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A review on the use of SrBr$_2$·6H$_2$O as a potential material for low temperature energy storage systems and building applications

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ABSTRACT

The combination of its sorption capacity, reaction enthalpy, melting temperatures around available industrial waste heat and solar source and high thermal efficiency (compared to others salt hydrates) makes strontium bromide and its two respective hydrates a potential material for low temperature energy storage and building applications. It is considered among suitable materials for low thermochemical and sorption energy storage application (N'Tsoukpoe et al. [7]) due to its high-energy storage density and end-user temperature. Strontium bromide is simultaneously considered as a phase change and a thermochemical material. A short analysis of the general physical and chemical properties such as thermodynamics, melting temperature, density, sorption kinetics, exergy, thermal conductivity, specific heat capacity and permeability highlights the advantageous properties. The review on the use of strontium bromide in pure or modified form is further extended to applications such as building structure, composite design for thermal storage, and heating and cooling. The usefulness and disadvantages of its use in closed/open processes are discussed. Possible solutions to issues are further presented or proposed.

1. Introduction

Inorganic salt hydrates have proven to be reliable in developing thermal energy storage systems for building applications [1–4] and heat recovery [5], under pure or composite forms. However, SrBr$_2$·6H$_2$O recently draw attention to low temperature application [6,7]. It is therefore important to gather reliable data on thermo-physical and chemical properties together with knowledge of maintaining these properties during the system's lifetime for future heating or cooling storage systems based on the present salt hydrate. Salt hydrates are widely used for latent [2] and thermochemical [7] heat storage systems in the temperature range between 10 °C and 200 °C. Though well known as thermochemical storage material, SrBr$_2$·6H$_2$O is not well studied as a latent heat storage material. SrBr$_2$·6H$_2$O can be considered as an inorganic phase change material [8] and thermochemical material (TCM) due to its isostructural stability [9] that allows sorption and/or hydration reaction without destroying the structure.

It is considered as a phase change material (PCM) since its phase change transition is regarded as dehydration or hydration of the salt, though similar to melting or freezing. Actually, the phase change occurs in the range of 76–88 °C. During the phase transition, liquid water within the salt hydrate is released and dissolves the non-hydrated salt molecules [4]. The idea of phase change is supported by the definition of a "phase", as two distinct phases in a system have distinct physical or chemical characteristics and are separated from each other by definite phase boundaries. Meaning this salt melts to either salt hydrate with fewer moles of water or to its anhydrous form. As a PCM, SrBr$_2$·6H$_2$O could present incongruent melting due to the insufficient release of water (uncompleted melting or charging) to dissolve the remaining salt crystals. Many solutions such as the use of excess water, addition of thickening agents and encapsulation exist to overcome this issue, as mentioned in Ref. [4]. It is considered as TCM since a thermal source is used for dehydration and another to provide water vapour for hydration. The major difference with PCM is that, melting is generally avoided during this reversible chemical process. Actually, material can melt if heated above melting temperature in a thermochemical process, but it is not reflected on the process. However, it is technically contained to rapidly recrystallize as previously demonstrated in [5].

For heating and cooling purposes, the hexahydrate is decomposed to the monohydrate, not to the anhydrous due to stability feature. In fact, Dyke and Sass [10] proved it in comparison to the stable barium halide crystal lattices, by showing that the greater stability of SrBr$_2$·

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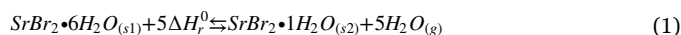| **Nomenclature**			*Subscripts*	
d_b	bulk density (kg m^{-3})		g	gas phase
ΔH_r^0	reaction enthalpy (J mol^{-1} K^{-1})		l	liquid phase
$\Delta H_{l/g}$	enthalpy of the evaporation (J mol^{-1} K^{-1})		$s1$	salt in hydrated form
k	permeability (m^2)		$s0$	salt in dehydrated form
m_s	sample mass of the salt hydrate (kg)			
V_0	volume occupied by the sample in the cylinder (m^3)			
Greek symbols				
λ_s	thermal conductivity of the salt bed (W m^{-1} K^{-1})			

H_2O over $SrBr_2$ is primarily due to the increase in coordination number of the strontium ion by the water molecule. As the present salt just draws attention to heating and cooling storage application, its actual price is seen as a major inconvenient. Depending on the purity of the hydrate salt, anhydrous ($SrBr_2$) costs between 210 and 320 €/kg for 95–99% of purity, respectively (Alfa Aesar GmbH$^©$) and the hydrate, 24 €/kg [11] or 17.6 €/kg [12]. However, N'Tsoukpoe et al. showed that, when an external heat source is used for the evapouration and that heat is considered as free and not considered in the evaluation of either the heat storage density and the thermal efficiency, the $SrBr_2 \cdot 6H_2O$ remained the best among over 125 screened materials from a thermodynamic point of view [7]. This salt hydrate has a white colour in the solid state and may change colour when reacted with other metals such as aluminium. In fact, this salt can turn pale yellow (Fig. 1 [13]) in the presence of Al ions under the action of heat. Compared to other salt hydrates, it is non-toxic and does not present any risk of explosion or combustion. However, eyes and skin irritation can occur when exposed to this product. The present review aims to gather and determine the thermo-physical properties of the reactive pair water/strontium bromide along with some paragraphs on ammonia/strontium bromide. The paper reviews the use of strontium bromide in different forms, pure or composite material, in thermal and building applications. Emphasis is put on theoretical and experimental investigations in order to point out interesting aspects of the material processing, physical and chemical properties, proven uses, remaining challenges and ideas for future researches.

2. Sorption characteristics and properties

The reactive couple $SrBr_2/H_2O$ has already been theoretically and experimentally investigated with success in previous works [5,6,14–17]. Its ideal energy storage density is very high: 628 kW h m^{-3} (referring to the density of 2390 kg m^{-3} and the molar mass of nonporous salt hydrate of 0.3555 kg mol^{-1}) but decreases when accounting for additional components at prototype level. For example, it was found to be 400 kW h m^{-3} in an open system [16] and 531 kW h m^{-3} in a closed system [18]. A temperature range of 80–90 °C is sufficient to

insure the dehydration from the hexahydrate to the monohydrate without incongruent dissolution of water vapour in the solid phase, as the solubility curve shows in Fig. 2a. The solubility line informs about the approximate limit of saturated solution of the $SrBr_2 \cdot 6H_2O$. An evaporator pressure above 12 mbar (~10 °C) is required to reach above 50 °C output in the reactor, which can be used directly for a desired application. Note that in those conditions, the energy required to afford 10 °C at the evapourator can be done with geothermal source energy. In an open-air system, the exothermic reaction of hydration induces simultaneously water vapour consumption (i.e. decrease of absolute water content) and temperature increase (Fig. 2b). If the inlet air conditions is in A, the outlet air conditions will be somewhere around B. In a similar way, for the endothermic dehydration, with inlet air conditions in C, the outlet air conditions would be somewhere around D [6].

The retained solid-gas thermochemical reaction in the system is related to the two following monovariant equilibriums:

$$SrBr_2 \bullet 6H_2O_{(s1)} + 5\Delta H_r^0 \leftrightarrows SrBr_2 \bullet 1H_2O_{(s2)} + 5H_2O_{(g)} \qquad (1)$$

$$H_2O_{(l)} + \Delta H_{l/g} \quad \leftrightarrows \quad H_2O_{(g)} \qquad (2)$$

with $\Delta H_{l/g}$=2519 kJ kg^{-1} H_2O (at 10 °C) the enthalpy of evapouration and ΔH_r^0=3744 kJ kg^{-1} H_2O, the reaction enthalpy. Further tests on a TGA-DSC show energy yield of 798 kJ kg^{-1} $SrBr_2 \cdot 1H_2O$ at 100 °C and of 834 kJ kg^{-1} $SrBr_2 \cdot 1H_2O$ at 200 °C.

The solid/gas equilibrium temperature for the dehydration phase and the hydration, which already indicates minimum expected output temperatures, are given on the basis of the diagram in Fig. 2. Under closed system, meaning operating under pure water vapour, the Clausius-Clapeyron stands for the solid/gas equilibrium temperature determination. However, the operating cycle for an open system is not easily represented in Clausius-Clapeyron diagram, because the process does not happen under equilibrium condition. For the present salt hydrate, in closed system, solid/gas equilibrium temperature for the dehydration phase and the hydration was found similar as 43 °C in Ref. [15]. Fopah-Lele et al., however found 58 °C for the dehydration phase and 45 °C for the hydration phase [5]. The difference lies in the evapo-
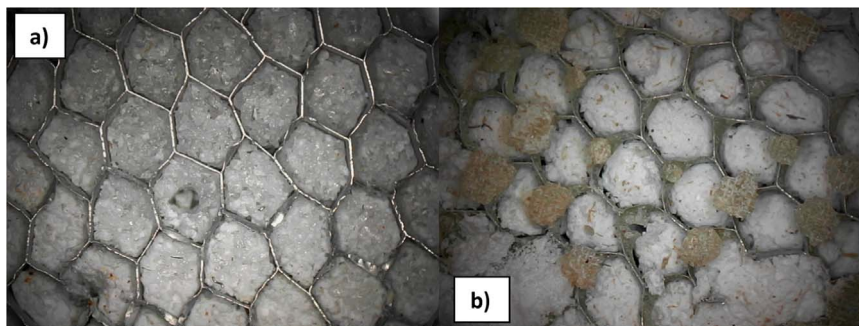

Fig. 1. Strontium bromide in the (a) hydrate form and the (b) dehydrated form in the honeycomb structure heat exchanger [13].