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Mechanical compressor-driven thermochemical storage for cooling applications in tropical insular regions

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Abstract

The energy situation in tropical insular regions, such as in the French Polynesian islands, presents a number of challenges, including high dependence on imported fuel, high transport costs from the mainland and weak electricity grids. With regards to electrical energy demand, the high temperatures in these regions throughout the entire year implies that a large proportion of electricity consumption (~40%) is used to cool buildings, even during evening hours. This paper presents an air conditioning system driven by photovoltaic (PV) electricity that combines a mechanical vapor refrigeration system and a thermochemical storage unit. Thermochemical processes are able to store energy in the form of chemical potential with virtually no losses, and this energy can be used to produce cooling during the evening hours without the need to run a compressor. The efficiency of such a hybrid system is evaluated and compared with alternative processes that utilize either electrochemical (Pb, Li-ion batteries) or thermal storage (ice, chilled water) for cooling production.

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Keywords: Microgrid, solar air-conditioning, solid/gas sorption, thermochemical storage, tropical and insular regions.

1. Introduction

The energy situation in tropical insular regions is complex. Although abundant with renewable resources, there is a strong dependence on foreign energy sources, mainly hydrocarburant. A viable alternative to imported energy is the exploitation of local renewable energy sources. The challenge, however, is that these sources, including solar and

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wind, are neither constant nor controllable. Therefore, energy storage systems and intelligent electric grid management (smart grids) are indispensable elements to harmonize energy production with consumption.

This concept is applicable in a region such as French Polynesia (FP), where there is a high level of dependence on foreign energy sources. An important parameter of this dependence is the ratio between primary energy imports and total energy consumption. FP has an energy dependence value above 80% [1], which puts the region in a vulnerable position due to the unpredictability of oil prices. Another element that distinguishes FP is its geographical situation. Comprised of more than one hundred islands and atolls, FP is distributed in a region approximately the size of Western Europe. Nearly half of these islands are uninhabited and many others have a very low population. Given this situation, small and medium storage systems and distributed generation offer interesting solutions to the region's energy requirements. FP also enjoys a climate of high temperatures and high humidity year-round. Air conditioning systems represent an important proportion of electricity consumption.

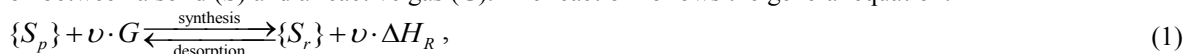
Given the above context, the present work investigates an energy storage system applicable to cooling production. The initial findings demonstrate such a system to be an effective method to meet cooling and energy storage needs in this type of region.

Nomenclature

| | | | |
|-----|------------------------------|---------------------|-----------------------------------------------------------------------------------------------------|
| FP | French Polynesia | R | Univ. gas constant, 8.3144 J/K/mol |
| PV | photovoltaic | P_{ref} | Reference pressure, 1 Pa |
| S/G | solid/gas | ΔH_V^0 | NH_3 , std. enthalpy of vaporization, 23,366 J/mol |
| TR | thermochemical reactor | ΔS_V^0 | NH_3 , std. entropy of vaporization, 193.3 J/K/mol |
| MVC | mechanical vapor compression | ΔH_R^0 | $\text{BaCl}_2\text{-NH}_3$, std. enthalpy of transform., 38,250 J/mol |
| COP | coefficient of performance | ΔS_R^0 | $\text{BaCl}_2\text{-NH}_3$, std. entropy of transform., 232.38 J/K/mol |
| DOD | depth of discharge | $q_{V,\text{cold}}$ | cooling capacity per volume of storage ($\text{Wh}_{\text{cold}}/\text{L}$) |
| | | $q_{S,\text{cold}}$ | cooling capacity per surface of solar collector ($\text{Wh}_{\text{cold}}/\text{m}^2/\text{day}$) |

2. Principle of solid–gas thermochemical sorption process

The principle of solid/gas (S/G) thermochemical reaction processes is based on the thermal effect of a reversible reaction between a solid (S) and a reactive gas (G). The reaction follows the general equation:



where S_r and S_p corresponds to the salt rich and poor in gas respectively, ν is the stoichiometric coefficient that balances the mass of the equation and ΔH_R is the enthalpy of the reaction [2]. The strong chemical bonding involved in these reactions translates into high values of ΔH_R . From left to right, the reaction (1) is called *synthesis*; the solid S_p absorbs and reacts with the gas in an exothermic manner, forming a new salt S_r . The generated heat of reaction must be released in order for the reaction to continue. From right to left *desorption* reaction occurs; the solid S_r , charged with gas, absorbs an amount of heat (i.e. endothermic process), releases the gas and transforms into S_p .

By coupling such a solid-gas reaction with a liquid/gas phase change of the same working gas, a cooling production process can be designed:



where ΔH_V correspond to the enthalpy of vaporization. The S/G pair used in this study is the barium chloride salt, BaCl_2 , that reacts with eight moles of ammonia (NH_3) to form $\text{BaCl}_2 \cdot 8\text{NH}_3$. This salt has been successfully used for solar ice-making and solar air conditioning processes using simple flat plate solar collectors [2]. This S/G pair is suitable for such application as it enables to operate (i.e. react) with relatively low temperature ranging from 10°C to 60°C and moderate pressure.

The two processes, i.e. the chemical reaction (1) and the phase-change (2), are mono-variant and their thermodynamic equilibrium conditions follow the Clausius–Clapeyron relation. The equilibrium conditions for the two processes are determined by only one variable, either the pressure or the temperature:

$$\ln \left(\frac{P_{eq,i}}{P_{ref}} \right) = - \frac{\Delta H_i^0}{R \cdot T_{eq,i}} + \frac{\Delta S_i^0}{R}, \quad i = \begin{cases} R \text{ (reaction)} \\ V \text{ (vapor-liquid)} \end{cases}, \quad (3)$$

where P_{eq} and T_{eq} correspond to the equilibrium pressure and temperature of each process, ΔH^0 and ΔS^0 are the standard enthalpies and entropies of the two processes and P_{ref} is a reference pressure [2]. The nomenclature section provides with the numerical values of all the mentioned parameters. Fig. 1 depicts the Clausius–Clapeyron diagram of the processes, which is a graphical representation of (3).

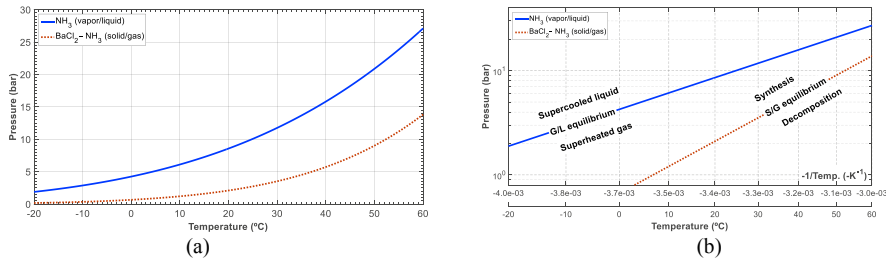


Fig. 1. Clausius–Clapeyron diagram of the BaCl₂–NH₃ TC sorption process (dashed) and the NH₃ phase-change process (solid); (a) pressure and temperature in linear scale; (b) pressure in log scale and abscissa linear in $-1/T$ (K^{-1}) (a second x axes shows the corresponding values in °C).

3. Implementation

To implement a basic S/G sorption thermochemical process, three main components are necessary: a reactor that contains the salt, a two-phase heat exchanger in which evaporation or condensation of the reactive fluid occurs, and a reservoir that contains the condensed gas. The reactor usually consists of one or various cylindrical containers with diameter in the order of 5 to 10cm, made of stainless steel that does not react neither with the gas nor the salt.

Fig. 2 shows a simplified diagram of the S/G sorption process. Fig. 2 (a) describes the desorption phase using a high temperature heat source, which gives an amount of heat Q_{desorp} at temperature T_{high} (endothermic process) and it dissociates the gas that was chemically bounded with the salt. The gas flows to the reservoir through the heat exchanger and is transformed into the liquid state. This condensation process occurs at ambient temperature T_{amb} , rejecting the heat Q_{cond} to the ambient. This is the conventional method used to desorb a S/G working pair. For the case of the pair BaCl₂–NH₃ used in solar cooling application, where the reactor is embedded in a solar thermal collector, the value of T_{high} is in the range of 60°C to 80°C.

Fig. 2 (b) illustrates a desorption phase driven by an electrical compressor with the reactor exposed at ambient temperature. The purpose of the compressor is to pump gas out of the reactor and force the dissociation of the gas from the salt. As the desorption process is always endothermic, the reactor will absorb an amount of heat Q_{desorp} at ambient temperature. On the discharge side, the compressor will release the gas at a higher temperature and pressure; finally, the heat exchanger will condense it at ambient temperature. This compressor–driven desorption method for energy storage and deferred cooling application has not been explored before in literature and it represents the core idea of this study.

Fig. 2 (c) shows the phase in which the reactor, emptied of gas, is isolated from the liquid/gas reservoir by closing the valve that connects them. The thermal energy absorbed by the reactor has been transformed into chemical potential energy and it cannot be lost by heat exchange with the ambient, as is the case of latent and sensible thermal energy

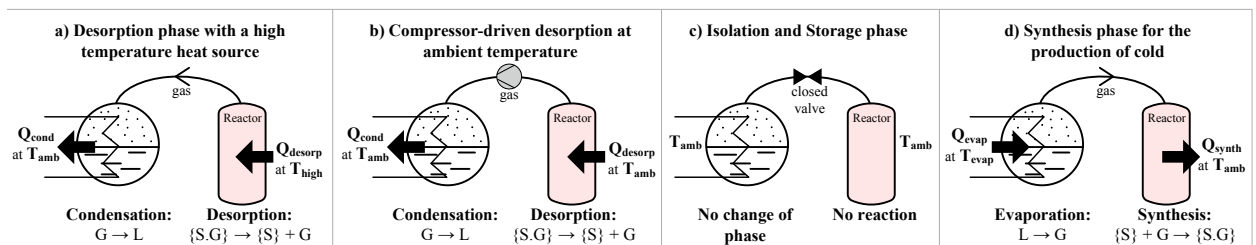


Fig. 2. Simplified diagram of the operating phases of a S/G sorption system.

storage methods. During this phase, both the reactor and the reservoir will stay at ambient temperature (but different pressures, given by (3)) and the energy can remain stored for an indefinite period.

Fig. 2 (d) shows the synthesis phase for the production of cold. Due to a pressure difference, the liquid fluid runs from the reservoir to the heat exchanger, that in this case acts as an evaporator, where it absorbs the heat Q_{evap} at a temperate T_{evap} lower than T_{amb} , thus producing a cooling effect. The liquid transformed into gas then flows to the reactor, where the exothermal synthesis reaction takes place and the reactor rejects the heat Q_{synth} to the ambient.

4. System overview

The architecture of the proposed hybrid system (Fig. 3) comprises the elements of a typical mechanical vapor compression refrigeration cycle (MVC) (i.e. evaporator, compressor, condenser, reservoir and throttling valve), a grid-connected PV installation (i.e. solar panels and inverter) and a thermochemical reactor (TR) for energy storage. Both the PV installation and the grid are used to meet electricity requirements of the building and, in particular, to run the compressor of the MVC cycle for cooling purposes. In addition, each time there is a surplus of energy from the PV panels and no cooling needs, the system switches its configuration mode and the extra power is used to run the compressor in order to drive the TR desorption, thus storing electricity in the form of chemical potential energy. The stored energy is later used to produce a cooling effect for the building, without the need of the compressor.

The system has 3 operating modes, summarized as follows: (a) *Mode 1, normal operation*: cooling is provided by the conventional MVC cycle; (b) *Mode 2, storage phase*: the compressor pumps the gas out of the TR, decomposing the charged salt. The heat of desorption is provided either by the environment at ambient temperature or by a low-grade waste heat source, resulting in reduced power consumption by the compressor; (c) *Mode 3, discharge phase*: the TR, connected to the evaporator, reabsorbs the NH_3 and produces a cooling effect without electricity.

Fig. 4 depicts the three operating modes. It includes a schema of the system configuration and a Clausius-Clapeyron diagram that shows the mono-variant equilibriums of the liquid/gas phase-change of NH_3 and the solid/gas reaction occurring in the TR.

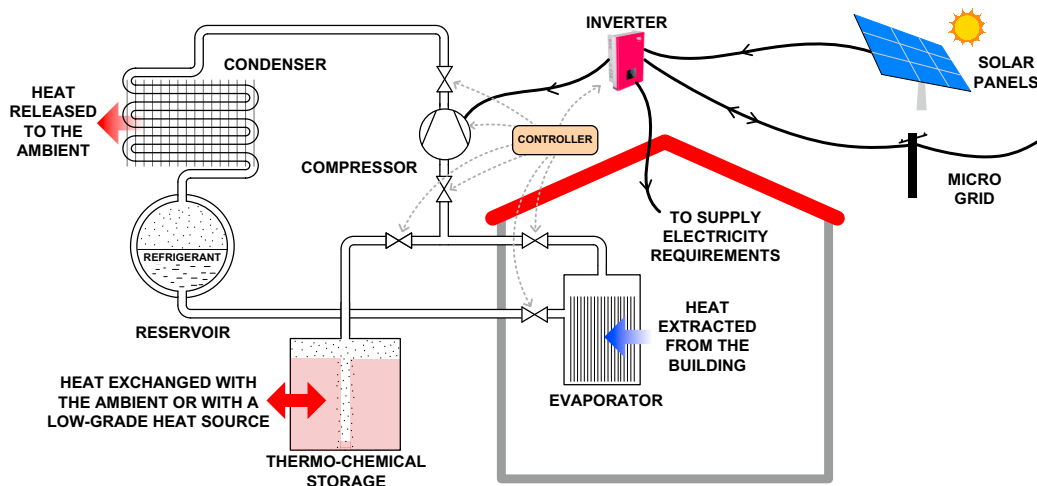


Fig. 3. System architecture combining a thermochemical storage unit and a typical MVC cycle powered by PV electricity.

5. System performance and comparison with other storage methods

The system presented in this study has two functions: refrigeration and energy storage. First, the main criterion used to analyze the refrigeration efficiency is the COP, which is defined here as the ratio between the cooling production in Mode 3 and the electrical energy consumption of the compressor in Mode 2. Note that for the conventional MVC cycle in Mode 1, cooling production and electrical consumption occur simultaneously. Second, energy storage systems are characterized by a set of parameters, including storage capacity, life span and the depth of discharge allowed. In this study, two criteria are analyzed: cooling capacity per volume of storage $q_{V,cold}$ and cooling

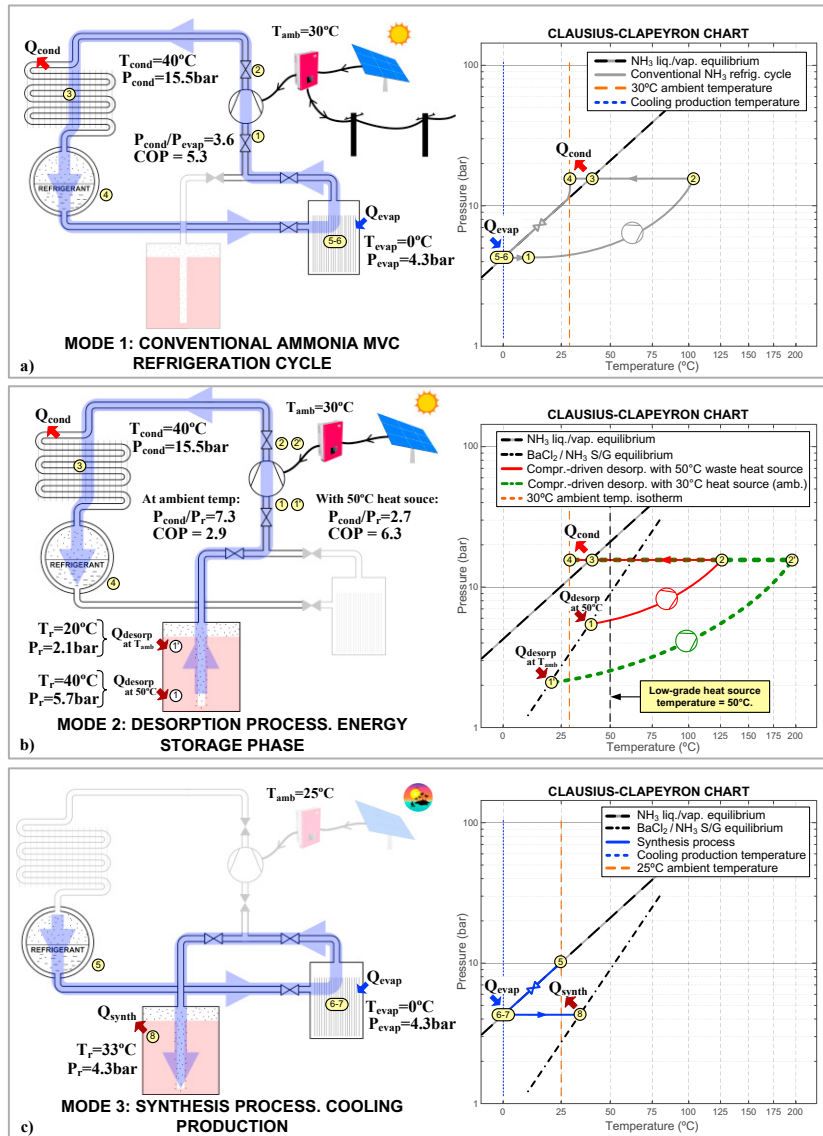


Fig. 4. Operating modes of the hybrid system; (a) normal operation; (b) storage phase; (c) discharge phase and cooling production.

capacity per surface of solar collector $q_{S,cold}$. This last criterion assesses how efficiently the system uses the surface exposed to sunlight (either PV or thermal collector).

The study also compares the following systems: Pb and Li-ion batteries running a MVC cooling unit, ice and chilled water storage, and thermochemical storage. For this last case, three configurations are assessed: compressor-driven only, compressor-driven assisted with low-grade waste heat and solar-heat-driven. This analysis takes into account the COP of the mechanical compression unit used to produce the cooling effect in each of the corresponding operating conditions (assuming an isentropic compression efficiency of 0.9). For the compressor-driven thermochemical storage method, the values of COP are computed taking into account the temperatures and pressures shown in the diagrams of Fig. 4, together with MATLAB Software and CoolProp library [4].

Table 1 and Fig. 5 show the results of the comparison. The value of $q_{S,cold}$ is computed by multiplying the daily solar radiation, the solar collector and storage efficiencies, and the COP. The comparison assumes a daily solar radiation of $6\text{kWh}/\text{m}^2/\text{day}$ (average value in French Polynesia), a solar efficiency of 14% for PV panels and 60% for thermal flat-plate solar collectors. Note that for the case of the batteries, the cooling storage capacity $q_{V,cold}$ equal their electrical volumetric capacity multiplied by the COP of the corresponding MVC cooling unit.

Table 1. Comparison of storage technologies for cooling production

| Storage Technology | DOD allowed (%) | Net Energy density (Wh/L) | Storage Efficiency | Storage cycle life | COP | $q_{V,cold}$ (Wh _{cold} /L) | $q_{S,cold}$ (Wh _{cold} /m ² /day) |
|---------------------------------------------------------------|-----------------|---------------------------|--------------------|--------------------|------------------|--------------------------------------|--------------------------------------------------------|
| Pb battery [5] | 50 | 45 | 0.90 | 1500 | 5.3 ¹ | 240 | 4000 |
| Li-ion battery [6] | 100 | 95 | 0.90 | 3500 | 5.3 ¹ | 500 | 4000 |
| Ice [7] | 100 | 50 | 0.95 | very long | 3.9 ² | 50 | 3100 |
| Chilled water [7] | 100 | 10 | 0.95 | very long | 5.3 ¹ | 10 | 4300 |
| Compressor driven TC, T _{desorp} =20°C | 90 | 60 | 1 | very long | 2.9 ¹ | 60 | 2500 |
| Compressor driven+heat assisted TC, T _{desorp} =40°C | 90 | 60 | 1 | very long | 6.3 ¹ | 60 | 5300 |
| Heat-driven TC T _{desorp} =63°C [2] | 90 | 60 | 1 | very long | 0.4 ³ | 60 | 1500 |

¹⁾T_{amb}=30°C, T_{cond}=40°C, T_{evap}=0°C

²⁾T_{amb}=30°C, T_{cond}=40°C, T_{evap}=-10°C

³⁾Thermal COP

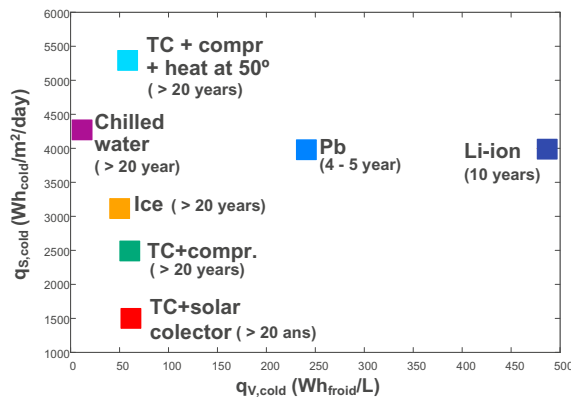


Fig. 5. Representation of results from Table 1

6. Conclusion

This study demonstrates that a TR coupled with a mechanical compressor has a competitive value of energy storage capacity for application in cooling production. Unlike the rest of the storage systems analyzed, where higher temperatures can be detrimental to performance, this system can benefit from heat sources with temperatures above ambient temperature, particularly low-grade waste heat sources (e.g. in the range 40 to 60°C), such as waste heat from photovoltaic installation and fuel cell stacks. When exploiting a low-grade waste heat source, the system can reach a cooling capacity value of ~5kWh/day per m² of solar collector (PV panels), which is higher than the values of the other systems analyzed. These results show a system that is worthwhile of being studied further, given its capability to fulfill both cooling and energy storage needs in tropical insular regions.

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