Applied Energy 219 (2018) 240–255

Contents lists available at ScienceDirect

Applied Energy

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

Mechanical compressor-driven thermochemical storage for cooling applications in tropical insular regions. Concept and efficiency analysis

Franco Ferrucci[a,*], Driss Stitou[b], Pascal Ortega[a], Franck Lucas[a]

[a] GEPASUD Laboratory, University of French Polynesia, BP 6570, 98702 Tahiti, French Polynesia
[b] CNRS-PROMES Laboratory, Tecnosud, Rambla de la thermodynamique, 66100 Perpignan, France

HIGHLIGHTS

- Combination of a thermochemical reactor and a mechanical vapor compression unit.
- The system can provide cooling and energy storage in the context of smart microgrids.
- Thermochemical method presents no self-discharge and long charge/discharge life cycle.
- The compressor aids the desorption and compensates for a low heat source temperature.
- With a waste heat source it attains a cooling capacity of 4 $kWh_{cold}/day/m^2$ of PV panel.

ARTICLE INFO

Keywords:
Solar cooling
Solid/gas sorption
Thermochemical
Chemical adsorption
Tropical and insular regions
Microgrid

ABSTRACT

The energy situation in tropical insular regions, as is found in French Polynesia, presents a number of challenges, including heavy dependence on imported fuel, high transport costs from the mainland and weak electricity grids. By contrast, these regions possess a variety of renewable energy resources, which are favorable for the exploitation of smart micro grids and energy storage technologies. With regards to electrical energy demand, the high temperatures commonly seen in these regions throughout the entire year implies that a large proportion of electricity consumption (~40%) is used for space cooling, even during evening hours. Framed within this context, this paper presents an air conditioning system driven by photovoltaic electricity that combines a mechanical vapor refrigeration system and a thermochemical storage unit. Thermochemical processes enable the storage of energy in the form of chemical potential with virtually no losses, which can be used to produce cold during the evening hours without running a compressor. These processes are implemented using thermochemical reactors, in which a reversible chemical reaction between a solid compound and a gas takes place. The solid/gas pair used in this study is barium chloride salt ($BaCl_2$) reacting with ammonia (NH_3), which is also the coolant fluid in the refrigeration circuit.

In the proposed system, the photovoltaic-driven electric compressor is used during the day either to run the refrigeration circuit when a cooling demand occurs or to decompose the ammonia-charged salt and to remove the gas from the thermochemical reactor when there is no cooling requirement. During the evening, when there is no electricity from solar sources, the system changes its configuration and the reactor reabsorbs the ammonia gas from the evaporator to produce cold. The efficiency of this hybrid system is evaluated in this work and compared with alternative processes which utilize either electrochemical (lead-acid, lithium-ion batteries) or thermal storage (ice, chilled water) for cold production.

1. Introduction

The energy situation in tropical insular regions is complex and presents both challenges and opportunities. In such environments, there is a strong dependence on foreign energy, mainly fossil fuels. Furthermore, these regions often present weak or poorly interconnected electricity grids, which make them prone to frequency and voltage perturbation [1]. These regions typically exhibit climate patterns of year-round high temperatures and humidity. Additional challenges in certain tropical insular regions include geographic remoteness, high transport costs from the mainland, low population density and the fact that large-scale energy projects are not typically considered viable.

* Corresponding author.
E-mail address: franco.ferrucci@doctorant.upf.pf (F. Ferrucci).

https://doi.org/10.1016/j.apenergy.2018.03.049
Received 31 December 2017; Received in revised form 7 March 2018; Accepted 18 March 2018

Nomenclature

PV	photovoltaic
S/G	solid/gas
TR	thermochemical reactor
MVC	mechanical vapor compression
COP	coefficient of performance
DOD	depth of discharge
CFCs	chlorofluorocarbons
HCFCs	hydrofluorocarbons
HP	high pressure
LP	low pressure
$BaCl_2$	barium chloride salt
ENG	expanded natural graphite
T	temperature
P	pressure
Ex	exergy
Q	heat (J)
I	solar irradiation ($kWh/m^2/day$)
W	compressor work (J)
M	molar mass (kg/mol)
N	number of moles
n	number of moles per m^3
V_{swept}	compressor's swept volume rate (m^3/h)
X	reaction global advancement (0…1)
$q_{V,cold}$	cooling capacity per volume of storage (Wh_{cold}/L)
$q_{S,cold}$	cooling capacity per surface of solar collector ($Wh_{cold}/m^2/day$)
S_0	anhydrous salt
S_1	ammonia-charged salt
P_{ref}	reference pressure, 1 Pa
R	universal gas constant, 8.3144 J/K/mol
$\Delta H_V{}^0$	NH_3, standard enthalpy of vaporization, 23,366 J/mol
$\Delta S_V{}^0$	NH_3, standard entropy of vaporization, 193.3 J/K/mol
$\Delta H_R{}^0$	$BaCl_2$–NH_3, standard enthalpy of transformation, 38,250 J/mol
$\Delta S_R{}^0$	$BaCl_2$–NH_3, standard entropy of transformation, 232.38 J/K/mol
c_{p0}	heat capacity of the anhydrous salt, 75.1 J/K/mol
c_{p1}	heat capacity of the ammonia-charged salt, 390 J/K/mol

Greek letters

Δ	difference
υ	stoichiometric coefficient
η	efficiency
τ	mixture mass ratio
ρ	effective density
θ	Carnot coefficient

Subscripts

0	reference
1	operating point 1
2–3	operating mode 2 combined with mode 3
amb	ambient
cold	cold (heat source)
cond	condenser
comp	composite
des	desorption
disch	discharge
eq	equilibrium
evap	evaporator
ex	exergy
g	gas (superheated)
gas	gas
init	initial
is	isentropic
liq-vap	liquid-vapor
max	maximum
r	reactor
ref	reference
room	room (heat source)
s	source (during desorption)
sat	saturated
synt	synthesis
vol	volumetric

Superscripts

0	standard (25 °C, 1 atm)
is	isentropic

French Polynesia, the region of relevance to this work, is faced with just such challenges.

French Polynesia is comprised of more than one hundred islands and atolls that are distributed in a region approximately the size of Western Europe [2]. Nearly half of these islands are uninhabited and many others have a very low population (see Table 6 in Appendix A). The ratio between primary energy imports and total energy consumption in French Polynesia is above 85% [3], which puts the region in a vulnerable position due to the unpredictability of oil prices. What is more, the price of electricity for a small household (3000 kWh/year) is about 0.30 USD/kWh [4], between two and three times the price found in North America [5] and Europe [6]. A study conducted in 2011 on the use and trends of electro-domestic equipment, including air conditioners, in Tahiti and Moorea, French Polynesia's most populated islands, showed that there was a steady rise in energy usage in the home, notably of air conditioning units, representing 36% of usage [7].

On the positive side, French Polynesia is rich in renewable resources, particularly solar energy. For instance, the average global solar horizontal irradiation (a key parameter that assesses solar energy potential) for fifteen of the most inhabited islands of French Polynesia and accounting for 94% of its total population (see Table 6 in Appendix A), is 5.8 $kWh/m^2/day$. Such a high value makes the exploitation of solar energy in French Polynesia an interesting proposition. This is especially the case for photovoltaic technology due to its maturity, declining costs and adaptability for use in both large and small-scale energy projects.

Notwithstanding the foregoing, electricity produced by solar energy presents some difficulties. For instance, due to its stochastic nature, solar energy is non-dispatchable–that is, its production cannot be regulated in order to meet electricity needs. Moreover, photovoltaic technology, the most commonly employed electricity production method using solar energy, does not possess an inherent energy reserve (normally called *inertia* or *spinning reserve*), meaning that sudden variations of solar irradiation are not attenuated at the output and strongly perturb the electricity grid. These characteristics make the supply of electricity using solar energy challenging, especially where the proportion of its use over total electricity production is high [1]. To overcome these difficulties, the combination of smart electricity grids with energy storage systems has proven to be an effective solution [8].

The term smart grid refers to an electricity network that performs intelligent management of resources, including production and storage, in order to deliver a reliable and sustainable electricity supply. Currently, there is a great deal of research in the field of control and optimization strategies applied to smart grids. For instance, Iqbal et al. [9] present a comprehensive review of publications concerning