Energy Conversion and Management 142 (2017) 426–440

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Salt impregnated desiccant matrices for ‘open’ thermochemical energy conversion and storage – Improving energy density utilisation through hygrodynamic & thermodynamic reactor design

Sean P. Casey [a], Devrim Aydin [b,*], Jon Elvins [c], Saffa Riffat [d]

[a] University Centre, North Lindsey College, Kingsway, Scunthorpe DN17 1AJ, UK
[b] Department of Mechanical Engineering, Eastern Mediterranean University, G. Magosa, TRNC Mersin 10, Turkey
[c] SPECIFIC, Baglan Energy Park, Baglan, Port Talbot SA12 7AX, UK
[d] Division of Infrastructure, Geomatics and Architecture, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 21 March 2017
Accepted 22 March 2017

Keywords:
Salt In Matrix
Open thermal energy storage
Vermiculite
Hygrothermal
Thermochemical

ABSTRACT

In this study, the performance of three nano-composite energy storage absorbents; Vermiculite-$CaCl_2$ (SIM-3a), Vermiculite-$CaCl_2$-$LiNO_3$ (SIM-3f), and the desiccant Zeolite 13X were experimentally investigated for suitability to domestic scale thermal energy storage. A novel 3 kWh open thermochemical reactor consisting of new meshed tube air diffusers was built to experimentally examine performance. The results were compared to those obtained using a previously developed flatbed experimental reactor.

SIM-3a has the best cyclic behaviour and thermal performance. It was found that 0.01 m^3 of SIM-3a can provide an average temperature lift of room air, $\Delta T = 20$ °C over 180 min whereas for SIM-3f, $\Delta T < 15$ °C was achieved. Zeolite provided high sorption heat in close approximation with SIM-3a, however, the higher desorption temperature requirements coupled with poor cyclic ability remain as obstacles to the roll out this material commercially.

The study results clearly show that the concept of using perforated tubes embedded inside the heat storage material significantly improves performance by enhancing the contact surface area between air → absorbent whilst increasing vapour diffusion. The results suggest a linear correlation between thermal performance and moisture uptake, ΔT–Δw. Determining these operating lines will prove useful for predicting achievable temperature lift and also for effective design and control of thermochemical heat storage systems.

1. Introduction

Energy technologies and management strategies have been gaining more attention in the last decade as energy is vital for a safer and sustainable future. Dependency on secure energy is much higher than in the past due to growth in the industrial sector, increasing population as well as comfort demands. According to Berners-Lee & Clarke, 2013, if global warming is not to exceed 2 °C then only 20% of the worlds established fossil fuel reserves can be burned by 2050 then this energy dependency represents a major threat to the future of all humans [1]. At the current rate of fossil consumption however, it is predicted that this 2 °C rise will be achieved by the year 2030 [1].

In the built environment, the domestic building sector currently represents the highest energy consumption as more people around the world aspire to better comfort living standards, driving the demand for air conditioning and thus electrical energy [2]. Urgent energy management solutions are required to increase the share of renewable sources for this comfort energy thus reducing the over reliance on fossil fuel driven systems [3]. Within this context, various international agreements such as the Kyoto Protocol seek to address this problem [4]. In addition, the EU commission aims to increase the share of renewables to 20% by 2020 in member countries [5,6]. The IEO 2007 report states that domestic buildings are responsible for 40% primary energy consumption, 70% of electricity consumption and 40% of atmospheric emissions in developed countries [7,8]. Additionally heating, cooling and air conditioning (HVAC) and domestic hot water (DWC) constitute more than half of the energy consumption in buildings [9].

Solar energy is counted as one of the primary renewable energy sources and it has promising potential for thermal applications (both space & water heating) in the domestic building sector. However, the mismatch between solar availability and building heat

* Corresponding author.
E-mail address: devrim.aydin@emu.edu.tr (D. Aydin).

http://dx.doi.org/10.1016/j.enconman.2017.03.066
0196-8904/

Nomenclature

c_p	specific heat at constant pressure [J/(kg K)]
c	temperature gradient [°C/min]
d	diameter [mm]
E_d	energy density [kJ/kg, kWh/m^3]
E_{cum}	cumulative thermal energy [Wh, kWh]
Ex	exergy [W, kW]
Ex_{cum}	cumulative thermal exergy [Wh, kWh]
H	Enthalpy [kJ/s]
m	mass [g, kg]
m_a	mass flow rate of air [kg/s]
Q	thermal power [W, kW]
RH	relative humidity [%]
P_v	partial vapour pressure [mbar]
S	entropy [kJ/kg]
t_{dwell}	time interval to reach ambient temperature [h]
t	time [s, h]
T	temperature [°C, K]
V	volume [m^3]
w	absolute humidity [g/kg]
ρ	density [kg/m^3]
f	mass uptake ratio [g_{wv}/g_{abs}]
Δ	difference [–]
η_I	1st law efficiency [–]
η_{II}	2nd law efficiency [–]

Subscripts

tr	transferred
dr	discharging
cr	charging
g	gain
cum	cumulative
abs	absorbent
a	air
wv	water vapour
w	wet
in	inlet
out	outlet
d	dry
avg	average
f	fan
h	heating
rxn	reaction
max	maximum
g	gain

demand constitutes a major obstacle in residential applications usually resulting in the need for auxiliary systems/energy sources such as heat pumps, electrical resistance heaters or gas heaters coupled with ever more sophisticated energy management systems. Although the combination of multiple systems (*i.e.* hybrid systems) enables higher energy utilisation, it also increases the complexity, capital and operational costs of these systems [10]. Heat storage systems can considerably improve the utility of solar thermal systems by acting as a 'thermal battery' by either thermophysically or thermo-chemically storing energy for later usage. Thermophysical systems are based on either sensible heat storage (SHS) or latent heat storage (LHS) whilst thermochemical systems are based on thermochemical heat storage (THS) [11]. All these systems can allow for conversion of solar energy for either short or long term storage, dependant on system type and material used. Although both SHS and LHS systems have been widely researched in the past [12] and are somewhat mature technologies, THS is a relatively new technology for converting and storing heat with much research ongoing on these systems. Caliskan et al. [13] performed energetic, exergetic and sustainability assessments for SHS, LHS and THS. Researchers found the effectivity of three different storage methods in the order of SHS > THS > LHS in terms of energetic and exergetic efficiency. Henninger et al. [14] reviewed new materials for adsorptive heat transformation and storage. Similarly, Aristov [15] investigated the current trends in dynamic optimization of adsorption heat storage. An overview on sorption materials and technologies for heat pumps and thermal energy storage applications was presented by Cabeza et al. [16]. In a recent study, Scapino et al. [17] investigated the latest advancements at material and prototype scale for long term sorption heat storage. A literature survey on adsorption thermal energy storage processes for heating applications was presented by Lefebvre and Tezel [18]. Schreiber et al. [19] experimentally investigated a Zeolite based adsorption heat storage. Researchers demonstrated that heat losses have a major impact on adsorption heat storage performance particularly in long term applications. Gaeini et al. [20] developed a model for predicting thermal dynamics of a Zeolite based adsorption bed. It is concluded that the model could be useful for design and optimization of THS systems. Michel et al. [21] developed a large scale sorption reactor consisting of multiple sorption beds and air flow channels. Strontium bromide/water ($SrBr_2/H_2O$) as a reactive pair is used in the system. A novel "revolving drum" reactor prototype was investigated by Zettl et al. [22]. Likewise, a composite sorption reactor consisting of $CaCl_2$ impregnated mesoporous ceramic (Wakkanai siliceous shale) honeycomb filter was developed by Liu et al. [23] for low-temperature (<100 °C) industrial waste heat recovery. Zhang et al. [24] experimentally investigated the performance of a 10 kWh absorption thermal energy storage prototype using LiBr–H2O. Energy storage densities for cooling, hot water and heating were found 42, 88 and 110 kWh/m^3. Lele et al. [25] investigated a closed THS system operating with $SrBr_2{\cdot}6H_2O$, as an addition to cogeneration systems for storing the process waste heat. Results demonstrated a theoretical reactor E_d of 115 kWh/m^3, storage capacity of 61 kWh and thermal efficiency of 78%. In another study, Jiang et al. [26] developed and experimented a sorption energy storage for industrial heat recovery applications. E_d was found in the range of 596–662 kJ/kg where energy and exergy efficiencies varied between 27.5–40.6% and 32.5–47%, respectively. Hamdan et al. [27] performed a parametric study on the potential of storing thermal energy with thermochemical heat pump using water - sodium chloride as sorbate - sorbent couple. Fernandes et al. [28] developed a dynamic model for investigating an adsorption heat storage unit (using silica gel/water pair) integrated with a solar water heating system. Study results revealed that adsorption heat storage provides up to 16% savings in annual backup energy when compared with a similar conventional storage system. In a recent study, a novel sorption heat pipe that utilizes composite sorbent-sorbate ($NaBr\text{-}NH_3$) as working media is developed by Yu et al. [29]. In another experimental study performed by Tatsidjodoung et al. [30], it was found that open sorption reactor loaded with 40 kg of zeolite can supply a constant power of 2.25 kW during more than two hours corresponding to 27.5 W kg^{-1} of material. Abedin and Rosen [31] investigated both closed and open THS