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Experimental Investigation of a Solid/Gas Thermochemical Storage Process for Solar Air-Conditioning

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Abstract: This paper focuses on studying the experimental performances of a solar air-conditioning pilot plant for housing, which is running in PROMES laboratory (Perpignan-Odeillo, France) since 2006. This pilot of daily cooling capacity of 20 kWh, consist of a solid/gas thermochemical sorption process powered at 60-70°C by 20 m² of flat plate solar collectors. The thermochemical sorption process is based on the coupling of a liquid/gas phase change of a refrigerant (NH₃) and a reversible chemical reaction between a reactive solid (BaCl₂) and this refrigerant. Its functioning mode is intrinsically discontinuous and cyclic. It is well adapted to the storage/transformation of solar energy. An analysis of experimental results leads to an averaged efficiency of 50% for the solar collectors and a process COP ranging from 30 to 40%, leading thus to a daily cooling productivity for the thermochemical process of about 0.8 to 1.2 kWh of cold produced at 4°C per m² of solar collector.

Keywords: Solar Air-Conditioning, Solid/Gas Sorption, Thermochemical Reactor, Solar Collector

1. Introduction

Nowadays, peaks in electricity demand occur more frequently during the summer period in most developed countries, because of the increasing use of air-conditioning. The reasons for this lie in higher thermal comfort expectations, in lower initial costs for air-conditioning equipments and in the heat island effect in urban areas, which leads to microclimatic changes. Moreover, final energy consumption in buildings in the European Union represents about 40% of the total energy consumption. This energy consumption means that the building sector is responsible for about 20% of the total CO₂ emissions.

Moreover, solar assisted refrigeration appears to be a promising alternative to the conventional electrical driven air-conditioning units from an environmental point of view, since it results in decreased CO₂ emissions and in the elimination of CFCs and HCFCs. Considering the problem of peak load increase during summer months caused by electrically driven air-conditioning systems, and the close coincidence of the maximum solar irradiation with both the cooling loads and the peak electricity, solar assisted refrigeration may be an interesting option to handle successfully the

issue of reducing peak electricity demand due to air-conditioning.

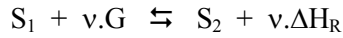
Solar sorption refrigeration technologies such as thermochemical reaction, adsorption, absorption and desiccant cooling processes, are the prevailing option for the utilisation of solar energy in air-conditioning. Solar coolers and refrigerators have been developed for more than 40 years using solid adsorption [1-3], liquid absorption [4,5] or thermochemical reaction processes [6,7].

These solar heat driven cooling processes seem to have an excellent potential in the space air-conditioning business, albeit that so far they are not really a competitive alternative to the conventional vapour compression chillers. There is still a development demand to optimise these systems and to carry out experimental investigations on such processes.

The present study focuses on experimental investigations carried out on a solar powered solid/gas thermochemical pilot plant whose size is representative for air conditioning in housing.

2. Principle of solid-gas thermochemical sorption process

Thermochemical processes are usually based on a monovariant reversible reaction between a solid reactant and a gas:



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



Following the right direction, the solid S_1 (gas G-free) reacts with the gas G produced by evaporation, to form the solid S_2 . This synthesis reaction is exothermic and produces the heat of reaction ΔH_R . In the reverse direction, the decomposition reaction is endothermic: S_2 is decomposed into the initial salt S_1 and releases the gas G which is condensed. This endothermic reaction requires the heat quantity ΔH_R to proceed.

The two processes are monovariant and their equilibrium conditions follow the Clausius–Clapeyron relation (1). The thermodynamic equilibrium conditions of the reactor are determined by only one parameter (P or T):

$$\ln\left(\frac{P}{P_{ref}}\right) = -\frac{\Delta H_i}{RT} + \frac{\Delta S_i}{R} \quad (1)$$

Then, the simplest sorption machine consists of a solid/gas reactor coupled with an evaporator/condenser. A solar sorption process operates according to two different phases that correspond to the diurnal period during which the system is regenerated and nocturnal period during which the cooling effect is produced by the system:

- During de daytime, the reactor is heated by solar energy and desorbs the gas that condenses in the condenser at ambient temperature. The system is thus regenerated at a high pressure due to the condensation temperature of reactive gas.
- During the nighttime, as the reactor is cooled down, it reabsorbs the gas and induces a pressure decrease in the system. This enables the boiling of the liquid in the evaporator that produces the cooling effect below the ambient temperature.

The reactive salt chosen for the pilot plant is the barium chloride, $BaCl_2$, that reacts with 8 moles of ammonia to form $BaCl_2 \cdot 8NH_3$.

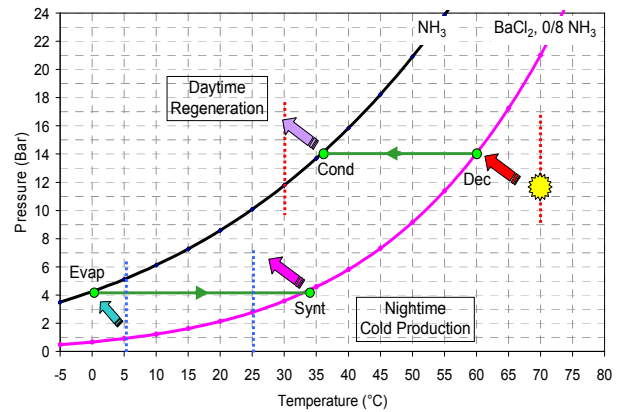


Fig. 1 : Operating thermodynamic conditions of the solar solid/gas sorption process

This salt has already been used for refrigeration and air-conditioning processes [8-10]. Its main advantages lie in the low decomposition temperature of the salt which is ranging from 50–70 °C for the high-pressure phase depending on the condensing pressure (Fig. 1). This allows simple heating systems such as flat plate solar collectors. Moreover, it presents a high stoichiometry v , which minimizes the size of the reactor.

For these thermochemical processes, the solid reactant is mixed with natural expanded graphite (GNE), and recompressed together in order to form in consolidated blocs. Expanded graphite has been widely used as a porous additive in composite reactive medium due to its high thermal conductivity and gas permeability. This implementation was first developed in PROMES laboratory in 1983 to enhance heat and mass transfer in the reactors [11].

3. Pilot Plant Description

The pilot plant was designed to provide a cooling capacity of 20 kWh of cold per day. This corresponds to the air-conditioning needs of a conference room of 120m² during 4-5 hours.

3.1 Components of the pilot plant

Figures 2 and 3 display some views of the pilot plant and a schematic diagram of the installation.



Fig. 2: Flat plate solar collectors and the thermochemical reactor design

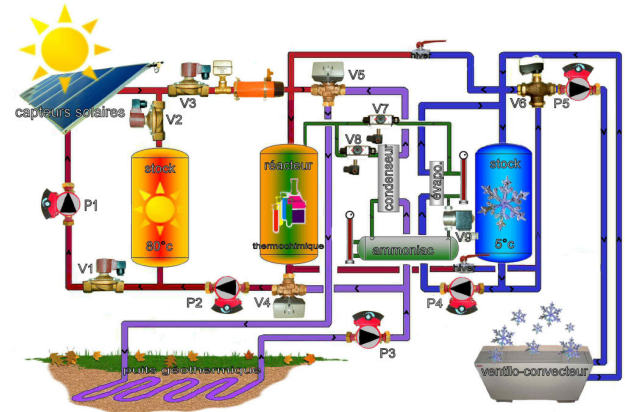


Fig 3 : View of the solar sorption pilot plant and schematic description of the solar air-conditioning thermochemical unit.

The pilot plant consists of four subsystems:

- a solar heating loop,
- a thermochemical sorption unit,
- a water cooling loop,
- a cold water loop.

The solar heating loop, which consists of 21.6 m² of flat plate collectors connected to the reactor and a thermal storage filled with 360 kg of a phase change material (wax) that melts at 78°C. The PCM heat storage enables:

- the storage of the surplus of the available solar heat when the reactor decomposition is accomplished during the afternoon,
- the partial storage of the sensible heat released by the reactor when it begins to cool down at the end of the decomposition phase,
- the heating of the reactor at the beginning of the day, when the solar heat is not sufficient.

The thermochemical sorption unit consists of one reactor, which is composed of a set of 19 tubes filled with a composite reactive porous medium, consisting of a recompressed mixture of 140 kg of

BaCl₂ and 35 kg of expanded natural graphite to enhance heat and mass transfer in the reactive composite. The reactor is either connected to a condenser during the day and the evaporator during the night through the valves V7 and V8. The condensed ammonia is stored in a reservoir in order to be used during the night.

The water cooling loop enables alternatively the cooling of the condenser during the day and the cooling of the reactor during the night thanks to a set of two 3-way valves (V4 and V5). This cooling loop is composed of a horizontal in-ground plate heat exchanger of 16m², which is buried at two meters depth.

The cold water loop is connected to the evaporator. The cold water is produced at 2°C during the night phase. The cooling capacity is stored into a second cold storage, which is filled with 340kg of a PCM (wax) that solidify at 5°C. During the day, fresh water at 13°C is distributed from the PCM storage via a mixing valve (V6) to the fan-coil units placed in the conference room.

3.2. Control of the solar process

The pilot plant is instrumented and controlled under Labview software :

- The solar heating loop is controlled by a pyranometer and temperature measurements at the outlet of solar collectors, and inside the reactor and hot PCM storage.
- The connection of the reactor with either the condenser or the evaporator is controlled by pressure sensors (reactor, evaporator and condenser) and a level gauge placed in the reservoir of the condensed ammonia. When the high level is reached then the decomposition phase stops, and the reactor is cooled down by the cooling loop. The synthesis phase is stopped when a low level in the liquid reservoir is reached due to the absorption of the ammonia by the reactor.
- The cooling of the condenser is started when the reactor is connected to the condenser during the decomposition reaction, while the cooling of the reactor is started when the pyranometer indicates a low irradiation value at the end of the afternoon or when a high level of liquid ammonia in the reservoir is obtained. The cooling loop feeds separately either the reactor or the condenser.
- The cold water loop is started when the reactor is connected the evaporator and if the evaporating temperature is lower than the cold PCM storage temperature.
- The distribution of the fresh water from the cold PCM storage to the fan-coil units is activated on user's demand during the day.

Some security procedures are foreseen to prevent an overpressure that may occur during hot summer days in the reactor. In this case, the solar heating loop is stopped and/or the connection between the reactor and the condenser is strained.

4. Experimental Results

A typical thermal cycling of the pilot plant is shown in Fig. 4. During the day, the solar collectors deliver hot water at a maximum temperature of 75-80°C and enable the heating of the reactor, which reaches a maximum temperature of 68-73°C. The connection of the reactor with the condenser begins when the reactor attains a temperature of around 60°C or more precisely when its pressure becomes greater than the

condenser pressure. During the night, as the reactor is cooled down below 40°C, cold is produced at the evaporator at a temperature of about 0°C (Fig. 1). Chilled water is then produced at a temperature below 3°C, which is enough to solidify the PCM contained in the cold storage. During the day, fresh water is delivered at 13°C by a mixing valve to fan-coil units placed in the conference room.

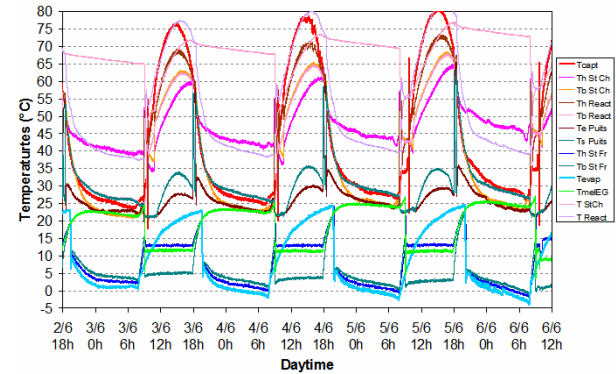


Figure 4: Temperature evolutions for the main components of pilot plant

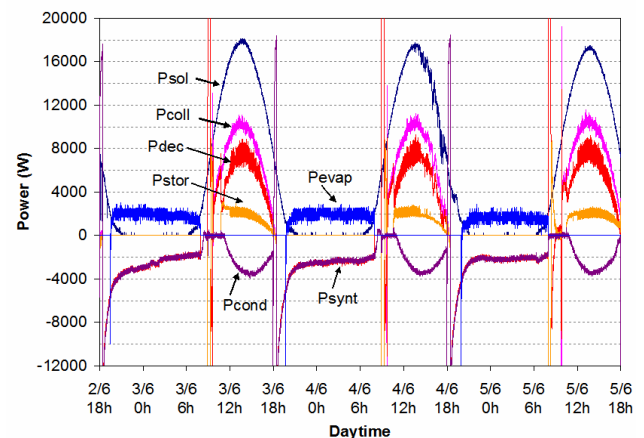


Fig. 5. Evolution of the thermal powers (W) involved in the thermochemical process

Fig. 5 represents the thermal powers obtained in the process. The solar collectors supply a maximum power of 10 kW. The reactor absorbs approximately 70% of the supplied power for the decomposition reaction and the rest is stored in the hot PCM. The efficiency of the solar collector is in the order of 55% for these sunny days.

During the night, the evaporator enables a cooling power of about 2 kW during 10 hours. The heat of synthesis reaction is released into the ground with a power of about 3 kW.

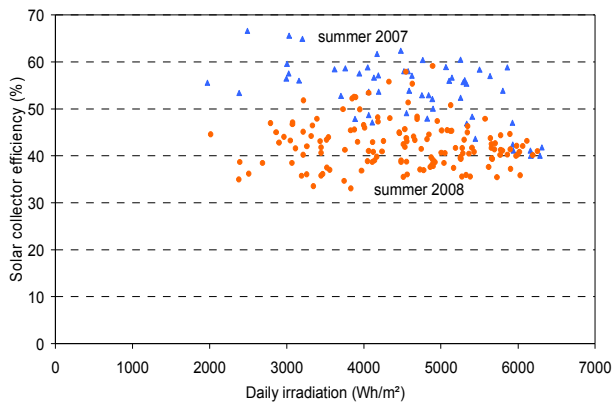


Fig. 6. Evolution of the solar collector efficiency over the summer periods of 2007 and 2008

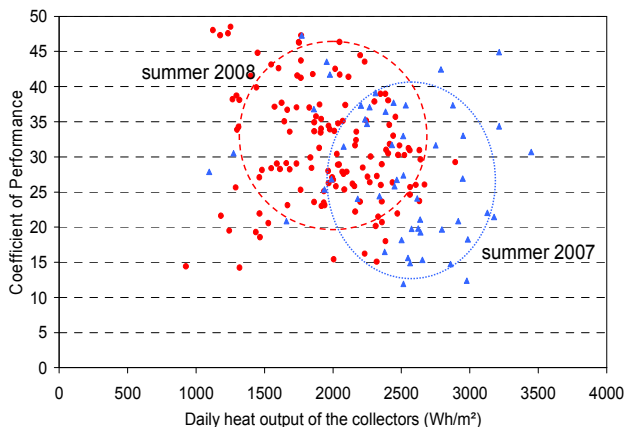


Fig. 7. Evolution of the daily process COP over two summer periods

The pilot plant is running since 2006. Figures 6 and 7 present the performance of the thermochemical process over the two summer periods 2007 and 2008. Each point in the graphs represents a daily performance. A decrease of the efficiency of the solar collector is observed in Fig. 6. In summer 2007 the collector efficiency was about 50 to 60% while in summer 2008 the solar collector efficiency was reduced to a value ranging from 40 to 50% due to a bad aging of the solar collectors.

This decrease in the solar collector efficiency has been counter-balanced by a better control and management of the solar heating loop that has been improved during the summer 2008. As a result, the solar collectors heat output is efficiently used by the reactor, enabling thus a greater cooling production. Figure 7 shows the evolution of the coefficient of performance of the thermochemical process, which is defined as the ratio of the cold production to the heat supplied to the reactor. Even

if the heat supplied by the collectors during summer 2007 is greater, due to a better solar collector's efficiency, the daily COPs were globally lower than those obtained during summer 2008. Thus the daily COPs are ranging from 25 to 45 % with an improved management of the different components of the sorption pilot plant.

The daily cooling productivity of such thermochemical process is ranging from about 800 to 1200 Wh of cold produced at 4°C per m² of solar collector.

5. Conclusions

Solar cooling can become a promising solution for the clean and sustainable air-conditioning of urban buildings. As the demand for air-conditioning is increasing in the urban environment and, considering the fact that soft technologies like passive cooling are very difficult to apply in existing buildings, the sorption cooling technology discussed in this paper may provide a competitive alternative to conventional air-conditioning systems. Solar refrigeration is a technology that has a great variety of methods of producing low temperatures; however, very few have demonstrated a technical and economical viability.

The experimental study presented in this paper shows that is possible to develop thermochemical solid-gas sorption process for air-conditioning using only simple flat plate solar collectors operating at 70°C. Our results shows that an optimal management and control of the different components of the sorption pilot plant, e.g. the coupling of the solar collector loop with the hot PCM storage and the reactor or the connection of the reactor with the condenser and evaporator, can result in a substantial increase in the daily cooling production. The yearly solar COP of such process is around 18%, which is not far from those obtained (around 22 %) by other more efficient solar sorption process, e.g. liquid/gas absorption machines.

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