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Lab-scale experiment of a closed thermochemical heat storage system including honeycomb heat exchanger

Armand Fopah-Lele [a, b, *], Christian Rohde [a], Karsten Neumann [a], Theo Tietjen [a], Thomas Rönnebeck [a], Kokouvi Edem N'Tsoukpoe [c], Thomas Osterland [d], Oliver Opel [a], Wolfgang K.L. Ruck [a]

[a] *Sustainable Energy Research and Environmental Chemistry Institute, Faculty of Sustainability Sciences, Leuphana University Lüneburg, Scharnhorststraße 1, Geb. 16, 21335, Lüneburg, Germany*

[b] *Univ Lyon, CNRS, INSA-Lyon, Université Claude Bernard Lyon 1, Center for Energetic and Thermal Sciences of Lyon (CETHIL) UMR5008, F-69621, Villeurbanne, France*

[c] *Laboratoire Energie Solaire et Economie d'Energie (LESEE), Département Génie Electrique, Energétique et Industriel, Institut International d'Ingénierie de l'Eau et de l'Environnement, 01 BP 594, Ouagadougou 01, Burkina Faso*

[d] *Faculty of Mechanical and Process Engineering, University of Applied Sciences, An der Hochschule 1, 86161, Augsburg, Germany*

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ABSTRACT

A lab-scale thermochemical heat storage reactor was developed in the European project “thermal battery” to obtain information on the characteristics of a closed heat storage system, based on thermochemical reactions. The present type of storage is capable of re-using waste heat from cogeneration system to produce useful heat for space heating. The storage material used was $SrBr_2 \cdot 6H_2O$. Due to agglomeration or gel-like problems, a structural element was introduced to enhance vapour and heat transfer. Honeycomb heat exchanger was designed and tested. 13 dehydration-hydration cycles were studied under low-temperature conditions (material temperatures $< 100\ ^{\circ}C$) for storage. Discharging was realized at water vapour pressure of about 42 mbar. Temperature evolution inside the reactor at different times and positions, chemical conversion, thermal power and overall efficiency were analysed for the selected cycles. Experimental system thermal capacity and efficiency of 65 kWh and 0.77 are respectively obtained with about 1 kg of $SrBr_2 \cdot 6H_2O$. Heat transfer fluid recovers heat at a short span of about 43 °C with an average of 22 °C during about 4 h, acceptable temperature for the human comfort (20 °C on day and 16 °C at night). System performances were obtained for a salt bed energy density of 213 $kWh \cdot m^3$. The overall heat transfer coefficient of the honeycomb heat exchanger has an average value of 147 $W\ m^{-2}\ K^{-1}$. Though promising results have been obtained, ameliorations need to be made, in order to make the closed thermochemical heat storage system competitive for space heating.

1. Introduction

The addition of energy storage units to thermal energy systems for residential heating and cooling was proposed decades ago [1]. At that time, researchers believed that combining energy storage and existing systems (heat pumps for example) was economically not realistic. However, Katulic et al. [2] recently proved that, thermal energy can also be accumulated while electricity market prices remain low and discharged whereas prices remain high via a conversion chain-like electricity-heat-chemical-heat-electricity. Therefore, thermochemical heat accumulation appears promising, though not yet commercialized. In a similar approach, while considering combined heat and power (CHP) or cogeneration plant and hot water tank for district heating, Bogdan et al. [3] noted both the economic and environmental benefits of using thermal energy storage system within a CHP plant. Streckienė et al. [4] studied the feasibility of a coupled CHP with a thermal energy storage system in the German energy market. From their work, they draw the conclusion that combining thermal energy storage (TES) with a CHP could reduce the CHP-plant investment and reduce the simple

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* Corresponding author. Univ Lyon, CNRS, INSA-Lyon, Université Claude Bernard Lyon 1, Center for Energetic and Thermal Sciences of Lyon (CETHIL) UMR5008, F-69621, Villeurbanne, France

E-mail addresses: armand.fopah-lele@insa-lyon.fr (A. Fopah-Lele), ruck@leuphana.de (W.K.L. Ruck).

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payback time from 9 to 10 years down to 5 years.

The above-mentioned reasons gave impulses on working on such storage systems, particularly thermochemical heat storage systems. Benefits of thermochemical heat storage over conventional heat storage are a higher energy density and storage of the heat without losses after charging, since the heat is stored in chemical form. Years ago, Kato [5] showed the potential of a system improvement using chemical heat storage process for cogeneration systems. He then proposed a system consisting of a combination of cogeneration engine and chemical heat storage system showing an impressive heat upgrade. Thermochemical heat storage has a possibility to enhance the energy use efficiency of a cogeneration system. Thermochemical in the present context is about storing energy from chemical reactions between a solid and a gas. It differs from ab-, adsorption though applications to space heat or cooling are similar [6,7]. Previous works dedicated to this application show some features such as expected system potentials [8,9]. However, the team of the laboratory of processes materials and solar energy (PROMES-CNRS) focused on developing such heating systems for buildings using solar source [10–14] at low temperature, with a few studies dedicated to waste heat recovery [15,16]. In some laboratories of the French Alternative Energies and Atomic Energy Commission (CEA), thermochemical solar energy storage was developed on an open process for household applications [17]. Most of the previous studies they cite use $SrBr_2 \cdot 6H_2O$ as the reactive material, which was later demonstrated as the most promising for CHP application [8]. Lahmidi et al. [10] investigated a closed system based on composite ($SrBr_2 \cdot 6H_2O$ and graphite) for heating and cooling purpose using solar heat source. Their conclusion showed that, as long as the heating storage density of the reactive material bed is higher than 250 $kWh \cdot m^{-3}$, a system storage capacity of 52 $kWh \cdot m^{-3}$ or more is achievable. Two years later, they constructed and tested a prototype with a storage capacity of 60 $kWh \cdot m^{-3}$, where the initial objective was to design and test a 100 kWh prototype [12]. Further important demonstrators and prototypes using thermochemical reactions are summarized in Ref. [18]. Heat source for the present work is waste heat generated by cogeneration systems (CHP). To the best of our knowledge, there are only a few studies investigating the feasibility and performances of such closed thermochemical storage systems using $SrBr_2 \cdot 6H_2O$ as storage material. There are very few lab-scale up-to-date studies making the state-of-the-art not up to date. As a matter of fact, this work is the first using only pure $SrBr_2 \cdot 6H_2O$ in closed system with a special heat exchanger.

This paper presents the lab-scale design and the first experimental results observed during charging and discharging processes of a closed thermochemical heat storage system. Various optimization aspects are addressed such as compact reactor design, heat exchanger design. In addition, the authors wish to emphasize that, the honeycomb heat exchanger presented in this paper, is a completely new one adapted to such system. The honeycomb structure is used to avoid the agglomeration (gel-like formation) issue encountered in most heat storage systems based on thermochemical reactions using only pure salt hydrates.

2. Experimental system design and procedure

Previous modelling and simulation were made for the design of a prototype [19]. Before building a prototype, a lab-scale is rather developed to test the system in known and controlled conditions so that the feasibility of the concept can be proved. The laboratory reactor has the target described in Ref. [19]. The comparison of numerical-experiment values was within the 70–82% confidence interval.

2.1. Lab-scale description

For experiments in the present work, an operated reactor based on a honeycomb heat exchanger concept is manufactured and integrated into the test bench. This choice of heat exchanger is based on the improvement of aspects such as agglomeration, swelling, expansion of the bed and diffusion [20]. The honeycomb structure prevents agglomeration of salt particles as precedent studies have shown the need to re-design the exchangers for proper heat and vapour transport [21,22]. Therefore, an optimal bed thickness was assessed. However, the agglomeration occurs much more in the width than in the length of the bed. Hence, introducing a structural honeycomb element reduces these dimensions. That structure involves equal-size cells, smaller in dimension than the bed thickness. The structural element has the functions of heat transfer and geometry optimization for an improved mass transfer and the avoidance of agglomeration in larger scale. In this way, the bed is subdivided into multiple small-sized (optimal length and width) beds so that each bed reacts (dehydration/hydration) without transfers' limitation. Besides, the aluminum walls within the bed serve as heat distribution all around the bed. The reactor vessel is made of stainless steel and the exchanger of aluminium. Roughly corrosive tests (without heating constraints) were performed on aluminium, prior to the experiment. After 24 h, strontium bromide does not affect the metal but it starts degrading the metal structure after five days. Since a cycle test does not last more than a day, corrosion problems are not expected.

A laboratory test reactor filled with 974 g $SrBr_2 \cdot 6H_2O$ has been set up at the Institute of Environmental Chemistry (IEC) of the Leuphana University in Germany and a process flow diagram of the experiment is shown in Fig. 1. It consists of three main units:

i. The cylindrical reactor (diameter = 200 mm, height = 400 mm for an internal volume of 0.012 m^3) containing the integrated honeycomb heat exchanger with $SrBr_2 \cdot 6H_2O$,
ii. A thermal bath playing the role of an evapo-condenser and
iii. The Unistat, a temperature control device playing both the role of a micro-CHP for the charging process and the households for the discharging process.

All these units allow the monitoring of the heat transfer fluid (HTF) at fixed temperatures, the measured mass flows, the reactive gas supply, the cooling and disposal of the vapour stream. The heat exchanger consists of two parts, a bundle tubes transporting the heat transfer fluid and the honeycomb bed structure containing the salt ($SrBr_2 \cdot 6H_2O$). Ten thermocouples (sheathed NiCr–Ni, type K of different lengths: 200, 300, 400, 500 and 600 mm) were then inserted into the bed by making some holes. Care was taken to not destroy the bed structure. An eleventh thermocouple was placed in the reactor environment to record reactor ambient temperature.

Mass flowmeter F_1 (capacity up to 3000 kg h^{-1} of type Yokogawa RCCT34-AV0M02D4SL) records the mass flow of the heat transfer fluid. To observe the reaction front and identify possible limitations due to heat and mass transfer of pure vapour, thermocouples were installed inside the reaction bed. Two sheathed platinum resistance thermometers (Pt-100, RM-Type from Rössel Messtechnik) T_{201} and T_{202} were plugged (perpendicularly to the flow) into the tube conducting the HTF to record inlet and outlet temperatures. Temperature was recorded through these thermocouples connected to a BenchLink Data Logger software “Agilent”. The heat transfer fluid in this experiment was the thermal DW-Therm HT P20.330.32. A pressure transmitter (SD-37 from Rössel Messtechnik) plugged to the top cover of the reactor records the pressure evolution in the reactor. Data acquisition was done using