1$ cm, length, $L = 13$ cm) where the heat transfer fluid (hot water) heated the ettringite based material placed around it ($R_3 = 11$ cm, $L = 13$ cm) during the charging period (Fig. 3). The ettringite material was then insulated to avoid thermal losses to the environment. The ettringite material was isolated from the steam by a PVC cylinder. In addition, thermal insulation was provided by a 10 cm thick layer of glass wool with a thin layer of polystyrene on its surface (Fig. 3).

Longitudinal humidification systems, where the steam circulates through the material porosity in the longitudinal direction (z), are widely used with thermochemical reactors containing zeolite [48,49]. A radial humidification system, around the storage material, was selected to hydrate the ettringite based material here (Fig. 3). This had the advantage of enabling a uniform water vapour pressure to be reached quickly within the adsorber [50,51].

Temperature and relative humidity sensors (uncertainty ± 0.5 °C and ± 3% RH) placed inside the reactor were used to measure the evolution of state variables during the charging and discharging phases

Charging	Ettringite (30 H_2O) + Heat → Metaettringite (12 H_2O) + Water (18 H_2O)
Discharging	Metaettringite (12 H_2O) + Water (18 H_2O) → Ettringite (30 H_2O) + Heat

Fig. 1. Reactions of ettringite - metaettringite conversion [34].