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Energy Performances of Open Sorption Reactor with Ultra-Low Grade Heat Upgrading for Thermochemical Energy Storage Applications

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Abstract

The work discusses a problem of harvesting and upgrading of ultra-low grade heat with thermochemical energy storage technology for space and domestic water heating in residential area. The laboratory scale prototype, operating on the principle of an open packed bed sorption reactor and using moist air as a heat/mass transfer fluid, is experimented. The range of experimental air temperature was set to 17–40 °C, which corresponds to the typical range of domestic waste thermal energy. The tested sorbent was a salt-in-matrix composite material composed of a silica gel containing 43 wt.% of calcium chloride ($CaCl_2$) salt. Hygrothermal behavior and energy performances of the prototype control volume filled with 245 g of material, representing the reactive front of a thermal wave, were analyzed at constant inlet hydration conditions (water vapor pressure of 12.5 mbar). The average temperature lift was recorded as 9–13 °C, representing the amplification of a supplied heat on 23% – 75% depending on the inlet temperature. The average specific thermal power inside the material bed was measured to be 168–267 W kg^{-1}. The apparent energy density, based on the prototype control volume, ranged between 1.0 and 1.6 GJ m^{-3}. Taking into account the heat of water vaporization, the coefficient of performance of the process was determined to be 0.96–1.57.

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Keywords: Thermochemical energy storage; ultra-low grade heat; composite material; open sorption; residential building;

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1. Introduction

Heat and electricity are the dominant types of energy end-used by buildings. The conversion of thermal energy into electricity [1, 2] and vice versa [3] is approved and perspective way for a large scale energy management. Such technological processes are based on various thermodynamic cycles and operate typically at temperatures from 500 °C to 1500 °C. The resulting high (>400 °C) and medium grade (200 °C – 400 °C) waste heat can be successfully recovered for the further reuse. However, harvesting low and ultra-low grade heat (up to 200 °C or <100 °C) is associated with a low economic viability [4]. Recently the potential of utilization of waste and ultra-low grade heat presented a live interest in different fields of thermal engineering applications, including combined power and heat generation (CHP) [5, 6], cascaded heating/cooling processes [7 – 11]. According to Rattner et al. [12], 20.3% of electricity usage and 12.5% of primary fuels could be replaced directly by a waste heat for end-use temperatures below 100 °C.

Space heating and domestic hot water preparation (SH&DHW) directly concern the vital spheres of human being and require usually temperature range between 30 °C and 65 °C. The recovery of a waste heat or the upgrade of an ultra-low grade heat to this temperature range meets particularly the objectives of energy saving and rational utilization in the future decarbonized society.

Ammar et al. [13] have studied the transportation of a low-grade heat over long distances from industries to domestic heat sinks. The authors have identified the economically viable distance of 30 – 40 km for the temperature as low as 80 °C using the chemical sorption technology from liquid solution of ammonia (NH_3). The heating coefficient of performance (COP) was observed to be nearly 0.5. NH_3/H_2O chemical pair was selected for economic reasons. The authors accented though on risks associated with high concentrations of NH_3 in the air. Mazet et al. [14] investigated relevant solid/gas sorption cycles for low grade heat upgrading and transportation to the user site using a distant thermal source located over 10 km. Numerous well-known chemical pairs (chlorides and bromides as solid sorbents reacting either with NH_3 or with H_2O as sorbate) have been evaluated. The described concept is typically adapted to the temperature range below 100 °C. The heat upgrading performances of investigated cycles resulted in COP bounded between 0.5 and 0.6. Li et al. [15] have proposed the thermochemical sorption heat transformer using reversible solid/gas reaction for the integrated energy storage and the low-grade thermal energy upgrading. The magnitude of the temperature upgrade could be adjusted in the range 19 °C – 152 °C according to identified chemical pairs ($MnCl_2-NaBr/NH_3$, $MnCl_2-CaCl_2/NH_3$ and $NiCl_2-SrBr_2/NH_3$). The energy efficiency of low grade thermal storage ranged between 0.34 and 0.72. Yu et al. [16] suggested that the utilization of solid/gas reactive heat transformers, exploiting directly the low grade heat, is more reasonable compared to compression heat pumps based upon electricity, that was being derived from high grade thermal energy.

In order to improve the energy efficiency and economic effectiveness resulting from recovering a waste heat and upgrading an ultra-low grade heat to the end-use purposes, there is a need for energy storage [17]. Bao et al. [18] explored the simultaneous electric and thermal energy storage integrated cycle using the ultra-low grade heat with temperatures from 30 °C to 100 °C. The proposed principle uses $MnCl_2-CaCl_2/NH_3$ and $CaCl_2-NaBr/NH_3$ as reactive chemical systems and is characterized as a highly efficient reversible chemisorption-to-power process with overall efficiency between 0.6 and 0.65 at 30 °C (source temperature). The thermal energy storage density of the integrated cycle was up 0.28 GJ m^{-3}, while the electrical energy storage density was limited only by 0.02 $GJ\ m^{-3}$. Zhao et al. [19] have designed the laboratory scale sorption heat storage prototype aiming to replace the conventional hot water storage tank in SH&DHW applications. The prototype was tested for energy charging at 85 °C and energy discharging at 40 °C as temperature conditions. The recovery process of ultra-low grade heat at 30 °C allowed lifting the energy density of the prototype by 50%, compared to initially used heat source at 18 °C without heat recovery. The applied material was the consolidated composite material (expanded graphite + 93 wt.% of $LiCl$) that reacted with H_2O vapor. Lu et al. [10] have developed multi-step sorption cycles with temperature upgrading and thermal energy storage for solar heating and cooling purposes. The developed cycles were based upon $LiCl/H_2O$ working pair. The heat upgrading cycles shifted the source temperature by 50 °C – 60 °C. The discharging heat storage density arrived to 2.0 GJ m^{-3} and provided COP of 0.61 – 0.64 for the temperature upgrading cycle. Liu et al. [20] have synthesized a novel thermal energy storage material (Wakkanai siliceous shale + 22.4 wt.% of $CaCl_2$) to work in an open sorption system for ultra-low grade industrial waste heat recovery. The source air temperature was supplied at 25 °C to the prototype installation and the resulting temperature was upgraded greater than 40 °C. The developed system required