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To cite this version:

Nolwenn Le Pierrès, Driss Stitou, Nathalie Mazet. New deep-freezing process using renewable low-grade heat: From the conceptual design to experimental results. Energy, 2007, 32 (4), pp.600-608. 10.1016/j.energy.2006.07.024 . hal-00685568

HAL Id: hal-00685568

https://hal.science/hal-00685568v1

Submitted on 2 Oct 2023

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New deep-freezing process using renewable low-grade heat: From the conceptual design to experimental results

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Abstract
An exergy-based analysis applied to ideal thermochemical dipoles allowed to design an original process that could use low-grade energy, produced from a thermal solar collector at around 70 °C, to provide low-temperature cold, below -23 °C, in order to store deepfrozen food. The ideal coefficient of performance (COP) of this system is 0.5 and the exergetic yield is 1. Taking into account the process enthalpies and the sensible heat of the reactants, the COP_{thermo} is 0.17. The process functioning is described in this paper. It alternates between a regeneration mode during daytime and cold production mode during night-time. An experimental prototype was designed and built. It proved the feasibility of the concept and showed an experimental COP of about 0.06, which is similar to the up-to-date solar cooling systems, but at higher cold temperatures. The mean annual exergetic yield of the process is about 0.06.

Keywords: Exergetic analysis; Thermochemical dipole; Deep freezing; Prototype; COP

Nomenclature

a	primary dipole (cools the cold box)
b	secondary dipole (cools the primary dipole)
COA	coefficient of amplification of heat
COP	coefficient of performance
Cp	specific molar heat ($J\,mol^{-1}\,K^{-1}$)
D	exergetic losses (J)
dec	decomposition
E'	inlet exergy (J)
E''_u	useful produced exergy (J)
G	reactive gas
n	ratio of the reactant amounts in dipoles b and a.
P	pressure (Pa)
Q	heat quantity (J)
S_1 and S_2	reactive salts
T	temperature (K)
T_0	reference temperature (K)
α	direction of the gas flow in the dipole during regeneration
β	direction of the gas flow in the dipole during cold production
γ	stoichiometric coefficient
η	exergetic yield
θ	Carnot factor ($= 1-T_0/T$)
ΔH	heat of transformation ($J\,mol^{-1}$)

Subscripts:

0	reference
1	evaporator/condenser pole
2	reactor pole
c	cold
cond	condensation
dec	decomposition
evap	evaporation
g	reactive gas
h	hot
i	ideal/intermediate
liq	reactive fluid in liquid form
r	solid reactant rich in reactive gas
R	reaction
syn	synthesis
thermo	thermodynamic
vap	evaporation

1. Introduction

When one designs new processes, one has to take into account environmental questions and thus the kinds of energy used and produced in this process. It is important to design new systems that use or produce little or no greenhouse or ozone-depleting gases and the use of renewable energies as the driving source is an interesting option. In the case of solar energy, either transformed into heat

or cold or converted into electricity, the question of the quality of the energy source is of particular importance. Indeed, both the quantity and quality of the energy produced by the new process should be adapted to its use and usable at the time when it is needed, independently from the discontinuous availability of the energy source.
In this study, focus is directed toward the use of lowgrade solar energy to drive cooling at -23 °C. Nowadays, solar energy is commonly only used in domestic water heating systems. Recent developments were made concerning solar cold production and particularly in solar air conditioning systems. Solar liquid–gas absorption systems were developed more than 50 years ago to transform solar heat into cold, but still present major drawbacks and constraints. Indeed, this type of process works in a continuous way, thus with a continuous heat source. For solar systems, the storage of the required heat or of the produced cold allows a good functioning of the process, but necessitates heavy and voluminous storage capacities. Moreover, the needed temperature of the heat source is high: from 90 to 140 °C [1], what requires the use of expensive solar collectors, as parabolic concentrators or with vacuum tubes. Problems are of the same kind concerning the solid–gas adsorption systems, with however a lower temperature of the heat source, around 80–100 °C [2]. Adsorption and absorption solar systems allow to obtain cold at a temperature as low as -10 °C. Sorption processes based on a chemical reaction between a solid and a gas also allow the production of cold at around -5 to -10 °C from heat at 80–90 °C [3], and a prototype driven by solar energy proved the effectiveness of that concept as soon as 1986 [4]. The reactive gas used is ammonia. This refrigerant fluid is toxic but is totally neutral with respect to ozone depletion and global warming problems. Lower temperature levels were also obtained using this thermochemical technology, but from a higher heat source temperature, about 140–160 °C [5].
The aim of this study is to examine the possibility to design a new process to produce cold at low temperature (about -30 °C for storage of frozen food) from a heat source at about 60–70 °C compatible with the use of flat simple glazed solar collectors. The process should be reliable and robust, to prevent the risk of ammonia leakage in housing.
Recent work based on the exergetic analysis characterised classical and original processes. Studies were directed toward cold production systems with ideal coefficient of performance (COP) of 1, 2 and 3 [6], and systems producing both cold and heat at higher temperature level (with a coefficient of amplification of heat COA = 0.5) with the possibility of heat transport over long distances [7,8]. In this work, the same type of exergetic analysis was used to design a new process to produced cold at low temperature from low-grade heat.

2. Analysis basis

Considering an ideal process, the inlet exergy E' leads to the production of unused exergy that only transits through the ideal system and exergy that is converted or transformed in the process. In real processes, destroyed exergy, exergy produced in excess and untapped exergy must be minimised, such that the useful produced exergy E''_u is maximal. The exergetic yield η is defined as :

$$\eta = \frac{E''_u}{E'} \qquad (1)$$

The second basis of the analysis is the exergetic dipole, used for the study of heat transformation processes by Spinner et al [8]. An exergetic dipole is a closed system that results in the coupling, via an active gas transfer (Figure 1.A), of two reversible processes: an endothermic one (such as an evaporation or gas-liquid or gas-solid desorption or decomposition reaction) and an exothermic one (such as a condensation or gas-liquid absorption or gas-solid adsorption or synthesis reaction). The two processes are reversible.

We focus our study on the reaction (2) between a solid S and a gas G in pole '2' Figure 1, which can be coupled in pole '1' to a liquid-gas phase change of G or to another gas-solid reaction involving the same fluid but a different reactive solid.

$S_1 + \gamma\ G \leftrightarrow S_2 + \Delta_R H$ (2)

The representation of the thermodynamic equilibrium of these monovariant processes is linear in Clausius-Clapeyron diagram (lines 1 and 2 in Figure 1.B).

Thermodynamic conditions applied to each pole of a closed dipole lead either to a useful heat or cold production phase, or to a regeneration phase. The two phases are independent temporally from each other (Figure 1.C). For cold production cycles, the useful cold production phase 'β' is followed by the regeneration phase 'α' of the dipole.

Transfers in each pole are characterised by the involved heat quantity and quality. The quantity of transferred heat is proportional to the enthalpy of the involved transformation. The quality depends on the temperature levels at the poles.

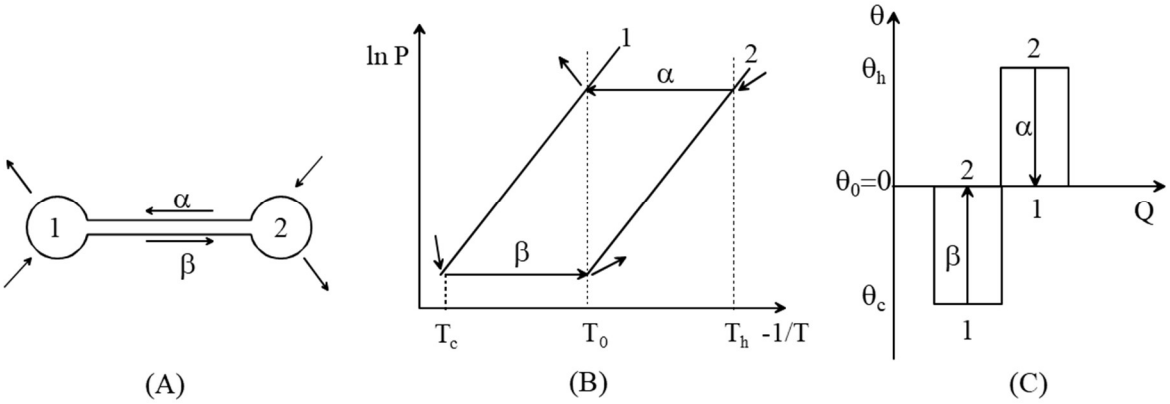

Figure 1:

(A) Dipole functioning with the physico-chemical processes (2) and (1). It is regenerated when gas flows in direction (α) and produces cold in direction (β).Pole 2 contains a solid that can decompose in a gas and another solid. Decomposition in pole 2 and condensation in pole 1 prepares the dipole for cooling action. During cooling, liquid evaporates in pole 1 and the gas reacts with the solid in pole 2, leading to a closure of the cycle

(B) Monovariant equilibriums in poles 1 and 2 respectively, represented in a Clausius-Clapeyron diagram.

(C) $\vartheta = f(Q)$. ϑ is the Carnot factor. Heat is provided to pole 2 at a high value of ϑ which is ϑ_h. cold production takes place in pole 1 at a low value of ϑ which is ϑ_c. For an ideal dipole the exergy input $\vartheta_h.Q$ is equal to the exergy output $\vartheta_c.Q$.

T_h is the regeneration temperature, the highest temperature level involved. T_c is the cold production temperature. T_0 is the reference or ambient temperature. If the process releases heat at T_0, the corresponding Carnot factor θ_0 equals zero and thus the unused and untapped exergies equal zero. Moreover, if T_c is the cold temperature level required by the user, the excess exergy production is zero and consequently, following Eq. (1) the ideal exergetic yield η_i is maximum.

The ideal coefficient of performance COP_i of the basic dipole represented Figure 1 is defined as :

$$COP_i = \frac{\Delta_{vap} H_1}{\Delta_R H_2} \quad (3)$$

where pole 1 is the one where cold production occurs and 2 is the one that has to be heated for regeneration.

In the ideal case, the COP_i is proportional to the exergetic yield η_i:

$$COP_i = \frac{\Delta_{vap}H_1}{\Delta_R H_2} = \eta_i \frac{\theta_h}{|\theta_c|} \quad (4)$$

as exergies E' and E''$_u$ in the case of this dipole, are respectively $\Delta_R H_2 . \theta_h$ and $\Delta_{vap}H_1 . \theta_c$.

In real processes, the enthalpies ΔH depend on the process and the temperature. Moreover, the liquid/gas transformation heat is always smaller than the solid/gas reaction enthalpy [10]. However, in a first analysis of the ideal processes, all enthalpies are considered equal. Real values will be studied in a second step.

3. Definition of the new process

If the enthalpy values $\Delta_{vap}H_1$ and $\Delta_R H_2$ are equal, and the exergetic yield of the system is 1, it follows from Eq. (4) that if the lowest temperature T_c is – 22°C and T_0 = 20°C then the high temperature T_h should be at least 79°C.

For the purpose to develop a deep-freezing process driven by a heat source at a temperature of maximally 70°C, also taking into account that a reasonable temperature difference is necessary for heat transfer, the pole temperature of 79°C is much too high. Thus, to design a deep-freezing solar system using low temperature solar heat, the ideal system COP_i has to be lower than 1. Particularly will be focussed on systems with COP_i equal to 0.5. In that case, the high temperature level necessary to produce cold at -22°C is 47°C (reference temperature T_0=20°C). This is compatible with the limit temperature of 60 to 70°C for simple flat plate solar collectors. An extensive study of these systems has been performed [11]. This study uses the concept of a thermal coupling between two poles of two different dipoles with respectively an exothermic and an endothermic process [7]. The heat rejected by the exothermic process is assumed to be completely used by the endothermic process. A particularly interesting process concept has been extracted from the various potential dipole configurations, and is presented in Figure 2.

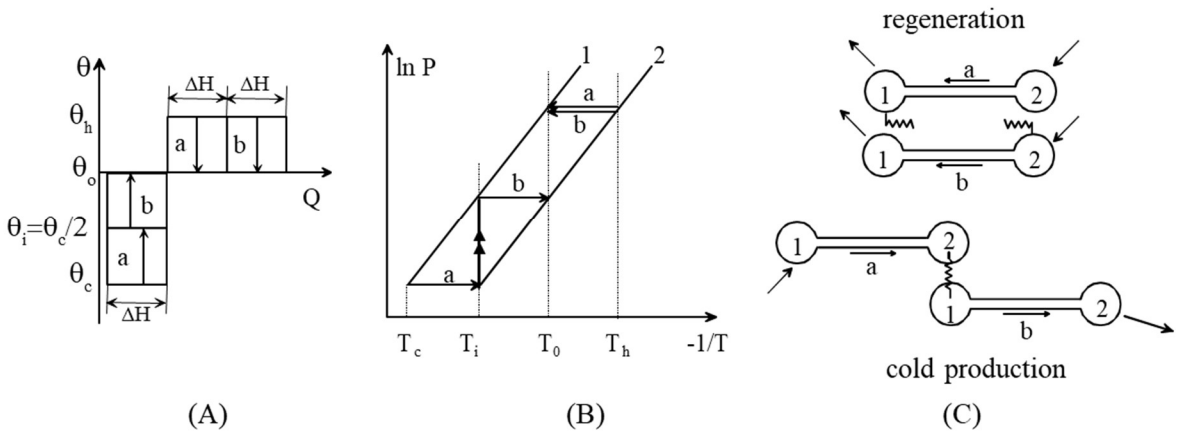

Figure 2:

(A) Exergies (Q.θ) involved in the ideal process with cold production at θ_c from heat at θ_h in the diagram θ = f(Q).

(B) Thermodynamic conditions of the two process phases in the Clausius-Clapeyron diagram.

(C) Dipoles functioning without thermal connection in the regeneration phase and with a thermal connection between dipoles 'a' and 'b' during the cold production phase.

In case of an ideal system with a COP_i = 0.5, we see from Eq. (4) that at T_h twice as much heat must be transferred to pole 2 than is transferred to pole 1 in the cooling stage. In the θ = f(Q) diagram, as shown in Figure 2.A, twice the amount of heat ΔH, has to be transferred at θ_h and once this amount at θ_c. The

Carnot factor $|\theta_c|$ can thus be twice as big as θ_h. In that case, the inlet and produced exergies, equal to the area θ.Q on the diagram Figure 2.A, are equal since the exergetic yield is 1. This system involves two dipoles. Both dipoles, named dipole a and dipole b, as shown in Figures 2.B and 2.C, have to be:
- without any thermal connections during the regeneration phase
- thermally connected during the cooling phase. Heat is transferred from the exothermic reaction taking place in pole a_2 to the endothermic boiling process in pole b_1.

This ideal process thus allows the production of cold at -22°C using ideally low-grade heat at 47°C from simple flat plate solar collectors. In that case, since solar radiation is the only thermal energy supply, the regeneration and cold production phases correspond respectively to the day-time solar radiation heating and nocturnal cooling periods. The monovariant processes chosen for this deep-freezing purpose are one solid-gas reaction (poles (2)) coupled to a liquid/gas transformation (poles (1)) in each dipole.

The fixed bed solid-gas reaction poles (2) of each dipole are located inside solar collectors (Figure 3). During the cooling/night period pole a_1 is an evaporator situated in the cold box; the boiling temperature under these conditions is –23°C. Pole b_1 acts as an evaporator and is thermally connected to pole a_2 where the exothermic gas solid reaction takes place, to ensure cooling of this pole during the night operation phase.

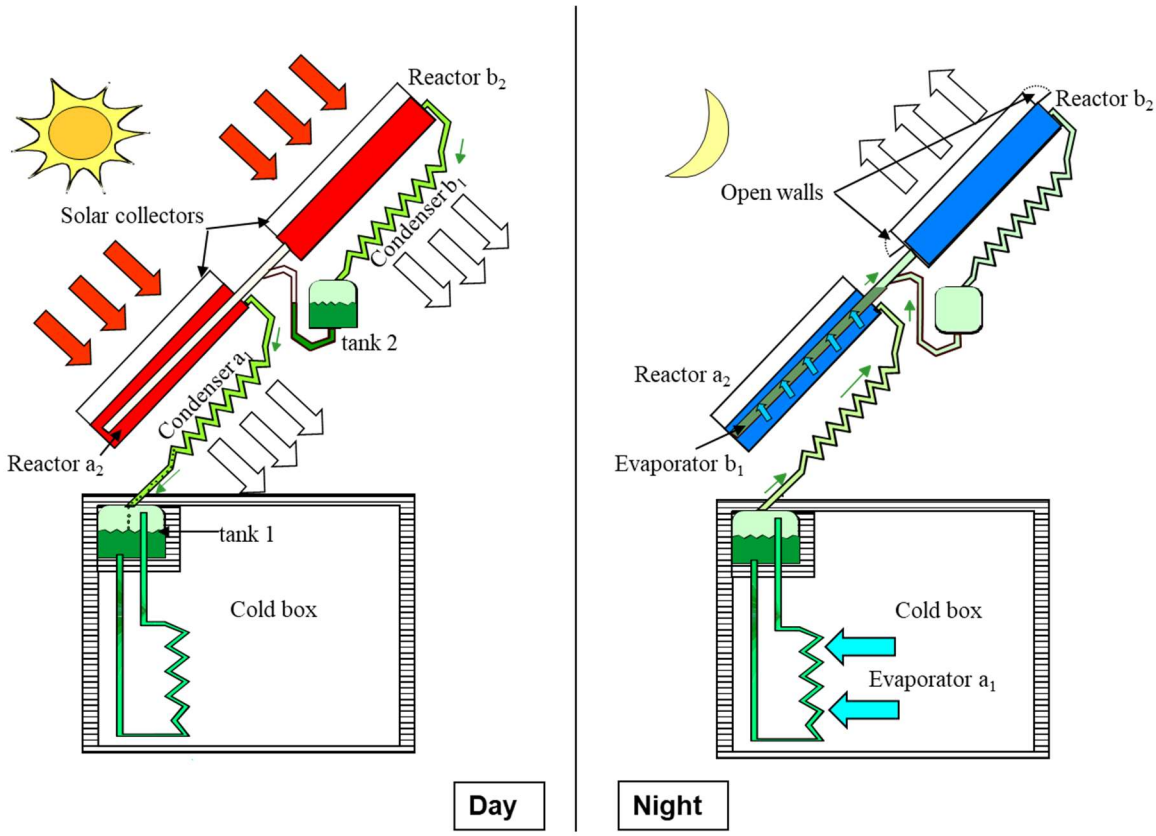

Figure 3: *Simplified scheme of the prototype during the regeneration and cold production phases.*

As can be seen from Figure 2.B and 3, both systems are brought to high pressure and temperature in the regeneration phase during day-time by using the solar radiation. Gas is desorbed from the reactor beds, and condensates at T_0 (ambient temperature) in the condensers (1). During the night cold production phase, the reactor b_2 is brought to ambient temperature by convection with outside air and radiation to the nocturnal sky. Thus, the gas solid reaction takes place in pole b_2. That leads to the evaporation of the liquid in pole b_1. The thermal connection between systems 'a' and 'b' during the

night phase allows the cooling of pole a_2 through the boiling of the fluid in pole b_1 at intermediate temperature T_i for which $T_c<T_i<T_0$. Consequently, synthesis happens in reactor a_2 and boiling at T_c of the liquid in evaporator a_1 can proceed.

4. Choice of the working components and adjustment of the calculation of the COP value

The reactive components have been chosen as described in [12]. The gas used in these dipoles is ammonia, and the reactive salt chosen is $BaCl_2$, reacting with NH_3 to form $BaCl_2$-$8NH_3$. The monovariant equilibriums (the liquid/vapour equilibrium curve of ammonia, and the $BaCl_2(s) + NH_3(g) \leftrightarrow BaCl_2\text{-}8NH_3(s)$ equilibrium) are given in Figure 4. The condensation/boiling enthalpy of NH_3 is about 23 kJ/mol, and the reaction enthalpy of the $BaCl_2$ with NH_3 is about 38 kJ/mol of ammonia. Thus, the monovariant equilibrium lines, as shown in Figure 4 are not parallel, as considered for ideal cases. In this case, the molar amounts in dipole a and b can not be the same. In the cooling phase, the heat transferred from pole a_2 must be completely taken up by the evaporation of ammonia in pole b_1. Thus, the ratio of the amounts of moles in the dipoles is deduced:

$\Delta_R H(\text{pole } a_2) + n.\Delta_{vap}H(\text{pole } b_1) = 0$

$$\text{Thus } n = \left|\frac{\Delta_R H(\text{pole } a_2)}{\Delta_{vap} H(\text{pole } b_1)}\right| \quad (5)$$

In this case the COP is given by the following expression :

$$COP = \frac{\Delta_{vap} H(\text{pole } a_1)}{\Delta_R H(\text{dec in pole } a_2) + \Delta_R H(\text{dec in pole } b_2)\cdot n} = \frac{\Delta_{vap} H_1}{\Delta_R H_2 + \Delta_R H_2 \cdot \frac{\Delta_R H_2}{\Delta_{vap} H_1}} = 0.23$$

(6)

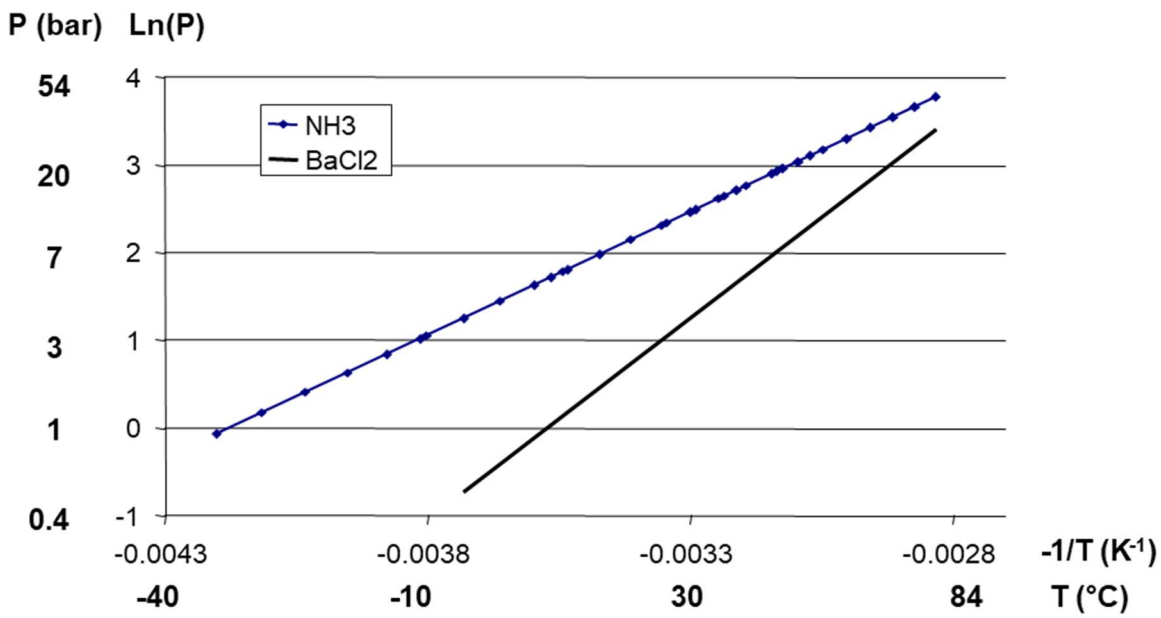

Figure 4: *Clausius-Clapeyron diagram of NH_3 liquid-gas transformation and the chemical reaction $BaCl_2(s) + NH_3(g) \leftrightarrow BaCl_2\text{-}8NH_3(s)$.*

Another important difference between the ideal case and the real system is the influence of the thermal masses of the system components, especially for a discontinuous system. One has to take into account the heat needed to heat up and cool the different system components during the transient phases of the functioning. Indeed, before evaporation or reaction with the salt, ammonia has to be cooled down (or respectively heated up) to the adequate temperature. Moreover, the reactive salt also has to be heated up or cooled down before decomposition or synthesis. Considering the thermal properties of the chosen reactants, a new more realistic system COP_{thermo} can then be calculated following (7) [14].

$$COP_{thermo} = \frac{\dfrac{\Delta_{vap}H_1 - Cp_{liq} \cdot (T_{cond} - T_{evap})}{\Delta_R H_2 + Cp_r \cdot (T_{dec} - T_{syn})}}{1 + \dfrac{\Delta_R H_2 + Cp_r \cdot (T_{dec} - T_{syn}) - Cp_g \cdot (T_{dec} - T_{evap})}{\Delta_{vap}H_1 + Cp_{liq} \cdot (T_{cond} - T_{evap2})}} \quad (7)$$

The COP_{thermo} value for these reactants is 0.17. This is the maximum possible COP for the real system, without taking into account the influence of the mass of the reactors walls, or other thermal masses of the real system during the transient phases. Their influence was studied through a dynamic model of the system to evaluate its functioning and performances depending on the meteorological conditions. The development of this model has already been described [12].

5. Experimental equipment and results of a 1 day's test

Simulations allowed the dimensioning of the process and a prototype has been built in Perpignan (South of France) [14]. An important criteria to be fixed was the respective reactant quantities in the two different systems. Indeed, during the spring and autumn period, the secondary system has to be about twice bigger than the primary system. But during the summer period, the secondary system has to be even bigger, for the same primary system. Indeed, the primary reactor is more difficult to cool down to 5°C at night during the warm months, due to the heating from the warm ambient air (about 25°C).

Another point to be set was the solar collector area. Indeed, during the summer period, the collectors areas can be small, as the solar irradiation is high in Mediterranean conditions. However, in autumn and spring, the collector areas have to be larger, but that induces problems during the sunniest months. With a large collector area, the necessary energy to insure the decomposition of the salt is received very fast, and once the endothermic decomposition is finished, the solar irradiation is used only to heat up the reactors. The reactor temperatures can then reach very high values [12]. Consequently, it is more difficult to cool the reactors during the following night. Collectors then mustn't be over-sized. The dimensioning of the prototype thus results from a compromise between a reasonable size and a suitable cold production for a given cold box during the 6 sunniest months of the year.

Characteristics of the prototype are presented in table 1. Minor differences due to technical questions can be observed compared to the scheduled dimensions given in [12]. The reactive salt $BaCl_2$ (respectively 41 and 82 moles in reactor a_2 and b_2) is inserted in consolidated blocs of expanded natural graphite (ENG) inside the reactor tubes. This composite material salt-ENG was developed to increase the heat and mass transfers in the thermochemical reactors [13]. Figure 5 shows the reactors a_2 and b_2 covered by a high solar absorptivity copper film and contained in simple flat plate solar collectors. Solar collectors are directed toward the South. The solar collector containing reactor b_2 can be opened (lower and upper walls of the collector) and has flat fins on the back of the reactor to increase the convection area during the cold production phase. During the day phase, for an efficient heating of the reactors, the collector walls are closed and convection is thus blocked. The solar collector containing

reactor a_2 is simpler, as the reactor cooling is insured by the heat transfer between the reactive salt and the evaporation of ammonia in evaporator b_1, which is located inside reactor a_2.

To study the functioning of the prototype, it was instrumented with 57 thermocouples. The following results are average temperatures of the components (3 thermocouples for pole a_1, 1 for a_2, 4 for a_2 and 8 for b_2). A pyranometer (Figure 5) is situated between the solar collectors and measures the irradiation received. Two level detectors measure the liquid levels in tank 1 and in evaporator b_1.

Figure 6 shows the temperature evolution of the prototype for the meteorological conditions of June 10th, 2005. This evolution starts at sunrise (at t=0). During the first hours of insulation, both reactors a_2 and b_2 reach high temperature around 60°C (corresponding to T_h on Figure 2). Then, the temperature stabilises and regeneration can occur through the endothermic decomposition of the salts in both reactors. Condensation occurs in the corresponding condensers a_1 and b_1 at outside temperature around 22°C (T_0 on Figure 2). There are no thermal or mass connections between the two dipoles during this phase. The temperature of evaporator b_1 increases slightly, as it is thermally connected to reactor a_2, but does not reach the same high value as it is not directly exposed to the solar radiations. After hour 6 for pole a_2 and after hour 8 for pole b_2, temperatures of these two reactors increase steeply, as the endothermic reaction of decomposition is completed. Indeed, all the solar radiations received by the solar collectors after that decomposition period is used only to heat up the reactors. During that day period, the temperature of evaporator a_1 increases slowly, as no cold is produced.

After the beginning of the night, around hour 13, both systems are cooled by convection with outside air and radiation towards the nocturnal sky. During the night, the temperature of reactor b_2 decreases to approach the ambient temperature T_0. At hour 15, synthesis begins and evaporator b_1, where evaporation of ammonia occurs, is brought to about 3°C (T_i on Figure 2). It absorbs heat from reactor a_2, which is thus brought to about 5°C. This allows the evaporation of ammonia at about -25°C in evaporator a_1. This pole reaches a minimum of -27°C during that night. Thus, experiments prove the possibility to reach deep-freezing temperatures using low grade heat from simple flat plate solar collectors.

These experimental results can be compared to the simulation results obtained in [12], Figure 4, between hours 24 and 48 for a sunny day. The reactors temperature evolutions are similar and show the same phases. The evaporators evolution do not follow exactly the same trends as the simulation had been performed for a cold box filled with ice. However, simulation and experimental results were fitted [14] to obtain satisfying simulation of the process evolution and determine its energy and exergy efficiencies.

	Dipole a	Dipole b
Reactive medium ($BaCl_2$ + GNE) in pole 2	12.7 kg	25.4 kg
Area of the solar collector of pole 2	2 m^2	3.8 m^2
Metal mass of reactor 2	45 kg	85 kg
Area of evaporator 1	5 m^2	1 m^2 (inside reactor a_2)
Metal mass of evaporator 1	25.4 kg	40 kg
Area of the condensers 1	9 m^2	22 m^2

Table 1: *Characteristic information about the prototype of the proposed dipole coupling*

Figure 5: *Prototype built at the PROMES laboratory in Perpignan (South of France). The solar collector of pole b_2 is shown on the left side and is separated by the pyranometer from the solar collector of pole a_2 on the right side.*

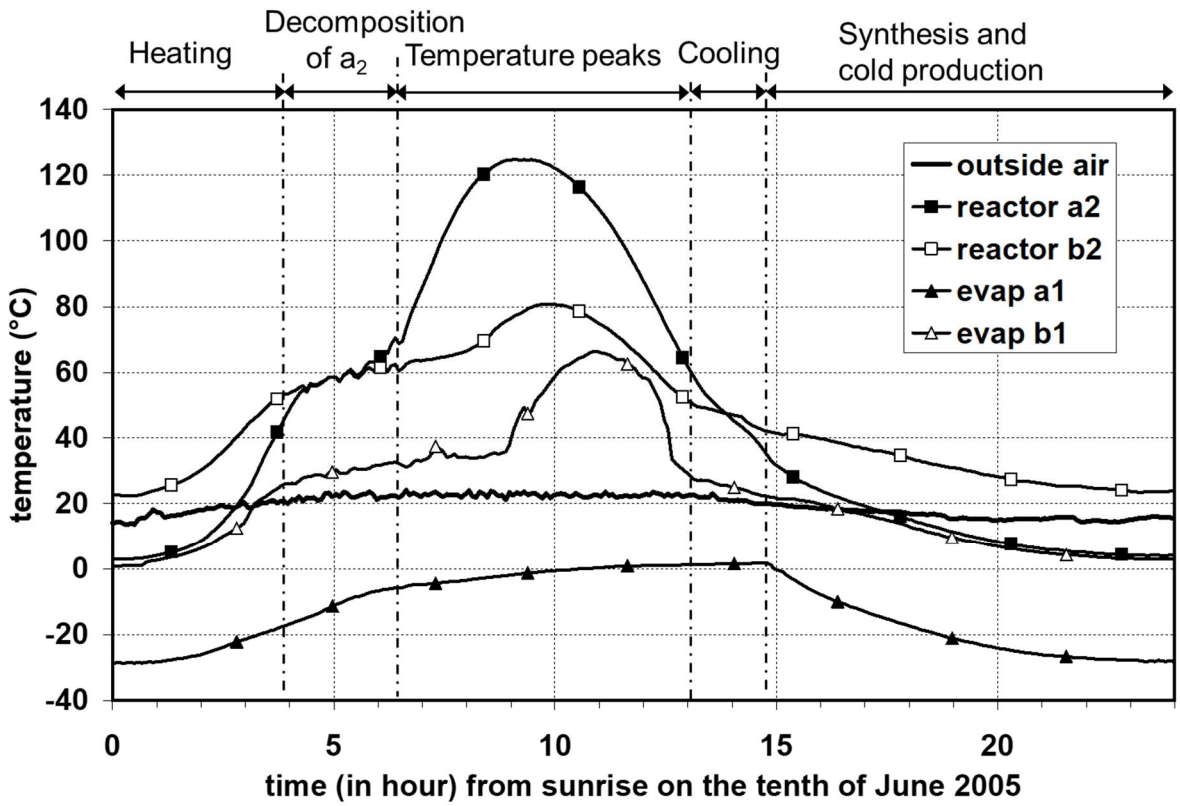

Figure 6: *Temperatures of the system components as a function of time during 24 hours starting at sunrise on the 10th of June, 2005.*

6. Energy and exergy efficiencies of the experimental set-up

The net solar COP of the solar system is defined as the ratio of the cold produced by evaporation in evaporator a_1 to the solar radiations received by the solar collectors of both dipoles. The net solar power received by the solar collectors of the prototype was measured continuously by a pyranometer (Figure 5). The quantity of ammonia rejected and absorbed by the reactors were also continuously measured, thus allowing the calculation of the system performances. The net solar COP of the process was 0.043, for that day of June.

The practical COP of the system is defined as the ratio of the cold produced by evaporation in evaporator a_1 to the heat absorbed by the two solar collectors. Simulations of the system [14] gave the solar efficiency of the collectors : 68% for the meteorological conditions of that day of June, thus the practical system COP was 0.063.

An exergetic analysis of the process leads to the determination of its exergetic yield. Figure 7 shows the evolution of the exergies inlets and outlets of the process on June 10th, 2005. During the day phase, the system absorbs exergy through the reactor poles a_2 and b_2. As the decomposition process in reactor b_2 is longer than in reactor a_2 (the plateau of temperature of reactor b_2 in Figure 6 is longer than for reactor a_2), the exergy input is also longer.

During the night phase, exergy is rejected by convection and radiations to the environment by reactor b_2. The downward peak observed on the evolution of reactor b_2 at hour 15 represents the opening of the collector walls at the beginning of the night, that increases the cooling of reactor b_2 and the power rejected to the environment. At the beginning of the night, exergy is both rejected to the environment by reactor a_2 and transferred from pole a_2 to evaporator b_1 through a thermal connection. Once the temperature of pole a_2 is lower than the outside air (hour 17 in Figure 6), pole a_2 is only cooled by heat transfer to evaporator b_1. The useful exergy is produced by pole a_1 at deep-freezing temperature.

The exergetic yield of the process is defined as the ratio of the exergy produced by pole a_1 during the night phase to the exergies absorbed by poles a_2 and b_2 during day-time. For this day of June, the practical exergetic yield is 0.145.

The solar exergetic yield is defined as the ratio of the exergy produced by pole a_1 during the night phase at low temperature to the exergies received by poles a_2 and b_2 during day-time. A simulation of the process over the whole year, using average data for each month of the year, showed that the average solar yield would be about 0.057 over the seven sunniest months of the year [14].

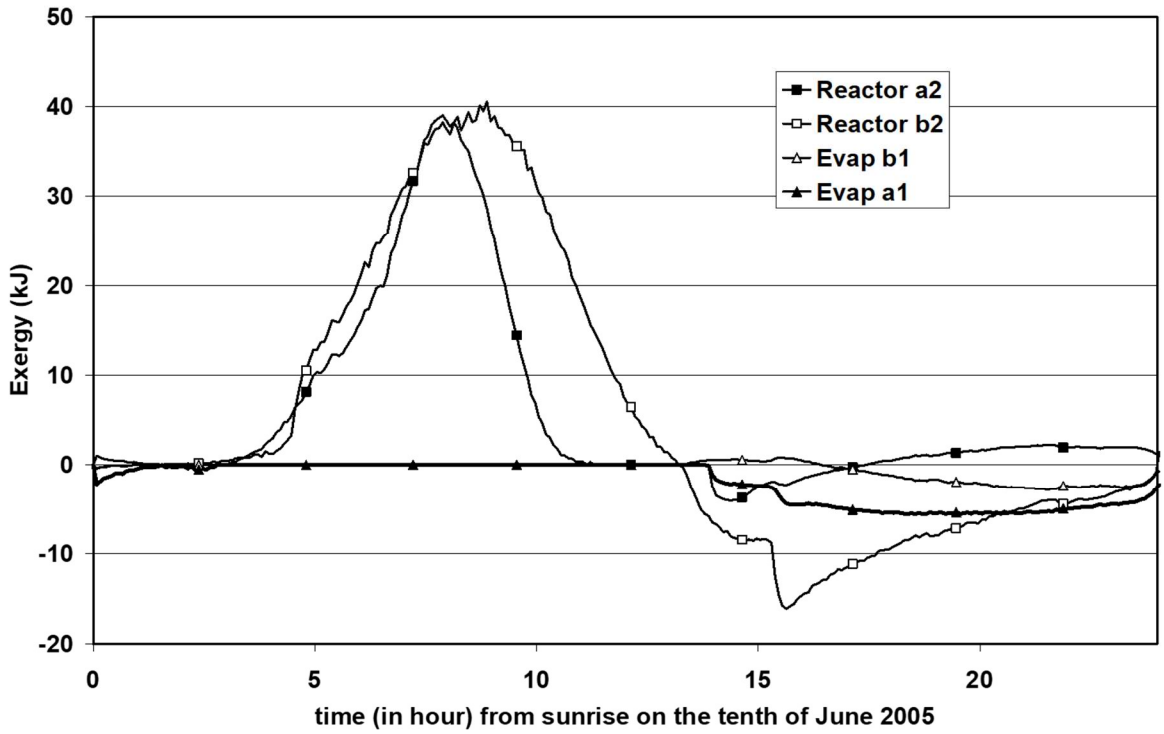

Figure 7: *Exergetic inputs and outputs of the system on the 10th June, 2005.*

7. Conclusions

The analysis of the exergies involved in a thermochemical process for cold production distinguishes between the quantity and quality of the inlet and outlet energies. A low quality of heat (near the ambient temperature) at the inlet must be balanced by a high quantity, if the quality of the heat desired at the outlet is also high for a given quantity. The study of the $\theta = f(Q)$ diagram allowed to design a new process to produce cold at deep-freezing temperature using low grade heat from simple flat solar collectors. This process presents an ideal COP_i of 0.5 and for the chosen reacting components $BaCl_2$ and NH_3, a COP of 0.23. Considering the thermal masses of the reactants, the system COP_{thermo} decreases to 0.17.

A prototype was built and experimented in Perpignan (Mediterranean conditions) and showed its behaviour in practice. It allowed to calculate the practical COP of the process in real conditions, taking into account the dynamic of the functioning and the influence of the metal, reactive medium and fluids thermal masses involved in the process. This practical COP was found to be about 0.06 for a functioning in June.

An exergetic analysis also showed that the designed deep-freezing process had an exergetic yield of about 0.14 and a solar yield of about 0.06, to be compared with the ideal exergetic yield of 1 fixed during the process design.

This prototype will be studied further, during a period of more than one year to investigate its performance for different meteorological conditions. Further improvement can be expected by reducing the metal masses of the reactors and the length of the lines between the different components. Then, using the model that was developed and validated with the experimental results, the system size can be optimised, depending on the weather conditions of the place where it is implemented.

Acknowledgements

This work was supported by the French governmental agency for energy management and environment ADEME and the 'ENERGIE' program of the research ministry – CNRS through PRI 'Froid Solaire' 6.1.

References

[1] Alefeld G. and Radermacher A. Heat conversion systems. Florida: FL CRC Press Inc., Boca Raton, 1994.

[2] Dieng AO, Wang RZ. Literature review on solar adsorption technologies for ice-making and air-conditioning purposes and recent developments in solar technology, Renewable and Sustainable Energy Reviews 2001;5:313-342.

[3] Crozat G, Spinner B, Amouroux M. Systèmes de gestion de l'énergie thermique basés sur des réactions solide-gaz, Proceedings of 'pompes à chaleur chimiques de hautes performances', Perpignan, 1988 (in French).

[4] Balat M, Crozat G. Testing of a prototype of a solar powered solid-absorption refrigeration system, Proceedings of the ISES Solar World Congress, Hamburg, 1987.

[5] Stitou D, Spinner B, Neveu P. Patent FR 02 09392, Installation et procédé pour la production de froid par un système à sorption renversable, 24/07/2002 - CNRS.

[6] Stitou D, Spinner B, Sorin M. An approach for structural design of cooling sorption processes, International Journal Heat and Technology 2005; 23 (1).

[7] Spinner B, Stitou D, Mazet N. New sorption cycles for heat and/or cold production adapted for long distance heat transmission, Proceedings of IMECE2002, ASME International Mechanical Engineering Congress and Exposition, New Orleans, Louisiana, 2002.

[8] Spinner B, Stitou D, Sorin M. New processes for heat transformation: exergetic analysis of cold production, heat upgrading, with long distance transportation from a discontinuous heat source at low temperature, Proceeding of the 53rd Canadian Chem. Eng. Conference, Hamilton, Canada, 2003.

[9] Brodyanski VM, Sorin M, Le Goff P. The efficiency of industrial processes: exergy analysis and optimisation, Elsevier Science, New York, 1994.

[10] Stitou D, Spinner B. A new characterization of real energy conversion processes: A contribution of finite size thermodynamics, Proceedings of the 53rd Canadian Chem. Eng. Conference, Hamilton, Canada, 2003.

[11] Le Pierrès N, Stitou D, Mazet N, Spinner B. Ideal Process conceptual design based on the exergetic analysis. New couplings of thermochemical dipoles for cold production from low grade heat, International Journal of Energy Environment and Economics 2003;12 (3):105-115.

[12] Le Pierrès N, Stitou D, Mazet N. Modelling and performances of a deep freezing process using low grade solar heat, Energy, February 20th 2006 (in press).

[13] Coste C, Crozat G, Mauran S. Procédé de mise en œuvre et réaction solide-gaz, patent FR 8,309,885, extension US patent 4,595,774, 1983.

[14] Le Pierrès N. Procédé de production de froid basse temperature (-28°C) par sorption solide-gaz, PhD thesis of Perpignan University, September 29th, 2005 (in French).