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Novel "open-sorption pipe" reactor for solar thermal energy storage

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ABSTRACT

In the last decade sorption heat storage systems are gaining attention due to their high energy storage density and long term heat storage potential. Sorption reactor development is vital for future progress of these systems however little has done on this topic. In this study, a novel sorption pipe reactor for solar thermal energy storage is developed and experimentally investigated to fulfill this gap. The modular heat storage system consists of sorption pipe units with an internal perforated diffuser pipe network and the sorption material filled in between. Vermiculite–calcium chloride composite material was employed as the sorbent in the reactor and its thermal performance was investigated under different inlet air humidity levels. It was found that, a fourfold increase of absolute humidity difference of air led to approximately 2.3 times boost in average power output from 313 W to 730 W and an 8.8 times boost of average exergy from 4.8 W to 42.3 W. According to the testing results, each of three sorption pipes can provide an average air temperature lift of 24.1 °C over 20 h corresponding to a system total energy storage capacity of 25.5 kW h and energy storage density of 290 kW h/m^3.

Within the study, vermiculite–calcium chloride performance was also compared with the widely investigated Zeolite 13X. Vermiculite–calcium chloride showed a good cyclic ability at regeneration temperature of 80 °C with a steadier thermal performance than Zeolite. Energetic and exergetic cyclic efficiencies varied in the range of 0.69 → 0.61 and 0.21 → 0.14 in the cycles performed with vermiculite–calcium chloride whilst energetic and exergetic cyclic efficiencies of Zeolite testing were between 0.72 → 0.48 and 0.25 → 0.06.

1. Introduction

Thermal storage plays a pivotal role in synchronizing energy demand and supply, both on a short and long term (seasonal) basis. Transformation of our existing building stock toward low energy buildings, nearly zero energy and Plus-energy buildings requires effective integration and full use of the potential yield of renewable energy. Thermal storage is a key priority to make such a step, particularly considering the energy renovation of the existing stock, where compact building level solutions are required [1].

In the building sector, a recast of the European Performance of Buildings Directive (EPBD2) is planned to enter into force by 2018, forcing all new buildings to become nearly net zero energy buildings (nZEB) [2]. The nZEB concept requires a high level of energy efficiency, in combination with on-site renewable energy use/production [3].

The building sector is one of the largest energy end-use sectors, accounting for a larger proportion of the total energy consumption than both the industry and transportation in many developed countries [4]. Building sector represents approximately 50% of the global final energy use [5] where residential buildings constitute roughly 30% of the total use [6]. Moreover, space and water heating together constitute over half of building final energy consumption [7]. Thermal energy storage (TES) systems could help in reducing global building energy consumption and also contribute to a more efficient and environmentally benign energy use [8]. These systems are employed when intermittent energy sources (*e.g.* solar energy) are utilized, or when there is a mismatch between thermal energy supply and energy demand [9]. Besides, they could be used for recovering waste heat from exhaust gasses of industrial processes or internal combustion engines for several purposes such as space heating or air conditioning [10]. TES can be accomplished using sensible heat storage (SHS), latent heat storage (LHS), physical sorption heat storage or chemical heat storage [11]. Although SHS and LHS systems have been heavily researched and are widely used domestically and industrially, thermochemical heat storage (THS) systems are currently undergoing a surge in research and development [12]. A major advantage of THS system is that it enables seasonal solar energy storage

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Nomenclature

c_p	specific heat at constant pressure, J/(kg K)
d	diameter, mm
E_d	energy density, kJ/kg, kW h/m^3
E_{cum}	cumulative thermal energy, Wh, kW h
Ex	exergy, W, kW
Ex_{cum}	cumulative thermal exergy, Wh, kW h
H	enthalpy, kJ/s
m	mass, g, kg
m_a	mass flow rate of air, kg/s
Q	thermal power, W, kW
p_w	water vapor partial pressure, mbar
$p_{w,s}$	water vapor saturation pressure, mbar
RH	relative humidity, %
S	entropy, kJ/kg
t	time, s, h
T	temperature, °C, K
T_{reg}	regeneration temperature, °C, K
V	volume, m^3
w	absolute humidity, g/kg
z	sorption/desorption rate, g/min
f	mass uptake ratio, g_{wv}/g_{abs}

Greek letters

Ø	diameter, µm
ρ	density, kg/m^3
Δ	difference
η_I	1st law efficiency
η_{II}	2nd law efficiency

Subscripts or superscripts

tr	transferred
dr	discharging
cr	charging
g	gain
cum	cumulative
ads	adsorbent
a	air, ambient
wv	water vapor
w	wet
i	inlet
o	outlet
d	dry
avg	average
f	fan
h	heating
p	peak
l	lowest
rxn	reaction
max	maximum
g	gain
s	sorption
des	desorption
v	volumetric

Abbreviations

CSPM	composite salt in porous matrix
IWT	insipent wetness technique
LHS	latent heat storage
nZEB	net zero energy building
SCH	solid crystalline hydrates
SHS	sensible heat storage
SIM	salt in matrix
SP	sorption pipe
TES	thermal energy storage
TGA	thermogravimetric analysis
THS	thermochemical heat storage
WSS	Wakkanai siliceous shale

which is difficult to accomplish with SHS or LHS systems due to the heat losses [13]. Recent studies suggest that THS has significant advantages when compared with the other heat storage methods including higher storage density, lower volume requirements and low heat loss (approaching zero) [14]. THS materials have approximately 8–10 times higher storage density over SHS, and two times higher over LHS materials for the same volume of heat storage material [15]. Essentially, THS materials can store heat for long term periods and without losses, as long as they are hermetically sealed to prevent the adventitious ingress of water to the sorbent [16]. In these systems, heat will be generated only when water vapor is purposely admitted. This particular aspect allows wider and more flexible usage of THS. The advantages and disadvantages of various SHS, LHS and THS are comparatively illustrated in Table 1.

Despite the superior properties of THS system, novel reactor design, process design and sorption material development are key issues on future advancement of this method for solar thermal energy storage [17]. Efficient THS systems should include;

- Novel sorption reactors with enhanced heat/mass transfer and low pressure drop both in the charging and discharging processes.
- Environmentally friendly sorption materials having high energy density, good cyclic ability, high thermal conductivity and low regeneration temperature (T_{reg}) (preferably < 80°).
- Compact integration of solar collectors and the sorption reactor for enhancing utility of solar energy while minimizing space requirement and heat losses.

1.1. Background and state of the art

Several studies on development and characterization of sorption materials have been performed and presented in the literature. Henninger et al. [20] evaluate the current developments on materials ranging from zeolites across aluminophosphates ($AlPO_4$) and silicoaluminophosphates (SAPO-34) to the novel class of metal organic framework materials for the use in adsorption processes for heat storage and transformation. In another study [21], authors investigated the water adsorption characteristics and performance of these materials for the use in thermally driven adsorptive heat pumping and cooling applications with water as refrigerant. Hongois et al. [22] developed and characterize a novel magnesium sulfate ($MgSO_4$)–Zeolite composite sorption material for long term seasonal solar energy storage. Through characterization of 10 mg samples, authors found that almost 80% of the total energy density can be stored at 150 °C although the material is not fully dehydrated. In a similar study, Janchen et al. [23] investigated the water adsorption characteristics of Zeolites and modified mesoporous materials for seasonal solar thermal energy storage. Janchen et al. [24] also characterized the sorption properties of water in potential thermochemical storage materials such as low silica X zeolites,