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Enhanced performances of macro-encapsulated phase change materials (PCMs) by intensification of the internal effective thermal conductivity

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A B S T R A C T

Performances of spherical macrocapsules (nodules) currently used in latent heat-based thermal energy storage (TES) industrial units have been enhanced by the addition of graphite particles to the phase change material (PCM). Two different graphite types, namely graphite flakes (GF) and expanded natural graphite (ENG), have been tested at constant PCM content in the nodule. Using water as PCM, both graphite types have been proven to lead to significant reduction in storage/discharge durations (up to 35% and 58% for a graphite load of only $13\%_{wt}$) without reduction in storage capacity. Therefore, enhancement using ENG greatly enhances efficiency, but it is also more expensive. GF maybe preferred, considering both its ease of use and economical issues. At the highest experimented graphite load ($13\%_{wt}$) the overall thermal behavior of the nodule is advantageously improved, with simultaneously no apparent supercooling,a very stable phase change plateau, and very sharp and straight sensible heat exchange periods. The graphites induce both extensive thermal power enhancement and improvement in thermal behaviors. These experimental results have been simulated using numerical *Comsol*®-based models with success. The simulated charge/discharge steps have shown that the air gap present in the nodules induces modifications in the phase change front profile only at the beginning of the periods.

1. Introduction

Global warming, a decrease in fossil resource availability, and other major environmental issues have led to a growing demand for thermal energy storage (TES) materials and systems. In the field of housing and buildings, integrated TES offers daily thermal shift [1] or potentially even seasonal phase lags [2]. In existing industries, TES is viewed as a potential tool to manage and use so-called waste heat [3]. In the extensively growing field of renewable energy, TES systems are a unique way to reach a suitable agreement between the resource availability and the demand [4] or to offer acceptable stability for grid injection [5]. Even for electric energy storage processes like CAES (compressed air energy storage), TES is a means toward adiabatic operation, potentially increasing the overall efficiency from 50% to 70% [6].

TES is commonly acknowledged as a cheaper and easier solution than electrochemical energy storage. Several basic phenomena are available to achieve TES: sensible heat, latent heat, sorption, and thermochemical reactions. Nevertheless, despite their potential, few applications are actually under current industrial use, and the different approaches still suffer from severe intrinsic limitations. Among them, latent heat is well known to offer simultaneously high storage capacity and thermodynamically stabilized working temperature for a wide range of possible temperatures depending on the selected materials. However, latent heat TES systems are very often limited by supercooling, segregation, corrosion, low thermal conductivity, non-symmetrical storage/discharge steps,

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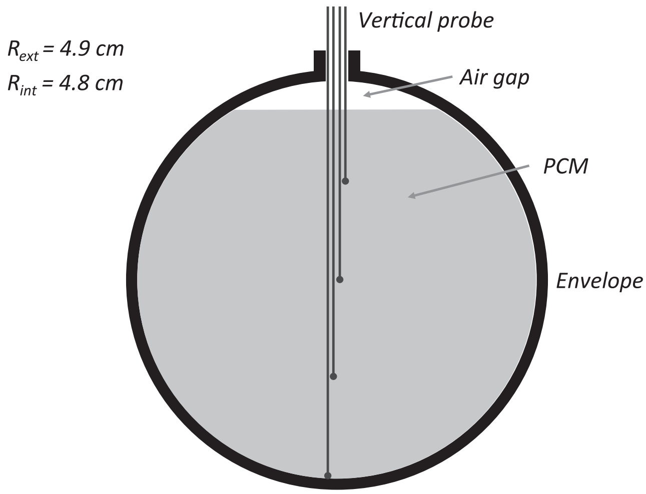

Fig. 1. Thermal energy storage nodule dimensions and thermocouple positions.

and cost. The low conductivity of TES materials leads to low and decreasing storage/discharge steps.

In order to reach the necessary power level, a conventional approach consists of encapsulating the PCM to develop the suitable specific surface area [7–13]. Another very different approach is to enhance the effective PCM thermal conductivity by adding dispersed conductive materials [14,15] or by infiltration of the conductive matrix by the PCM [16]. Graphite flakes (GF), fibers, or matrices as well as metallic foams can be used, each leading to rather different performances. The highest enhancement factors have been achieved using compressed expanded natural graphite (ENG) matrix infiltrated by organic PCMs [17].

The former technique has been applied at both macro [18] and micro [19] scales with success. Macrocapsules in the form of spheres, plates, or cylinders, as well as micro-encapsulated paraffins, are available industrially today and used in various applications from fragile products transportation to human thermal protection. This technique is very flexible in available capsule diameter for various applications, which leads to different corresponding costs. Comparatively, the composite approach is very efficient, but the added conductive media reduces the PCM amount and increases its overall cost, and an external envelope is usually still needed to interface with the heat transfer fluid.

The aim of the present study is to combine the two approaches by introducing conductive materials into PCM capsules. As a consequence, a unique envelope size can be used for different available power levels controlled by the conductive media amount, and the thermal power is significantly enhanced in a larger way than by a simple decrease in capsule size.

This first study is focused on water as PCM and the spherical plastic macrocapsules available industrially; it will be extended to organic PCM in the future.

2. Experimental set up and materials

2.1. Macrocapsules

The PCMs used in the present study have been encapsulated in as-received spherical macrocapsules manufactured by *CRISTOPIA Energy Systems* [20]. These spheres are made of a blend of polyolefins manufactured by hot molding, leading to a one-piece envelope that avoids any cracking, which is so often observed on spheres made of two pieces. A major concern of the study is to increase the internal thermal conductivities, leading to a flexible controlled thermal power. This approach was used on the spheres commercially referenced *AC.00* with an external diameter of 98 mm and a neck aperture diameter of a few mm. The thermal conductivity of the envelope is 0.52 W m^{-1} K^{-1}.

In order to balance the PCM density variation under thermal cycling, an air gap is currently left industrially in every sphere before closing. In order to allow a direct and easy comparison between conventional and enhanced nodules, this commercial standard volume of PCM was strictly kept constant in all experimented spheres.

In each sphere, a vertical probe holding four thermocouples was placed at the axis, leading to temperature measurements inside the sphere (see Fig. 1).

Additional temperature probes were placed in the bath to control the surrounding liquid temperature and homogeneity. All the temperatures were recorded automatically using an *Agilent* device.

2.2. Experimental set up

The experimental set-up (see Fig. 2a) is composed of a moving support holding four macrocapsules (see Fig. 2b) to be soaked in a thermostated bath of recirculated glycol solution (20%). The cryothermostated bath from German *Lauda* Company is well overscaled in order to ensure that no power limitation could occur on the bath side. Moreover, a stirring device was added in the bath to maintain suitable external heat transfer and good glycol solution temperature homogeneity.

Every experiment done on an enhanced nodule was systematically achieved with a reference nodule without graphite on the same support and therefore submitted to the same working

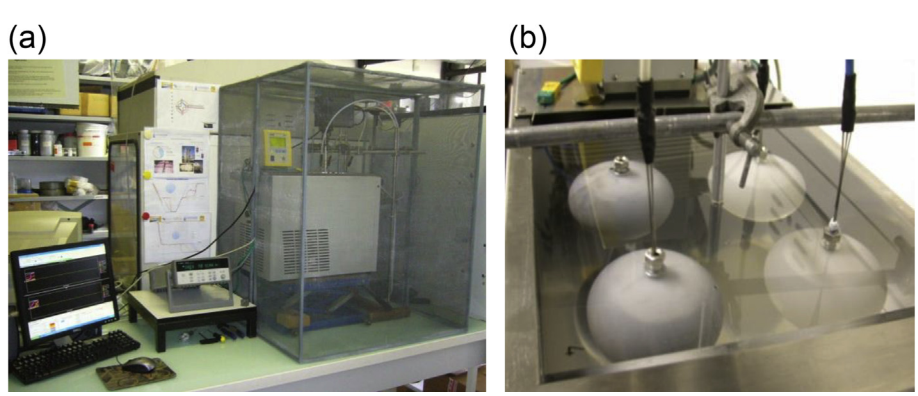

Fig. 2. Pictures of (a) the experimental set up, and (b) 4 macrocapsules soaked in the thermal bath.