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Numerical and experimental analysis of a novel heat pump driven sorption storage heater

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HIGHLIGHTS

- A novel heat pump driven sorption storage heater system was investigated.
- System enables utilizing PV panels or off peak electricity tariff to store heat.
- Five different sorbents were investigated in the developed system.
- System provides an energy density of 170 kW h/m^3 with the use of V-$CaCl_2$ as sorbent.
- Overall system heating COP was found 2.4 for long term operation (~1200 mins).

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ABSTRACT

This study investigates a hybrid "solid sorption heat storage/air sourced heat pump" system for energy efficient heating of buildings. The proposed system could convert excess energy generated using photovoltaic panels/off-peak electricity to heat and charge the sorption material to store that heat for later use. The novel heat recovery process employed in the system enables high heat storage efficiency through condensation of desorbed moisture in a heat storage charging cycle.

In this study five different sorbents were tested in a novel prototype system. Four sorbents were salt based composites (SIM's) and one was Zeolite 13X. According to the results, the coefficient of performance (COP) of the system varied in the range of 1–2 for short-term operation (where $t < 240$ min) depending on the sorption material properties and system operating conditions. The overall performance of the prototype sorption storage heater was determined through long cycle testing. The system provided ≈ 6.8 kWh thermal energy output with a sorbent volume, $Vs = 0.04\,m^3$ (over a 1200 min discharge time), corresponding to an energy density, $E_d = 170\,kWh/m^3$. The required charging duration, to desorb the moisture was experimentally determined as 360 min. Based on the total energy input–output for both charging and discharging processes, the COP_S was calculated at 2.39. According to the analysis, the experimental results were found in good agreement with the numerical simulation.

1. Introduction

In the building sector, a recast of the European Performance of Buildings Directive (EPBD2) is planned to enter into being by 2018, forcing all new buildings to become nearly net zero energy buildings (nZEB) [1]. The nZEB concept requires a high level of energy efficiency, in combination with on-site renewable energy use/production [2].

In this context, a vast amount of research has been performed on the development of new, efficient thermal energy storage (TES) technologies and materials to improve the utilization of solar air and water heating systems [3–5]. Technologies incorporating electrically sourced heating systems (*i.e.* heat pumps) with TES are also vital for improving energy efficiency in buildings. Although electricity is regarded as an expensive and inefficient way of producing heat, there is an emerging transition to solar and wind sourced 'on site' domestic electricity generation [6]. Due to the increasing trend in photovoltaic (PV) application, the storage of electricity is now being questioned. Current electrical energy storage technologies are expensive with research still ongoing. At today's battery prices, the point where the financial returns justify investment has not yet been reached [7]. However, without

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Nomenclature

c_p	specific heat at constant pressure, kJ/(kg K)
COP_s	system coefficient of performance, –
E	energy, kJ, kWh
E_d	energy density, kJ/kg, kWh/m^3
h	specific enthalpy, kJ/kg
n	mole number, moles
m	mass, g, kg
m_a	mass flow rate of air, kg/s
M	molar mass, kg/kmole
Q	thermal power, W, kW
p_w	water vapour partial pressure, mbar
$p_{w,s}$	water vapour saturation pressure, mbar
RH	relative humidity, %
t	time, s, min
T	temperature, °C, K
v	stoichiometric coefficient, –
V_s	storage volume, m^3
w	absolute humidity, g/kg
W	work, kW
x	reaction advancement, –
z	sorption/desorption rate, gr/s
f	mass uptake ratio, g_{wv}/g_{abs}
Δ	difference, –
η	efficiency, –

Subscripts or superscripts

d	discharging
c	charging
g	gain
ads	adsorption
des	desorption
a	air, ambient
wv	water vapour
w	water
i	inlet
o	outlet
avg	average
f	fan
h	heating
hyg-cyc	hygro-cyclic
p	process
max	maximum
s	secondary
rec	recovered
reg	regeneration
evap	evaporator
cond	condenser
comp	compressor
hum	humidifier

Abbreviations

COP	coefficient of performance
CSPM	composite salt in porous matrix
HVAC	heating, ventilating and air conditioning
nZEB	net zero energy building
PV	photovoltaic
LHS	latent heat storage
SHS	sensible heat storage
SIM	salt in matrix
TES	thermal energy storage
THS	thermochemical heat storage

storage, utilization of PV is low as electricity can only be generated during sunlight hours whereas the majority of building energy demand is during darkness. The highest percentage (> 40%) of that demand is for space and water heating. In terms of energy management strategies, advanced thermal batteries could be an option to balance the mismatch between energy supply and demand in buildings. Excess electrical energy generated via PV during daytime could be converted and thus stored as heat for later usage.

In addition to storage of PV sourced electrical energy, another promising option to benefit from storage heater technologies is charging the TES sorbent using off-peak electricity. This not only helps to provide a supply-demand balance for the electrical grid, but also represents a cost-effective heating method to be used in domestic heating. For instance, in the UK, Economy 7 and Economy 10 are variable rate electricity tariffs where householders pay a different price for electricity used at different times of a day. With Economy 7, the electricity used at night costs about a third of the price of the electricity used during the day which is a considerable difference [8,9].

Current electrically driven storage heater technologies use sensible heat storage (SHS) materials (i.e. bricks, water). However, low heat storage density and high heat losses remain the main barriers limiting the wider usage of these heat storage technologies. Thermochemical Heat Storage (THS) materials have several promising aspects such as low heat loss, high energy density and low space requirement [10]. In this respect, THS materials represent an important opportunity for energy storage to improve energy efficiency in buildings.

This paper investigates the development and demonstration of an electric-to-heat conversion and storage technology, which could help reduction of fossil fuel usage and achieving an energy supply-demand balance in buildings. The presented work covers the design, manufacture, and experimental/numerical investigation of a novel hybrid space heating/heat storage technology. Sensitivity analysis and optimization of the system was conducted alongside the real life operation of the system to help bridge the gap between research, development and implementation. Within this study a novel heat pump driven sorption storage heater (Heat-Store) that uses thermochemical materials as heat storage medium and that could be powered using both PV sourced electricity and off-peak electricity is proposed. The study is novel in that it combines the development of the new composite sorbents and the integration of sorption, heat pump and heat recovery technologies.

The high heat storage density and low heat losses of the proposed system could provide significant benefits such as;

- 5–6 times larger amount of heat storage for the same volume when compared with SHS and LHS respectively [10],
- A higher utilization of off-peak tariff/solar energy (*i.e.* solar thermal and PV),
- Flexibility in use of the storage heater (*i.e.* long-term heat storage),
- 2–3 times higher overall heat storage efficiency (charging + discharging).

1.1. Background and state of the art

Several studies on the development and characterization of new sorption materials have been performed and presented in the literature. Hongois et al. [11] developed and characterized a novel magnesium sulphate ($MgSO_4$) – Zeolite composite sorption material for long-term seasonal solar energy storage. Jänchen et al. [12] investigated the water adsorption characteristics of Zeolites and modified mesoporous