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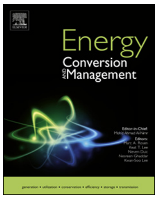

Definition and performance simulations of a novel solar-driven hybrid absorption-thermochemical refrigeration system

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ABSTRACT

This paper proposes a novel hybrid refrigeration system with energy storage, driven by low-grade solar heat and consisting of a single-stage absorption cycle coupled with a thermochemical process by sharing the same condenser, evaporator and refrigerant fluid. A first screening of ammonia-based working pairs for evaporation temperatures of −10 °C, condensation temperatures of 30 °C and heat source temperatures of 80 °C reveals $LiNO_3$ as suitable sorbent salt for the absorption subsystem, and $BaCl_2$, $PbBr_2$, $SrCl_2$, LiCl, NH_4Br and $SnCl_2$ as candidate reactive salts in the thermochemical subsystem. The subsequent parametric study indicates that the absorption subsystem with $NH_3/LiNO_3$ reaches close-to-maximum COP at the indicated conditions, and the thermochemical subsystem delivers its highest COP with the $NH_3/BaCl_2$ pair. Then, the power-storage and performance-storage relationships of the thermochemical subsystem are analyzed for the $NH_3/BaCl_2$ pair with respect to variations in operating conditions and several implementation parameters of the reactive composite. Finally, the performance of the hybrid system with the ($NH_3/LiNO_3$ + $NH_3/BaCl_2$) pair combination is compared to its subsystems against a variable demand profile calculated from climatic data of July in Barcelona, Spain. A novel indicator is defined to assess demand coverage: the Coefficient of Satisfaction of Demand (CSD). Depending on solar collector field area and amount of refrigerant storable by the thermochemical subsystem, the hybrid system reaches up to 24% higher CSD than the reference system (a solar single-stage absorption refrigerator with no storage), and at least 14% higher COP than the thermochemical process.

1. Introduction

Global warming of planet Earth requires diligent solutions towards a more sustainable model. This has become a priority also in the field of refrigeration, where some of the efforts are put into developing systems that are less dependent on fossil fuels, resulting in no or minor impact on the environment. Renewable energy sources, especially solar energy, are an interesting option full of perspectives.

Solar absorption refrigeration has been widely investigated in the recent decades [1]. While proven viable, mismatch between the solar resource and the demand of cold is still an important technological roadblock, traditionally addressed through energy storage [2]. Energy storage within the absorption system itself has been investigated for the water/lithium bromide working pair, both numerically [3–5] and experimentally [6,7]. The idea of using crystallization in this system for higher density energy storage has drawn attention in the recent years and is also under study [8]. On the other hand, systems based on thermochemical transformation [9] of energy have proved promising for the purposes of energy storage [2] and upgrade [10]. An interesting variation of this technology is to connect two different reactive salts (in two different reactors) through the same reactant gas. These advanced systems are usually called ‘resorption systems’ and have also been investigated for (seasonal) energy storage [11] and energy upgrade [12].

As the basic refrigeration systems reach their peaks in design, the idea of developing advanced systems by combining some of their components gains interest. The concept is not new and several proposals exist in the literature, both for absorption refrigeration and thermochemical processes separately. More of these combinations have been proposed for absorption refrigeration, given its maturity. One example is the absorption-compression refrigeration system, proposed under the idea of ‘integration’ by Riffat and Shankland [13]. Ayala et al. [14] concluded in a later study that with the $NH_3/LiNO_3$ pair, this hybrid allowed up to 10% increase in overall efficiency, and suggested to retrofit existing ammonia vapor compression plants. The study was

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Nomenclature

A	area, m^2
A	absorber
ARS	Absorption Refrigeration Subsystem
C	condenser
Cp	specific heat capacity, J/(mol K)
CDD	Cooling Degree Days
COP	Coefficient Of Performance
CSD	Coefficient of Satisfaction of the Demand
De	energy storage density, kW h/m^3
e	thickness, m
E	evaporator
EHX	Heat Exchanger Effectiveness
ENG	Expanded Natural Graphite
EV	Expansion Valve
f	solution circulation ratio, kg s^{-1}/(kg s^{-1})
G	gas
G	generator
h	specific enthalpy, kJ/kg
h_c	convective heat transfer coefficient, W/(m^2 K)
HATRS	Hybrid Absorption-Thermochemical Refrigeration System
L	liquid
M	molar mass, kg/kmol
MX	metal halide
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
$\dot{n}$	molar flow rate, mole/s
P	pressure, bar
Q	heat, kJ
$\dot{Q}$	heat rate, kW
$\dot{q}$	specific heat rate (referred to surface), kW/m^2
R	thermochemical reactor
$\mathfrak{R}$	universal gas constant, J/(mol K)
RST	Refrigerant Storage Tank
S	solid
s	specific entropy, kJ/(kg K)
SHATRS	Solar Hybrid Absorption-Thermochemical Refrigeration System
SHX	Solution Heat Exchanger
SP	Solution Pump
T	temperature, °C
t	time, h
TCS	Thermochemical Subsystem
U	global heat transfer coefficient, W/(m^2 K)
V	valve
V	apparent volume, m^3
v	specific volume, m^3/kg
$\dot{W}$	power, kW
w	mass fraction, kg/kg-total
X	reaction advancement degree ($X = 0$ for completely discharged salt and $X = 1$ for completely charged salt)

Greek symbols

α	correction factor
Δ	increment
ρ	density, kg/m^3
ν	reaction's stoichiometric coefficient
ε	porosity
λ	thermal conductivity, W/(m K)
ρ	apparent density, kg/m^3
η	efficiency
ξ	moles of refrigerant in the fully discharged salt
ξ	reactor's occupied volume

Subscripts and superscripts

0	reference point
1	composite with reactive salt at $X = 1$
A	absorber
Amb	ambient
ARS	absorption refrigeration subsystem
AUX	auxiliary system
avg	average
C	condenser
c	reactive composite
cold	cold fluid in the heat exchanger
d	demand of cold
day	daytime
E	evaporator
ENG	Expanded Natural Graphite
eq	equilibrium
ex	heat exchanger
G	generator
g	refrigerant gas
gdif	gas diffuser
gsat	saturated vapor
H	high temperature or pressure level
hot	hot fluid in the heat exchanger
hs	driving heat source
HYB	hybrid system
in	inlet
l	low pressure or temperature level
m	medium temperature level
min	minimum
max	maximum
net	net, useful
night	night-time
out	outlet
R	reaction
r	reactor
rad	solar radiation
rd	decomposition reaction
ref	refrigerant
rs	synthesis reaction
S	surface
s	reactive salt
s0	fully discharged reactive salt
s1	fully charged reactive salt
sa	anhydrous reactive salt
SP	solution pump
ss	strong solution (referred to ammonia)
st	stainless steel
TCS	thermochemical subsystem
v	vaporization
w	wall
ws	weak solution (referred to ammonia)

followed by a 7 kWt prototype which reached its maximum COP when using 90% compression and 10% absorption [15]. Several other studies exist for the absorption/compression system, for instance towards system optimization with the ammonia/water pair [16], optimization accounting for internal and external irreversibilities [17], waste heat utilization [18] including cascade use [19], or low evaporation