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Thermal performance evaluation of bischofite at pilot plant scale

Jaume Gasia [a], Andrea Gutierrez [b], Gerard Peiró [a], Laia Miró [a], Mario Grageda [c], Svetlana Ushak [b,c], Luisa F. Cabeza [a,*]

[a] GREA Innovació Concurrent, Universitat de Lleida, edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain
[b] Department of Chemical Engineering and Mineral Processing and Center for Advanced Study of Lithium and Industrial Minerals (CELiMIN), Universidad de Antofagasta, Campus Coloso, Av. Universidad de Antofagasta, 02800 Antofagasta, Chile
[c] Solar Energy Research Center (SERC-Chile), University of Chile, Av Tupper 2007, Piso 4, Santiago, Chile

HIGHLIGHTS

- A by-product from the non-metallic industry, bischofite, is tested as TES material.
- It is compared with other sensible and latent TES material candidates.
- Bischofite is thermally characterized at pilot plant scale.

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ABSTRACT

The selection of the proper thermal energy storage (TES) material for an application is crucial. On the one hand, these materials should have suitable thermal properties for the operational temperatures range of the systems they are planned to work for, such as thermal stability, high latent heat and high heat capacity. On the other hand, they should be available on the market and at low price. Besides, researchers have to bear in mind the importance of testing TES materials not only at laboratory scale but also at higher scale, since it has been demonstrated that some thermal characteristics are volume-dependant. In the present study, bischofite, a by-product obtained from the non-metallic industry in the North of Chile with desired thermal properties for mid-temperature applications (around 100 °C), has been studied. A first analysis was performed in terms of comparing the thermal properties and cost of bischofite with other material previously studied as TES materials in order to evaluate its potential in both latent and sensible phases. Afterwards, a second analysis was experimentally performed in terms of testing bischofite at large-scale (204 kg) in a pilot plant facility. The experimental procedure consisted on several charging processes within two different temperatures ranges: from 50 °C to 80 °C and from 80 °C to 120 °C in order to study the behavior of the material in the sensible solid phase and latent phase respectively. The temperature profiles, the power given by the HTF, the energy balance in the storage system and the accumulation energy rate of the bischofite were analyzed. Results of both analysis showed that bischofite has potential as TES material for mid-temperature applications.

1. Introduction

The population growth and the uncontrolled use of fossil fuels to supply the rising demand in the fields of industry and transport has a direct impact over the emissions of harmful gases, environment pollution and climate change. Therefore, the research for alternative sources of clean and renewable energies is crucial to overcome and address this conflict. Among all the alternative options, thermal energy storage (TES) is an effective technique which allows the storage of heat and cold when it is available but no needed to be later used when it is needed but not available, allowing the use and implementation of renewable energies. However, the implementation of TES systems entails an initial high economic inversion because of the usually elevated prices of the commercialized TES materials. An important manner to reduce costs related to the TES materials is the usage of recycled materials, wastes and industrials by-products, which are known for their low cost. Moreover, these materials should have high availability and lack of conflict of use [1] due to the fact that a large range of material amount is needed for TES purposes, from few kilograms in domestic systems to thousands of tones in solar plants [2].

Gutierrez et al. [3] reviewed in a previous work the wastes and by-products used or proposed as TES materials for different

* Corresponding author.
E-mail address: lcabeza@diei.udl.cat (L.F. Cabeza).

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Nomenclature

A	heat exchange surface, m^2
cp	specific heat, $J\cdot(kg\ K)^{-1}$
CP	charging process, –
E	energy, J
HTF	heat transfer fluid, –
k	thermal conductivity, $W\cdot(m\ K)^{-1}$
m	mass, kg
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
PCM	phase change material, –
$\dot{Q}$	power, W
t	time, s
T	temperature, °C
VHC	volumetric heat capacity, $J\cdot(K\ m^3)^{-1}$

Greek symbols

ΔH	latent heat, $kJ\ K^{-1}$
Δh	enthalpy, $kJ\cdot(kg\ K)^{-1}$
Δx	thickness, m
ρ	density, $kg\cdot m^{-3}$

Subscripts

b	bottom of the container
cond	conduction
ext	external wall of the container
fg	foamglass
g	ground
i	time interval
in	inlet
ins	insulation
int	internal wall of the container
loss	losses
n	control volume
out	outlet
rw	rock wool
ss	stainless steel
1	Charging Process 1
2	Charging Process 2

applications. This is the case of asbestos containing wastes (ACW) and fly ashes. ACW have been tested on the one hand as sensible TES material for adiabatic compressed air energy storages (ACAES), under operating condition within a temperature range from 50 to 650 °C and on the other hand for linear and central receiver concentrated solar plant (CSP), for a temperature range from 200 °C to 400 °C and from 400 °C to 800 °C, respectively [4]. Fly ashes, which are obtained from industrial combustions such as municipal solid wastes incinerators and coal fired power plants and are mainly composed of oxides such as SiO_2, Al_2O_3 and CaO, have been tested and characterized to be used as sensible heat storage material. These materials have to be previously thermally treated in order to be inert, stable and suitable to be used as TES materials, and the final material obtained was considered inert and stable. The properties determined were density as a function of temperature (from 25 °C to 1000 °C) with values between 2962 and 2896 $kg\ m^{-3}$, thermal capacity between 0.714 and 1.122 $kJ\cdot(kg\ K)^{-1}$, thermal conductivity between 1.16 and 1.59 $W\cdot(m\ K)^{-1}$ and a coefficient of thermal expansion of $8.7\cdot10^{-6}\ K^{-1}$ [5]. Some other industrial by-products such as NaCl [6], bischofite [7], astrakanite and kainite [8] were previously tested both as sensible and latent heat TES materials in a temperature range from 100 to 200 °C. Possible applications for this range of temperature are the recovery industrial waste heat [9], solar food processing [10] and solar cooling [11]. Moreover, metal industry wastes as ferrous slags have been previously tested for high temperature applications, showing stable thermal behavior up to 1200 °C [12–14].

The objective of the present study is to evaluate the suitability of bischofite, a by-product obtained from the non-metallic industry in the North of Chile during the processes of obtaining mineral materials and other salts from the Atacama Desert, as TES material candidate. In order to perform this evaluation two different analysis were carried out. The first analysis consisted of comparing the main thermal properties and economic cost of bischofite with other TES material previously proposed in the literature in order to evaluate its potential as TES material in both latent and sensible phases. Afterwards, a second analysis was performed in terms of testing the material at large-scale (204 kg) in a pilot plant facility. Several charging processes were performed and parameters such as temperature profiles, power given by the HTF, energy balance in the storage system and the accumulation energy rate were evaluated.

2. Material description

The material selected to be studied as candidate for TES applications in the present study is bischofite, which is a mineral that precipitates in evaporation ponds during the process of obtaining Li_2CO_3 and KCl. It is collected and accumulated in discard piles, where about 8% is sold for its use for de-icing roads, for abating dust in the mining roads of the north of Chile and for specific industrial applications to avoid wind erosion, especially in mining tailings [15]. In a previous work bischofite was characterized at laboratory scale [7]. Results from this publication showed that bischofite is composed of nearly 95 wt% of $MgCl_2\cdot6H_2O$ and the remaining 5 wt% of $KMgCl_3\cdot6H_2O$, $Li_2SO_4\cdot H_2O$ and ionic salts like NaCl and KCl. Moreover, other thermal properties such as a temperature of fusion of 98.9 °C, a latent heat of 120.2 kJ/kg and low volume change during melting and solidification (from 1481 kg/m^3 at solid state to 1686 kg/m^3 at liquid state) were determined. Finally, its temperature of fusion and its low price, which is function of $MgCl_2\cdot6H_2O$ price but always lower [7], makes bischofite attractive as TES material candidate for industrial waste heat (IWH) recovery as well as for combined heat and power (CHP) facilities.

3. Experimental set-up and methodology

3.1. Experimental set-up

The pilot plant facility located at the University of Lleida (Spain) was used to perform the experimentation presented in the present study at pilot plant scale. As it can be seen in Fig. 1, it is composed of three main parts: the heating system, the cooling system and the storage system. The heating system consists of a 24 kW_e electrical heater, which heats the heat transfer fluid (HTF) up simulating the energy source during the charging process in a real installation. In a facility based on solar energy this function is accomplished in the solar field by the solar collectors and in other facilities it is accomplished by fossil fuels or waste heat. The cooling system consists of