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### ► To cite this version:

Hasan Ghazale, Nathalie Mazet, Pierre Neveu, Maxime Perier-Muzet. Experimental analysis of a hybrid thermochemical cycle for simultaneous cold & work productions driven by low grade heat sources. Heat Powered Cycles Conference 2023, The University of Edinburgh, Sep 2023, Edinburgh, United Kingdom. hal-04310264

## HAL Id: hal-04310264 https://hal.science/hal-04310264

Submitted on 27 Nov 2023  $\,$ 

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# Experimental analysis of a hybrid thermochemical cycle for simultaneous cold & work productions driven by low grade heat sources

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#### Abstract

An original tri-thermal hybrid thermochemical multifunctional cycle is proposed in this study: a sorption cycle based on a reversible endothermic/exothermic solid-gas reaction, whose originality lies in the integration of an expander on the gas line to provide mechanical work. This discontinuous cycle is able to recover medium grade waste heat between 150 and 250 °C during a charging phase, store energy in its intermediate phase, produce cold by the evaporation of the gas working fluid, and produce mechanical power by its expansion during its flow in the production phase. For this purpose, an experimental prototype with MnCl<sub>2</sub>(6/2) NH<sub>3</sub> (solid-gas reactants) and a 1 kWe scroll expander, is developed at the laboratory. Primary results of this experimental prototype showed a validation of the hybrid thermochemical cycle concept, where cold and mechanical production are achieved continuously during the production phase. The dynamic behaviours of the components and their couplings are analysed in several thermodynamic conditions (thermodynamic equilibrium deviations (T-P) at the reactor, expander rotational speed and volumetric ratio, mechanical and cold productions...), and such experimental results lead to the validation of a numerical dynamic model to go further in the energetic, exergetic, and global performance optimization studies of the cycle (internal heat recovery of the exothermic reaction, cold temperature at the expander's outlet, control on the coupling between the expander and the electrical generator...).

**Keywords:** Hybrid thermochemical cycle, Heat waste recovery, Cogeneration, Cold and work production.

#### Introduction

Energy policies include important issues such as the use of low-temperature heat sources (renewable, industrial waste heat), the management of variabilities in both sources and demands, and a particular attention to the growing demand of electricity and cooling. In order to respond to this, thermochemical processes called 'hybrid' combining energy multigeneration and storage functions are being developed [1, 2]. As with any thermochemical cycle, it's based on a reversible chemical reaction where one of its phases is endothermic and the second is exothermic:

$$S' + \Delta h_r \rightleftarrows S + G.$$

In the forward direction of the reaction, known as the charging or decomposition phase, heat is supplied to the solid-gas compound S' to decompose it into another poor solid-gas compound S. The desorbed gas, G, is condensed and stored at ambient conditions. In the backward direction of the reaction, the discharging or synthesis phase, the condensed reactive fluid evaporates to flow, react with S, and reform again S' releasing the heat of the synthesis reaction. The endo or exothermic effects generated in these processes can be used to produce useful thermal effects: storage, cold and/or heat productions. The hybridization of such a cycle with a vapour power cycle by the integration of an expander between the reactor and the condenser or the evaporator of the thermochemical cycle allows adding to the thermal effects a mechanical



production effect (fig.1). Thus, this hybrid thermochemical cycle is a multifunctional cycle that valorises, beside the thermal energy, the mass flow of the reactive gas between the components.



Figure 1- Simultaneous hybrid thermochemical cycle scheme

The thermochemical solid/gas reaction as well as the liquid/vapour phase change process are mono-variant thermodynamic equilibria described by equilibrium lines in the Clausius Clapeyron diagram. In the diagrams, figures 2-4, the high temperature equilibrium (HTE) refers to the solid/gas reaction equilibrium, while the low temperature equilibrium (LTE) refers to the liquid/vapor equilibrium of the reactive fluid.

Hybrid thermochemical cycles can be adapted to a wide range of heat sources temperatures, depending on the chosen reactants and their equilibria with respect to the operating conditions [3]. Several cycle modes that differ in the phase of production of useful effects are defined for this process:

- The separate mode (fig.2), where mechanical production occurs during the charging phase and cold effect is produced during the discharging phase. In this mode, there is no storage of the mechanical work production.
- The simultaneous mode (fig.3), where mechanical and cold productions occur simultaneously during the discharging phase after being stored.
- The combined mode (fig.4) combines the two previous modes and thus mechanical power is produced in both phases of the cycle.



The application of the concept of hybridization to the solid/gas sorption cycle has only been in use since the 2010s. Despite being a relatively new area of study, the bibliography on these cycles is limited. An analysis of the available information reveals the following key points:

- Previous studies on this topic have primarily focused on static thermodynamic analyses. They have shown the feasibility of using these cycles to recover heat at low temperatures, below 200°C [1, 4].
- The dynamic behaviour has been investigated in only one study. It highlighted the significant impact of the coupling between the expander and the reactor [5].



- The proposed cycle architectures integrate two thermochemical reactors. Such processes avoid the management of liquid ammonia, but they imply delicate control of the process [6].
- The functionality of these systems in regards to storage has only been addressed in one study, which investigated the use of phase change material in a heat storage system combined with a thermochemical hybrid process [7].
- Only one experimental study has been conducted, but the hybridization concept was not achieved. The failure was attributed to an underestimate of the impact of heat transfer resistances, resulting in an undersized reactor [8].

The main objectives of the research work on these hybrid cycles conducted at CNRS-PROMES since 2016 are to numerically and experimentally analyse the behaviour and performance of single-reactor hybrid thermochemical processes, which seem simpler to control.

This paper provides a summary of the work conducted on the simultaneous mode. The main results of a thermodynamic analysis conducted in a static regime are presented, which was aimed at determining the potential of these cycles. Then, it summarizes the numerical dynamic analysis of the coupling between the expansion device and the thermochemical reactor. Finally, the paper describes the experimental prototype that has been designed to demonstrate the proof of concept, and presents the first results of its experimentation.

#### Numerical analysis

1- Steady state thermodynamic analysis

The aim of this thermodynamic study, based on equilibrium conditions and energy calculations, is to explore the potential of hybrid thermochemical cycles with different reactive salts and to retrieve the most promising ones.

This study is based on usual assumptions (steady-state process, heat losses and pressure drop inside components are neglected), detailed in a previous work [3]. Several temperature pinches are set for heat exchanges and for the deviation from chemical reaction equilibrium in the reactors. The cold source and ambient sink temperatures are set at  $T_{cold} = 0$  °C,  $T_{amb} = 20$  °C respectively, and a maximal hot source temperature is set at  $T_{hot,max} = 250$  °C, while the required heat source temperature T<sub>hot</sub> depends on the reactive salt.

A review of 103 reactive ammoniated salts from a database by Touzain and from CNRS-PROMES expertise has been carried out. For given operating conditions ( $T_{amb}$  and  $T_{cold}$ ), the salts selected for the analysis are those that can be decomposed with a hot source temperature  $< T_{hot,max}$  and that can be synthesized at a pressure lower than the evaporation pressure of the reactive fluid. For each of these salts, the required heat source temperature, the energy and exergy efficiencies of the cycle, and the mechanical work production ratio are calculated as follows:

energy efficiency:

$$\eta_I = \frac{|W_{mec}| + Q_{cold}}{Q_{hot}}$$

where  $W_{mec}$  is the produced mechanical work,  $Q_{cold}$  is the cold production and  $Q_{hot}$  is the heat supplied by the hot source.

• exergy efficiency:

$$\eta_{ex} = \frac{|W_{mec}| + Ex_{cold}}{Ex_{hot}}$$



where

 $Ex_{cold} = Q_{cold} \cdot \left(\frac{T_{amb}}{T_{cold}} - 1\right)$ 

and

$$Ex_{hot} = Q_{hot} \cdot \left(1 - \frac{T_{amb}}{T_{hot}}\right)$$

ratio of mechanical power production:

$$\tau_w = \frac{|W_{mec}|}{|W_{mec}| + Q_{cold}}$$

Figure 5 presents the results for the most common salts. It shows that the required hot source temperature is always higher than 100 °C and that the energetic and exergetic efficiencies of the cycle are weakly dependent on the reactive salts,  $\eta_I$  between 40 and 50 % and  $\eta_{ex}$  between 20 and 30%. However, the ratio of mechanical production ( $\tau_w$ ) is strongly dependent on the salt: this ratio increases with the requested hot source temperature of the cycle. This increase in the ratio of mechanical production is directly related to the equilibrium of the salt: each salt imposes its synthesis reaction pressure at the outlet of the expander leading to variable mechanical production ratios.



Figure 5- Energetic and exergetic analysis of the cycle as function of several salts and temperatures

Among this set, two salts,  $CaCl_2$  and  $MnCl_2$ , are particularly interesting for the first experimental investigations. Indeed, they are well known (used in commercial thermochemical processes) and stable; they have interesting thermodynamic performances; and their decomposition temperatures are reasonable for experimental developments in a research laboratory.

2- Analysis of the coupling between the expander and the reactor

In order to analyse the dynamic behaviour of hybrid thermochemical processes, numerical models were developed for each component (reactor, condenser, evaporator, and expander). In each component, internal variables (thermodynamic state of the reactive fluid, wall temperature, reaction advancement ...) were considered uniform (nodal approach). The model of the reactor, the condenser and the evaporator are based on the 1<sup>st</sup> law of thermodynamics and mass balances, solid/gas reaction or liquid/vapour phase change kinetics, and the ideal gas assumption. As a first approach, the expander is supposed to operate in steady-state and its global performance is described by two parameters: the isentropic efficiency  $\eta_{is}$  and the volumetric efficiency  $\eta_v$ . Moreover, its exhaust pressure is fixed to simulate user control. The reactant pair of CaCl<sub>2.8</sub>/4NH<sub>3</sub> is chosen and standard heat transfer coefficients have been



employed, with 100 W.m<sup>-2</sup>.K<sup>-1</sup> for the heat exchange between the reactive bed and the wall, and 1000 W.m<sup>-2</sup>.K<sup>-1</sup> for the heat exchange between the wall and heat transfer fluid. The hybrid cycle, composed of these models, was coded and simulated using the Python programming language (in an object-oriented method).

The coupling between the expander and the reactor involves antagonistic behaviours of these components, and it is a key issue in the operation of thermochemical hybrid cycles [9]. In the discharging phase of the simultaneous mode, the generation of mechanical power by the expander ( $\dot{W}_{mec}$ ) is dependent on the pressure levels of admission ( $P_{ex}^{in}$ ) and exhaust ( $P_{ex}^{out}$ ), as well as the mass flow rate of ammonia ( $\dot{m}_a$ ), expressed as:

$$\dot{W}_{mec} = \dot{m}_g. g(P_{ex}^{in}, P_{ex}^{out})$$

In the reactor, the advancement of the synthesis reaction (X) is a function of the exhaust pressure of the expander, and expressed as:

$$\frac{dX(t)}{dt} = K_s. \left(1 - X(t)\right). f\left(T_R - T_{eq}(\boldsymbol{P}_{ex}^{out}(t))\right)$$

where, X(t) is the advancement of the chemical reaction defined as the ratio of the number of moles of the synthetized salt (S') to the total mole number of the salt at an instant t, expressed as:

$$X(t) = \frac{n_{s'}(t)}{n_{s}(t) + n_{s'}(t)}$$

 $K_s$  is the kinetics constant coefficient of the synthesis reaction,  $T_R$  is the reactive solid temperature and  $T_{eq}$  is the equilibrium temperature of the reactant at the pressure of the synthesis reaction i.e. the exhaust pressure of the expander. The numerical analysis of the discharging phase, for a fixed cold source temperature at 0 °C (evaporation pressure  $P_{evap}$  = 4.26 bar), shows a variation of the mean mechanical power as the outlet pressure at the expander varies (fig. 6). While having low pressure differences at the expander's extremities, the mechanical work production is unfavourable. With varying the outlet pressure at the expander in this dynamic study between 0.5 and 3 bars, the mean mechanical power increases as the outlet pressure at the expander decreases below 3 bars until reaching an optimum of production at 1.5 bar. On the other side, while the pressure decreases more below 1.5 bars, the mean mechanical power decreases due to low mass flow rates of ammonia gas caused by a slow chemical reaction rate while getting closer to the equilibrium of the reaction (the pressure at the outlet of the expander approaches the equilibrium pressure of the synthesis reaction at the imposed temperature). From an energy point of view, as the exhaust pressure decreases, the mechanical energy increases even though the reaction's advancement slows down. This antagonistic behaviour between the expander and the reactor, leads to the definition of the optimum operating conditions for the discharging phase.





Figure 6- Evolution of the mean mechanical power as function of the exhaust expander's pressure for fixed evaporating conditions

#### **Experimental analysis**

1- Prototype description

A prototype of the simultaneous mode has been developed. This prototype schematized in figure 7 includes five main parts: the reactor, the expander coupled to an electric generator, an evaporator, a condenser and a throttling valve.



Figure 7- Schematic description of the thermochemical hybrid prototype

7 reactor tubes connected together and placed inside a cylindrical shell with baffle plates consist the whole thermochemical reactor. As noted in the static thermodynamic analysis, MnCl<sub>2</sub> salt was selected for this prototype because it shows high thermodynamic performance, and is a well-known salt with good stability. Each reactor tube contains the reactive material composed of 0.69 kg of Expanded Natural Graphite (to enhance conductive transfer), 4.15 kg of MnCl<sub>2</sub> charged with 3.35 kg of NH<sub>3</sub>. Mineral oil is used as a heat transfer fluid in the reactor shell. A thermo-regulator with a heat power of 14 kW operating between 20 and 180 °C is used to heat the reactor during the decomposition phase and to cool it during the synthesis one. The reversible thermochemical reaction that takes place in the reactor tubes is:

#### $MnCl_2.6NH_3 + \Delta h_r \rightleftharpoons MnCl_2.2NH_3 + 4NH_3$

The expander is a scroll type with a nominal mechanical power of 1 kW, volumetric expansion ratio of 3.5, a displacement of 14.5  $\text{cm}^3/\text{Rev}$ , maximum working pressure of 13.8 bars and a



nominal rotating speed of 3600 rpm bought from Airsquared. The expander is coupled through a magnetic coupling to a DC electrical generator which is electrically coupled to a rheostat (0  $\leq R_{elec} \leq 100$  Ohm) to vary the electrical load of the electrical circuit.

The evaporator is a stainless-steel plates heat exchanger with a total heat transfer area of 0.414 m<sup>2</sup>. The evaporation heat is supplied by glycolic water loop, between 0 °C and 25 °C. An electrical flow heater of 0.6 kW is connected to the outlet of the evaporator to control the superheating of the NH<sub>3</sub> flow.

The condenser is also a stainless-steel plates heat exchanger with a total heat transfer area of  $0.276 \text{ m}^2$ . The condensation heat is evacuated by a pressurized water circuit circulating between 10 °C and 30 °C. The throttling valve is an electronic one, coupled to a regulator in order to control the NH<sub>3</sub> flow rate and maintain the superheating condition at the outlet of the evaporator for a fixed value.

After a tuning phase (tightness control at high pressure and vacuum, evacuation of noncondensable gases...), classical thermochemical cycles (bypassing the expander) are carried out to test and validate the thermochemical part of the prototype before integrating the expander. The hybrid cycle is then exploited. A first discharging phase was done in an open circuit electrical condition (at the generator), to validate the concept of the hybrid thermochemical cycle. Once validated, experiments with different electrical charges were done. The purpose of such electrical variations is to study the effect of the variation of the electrical charge on the behaviour of the expander and thus the whole performance of the cycle: cold production, mechanical power, and reaction kinetics.

2- Charging phase: reproducibility and kinetics

The first decomposition was done under the following operating conditions: the inlet temperature of the reactor heat transfer fluid was set at 180 °C and that of the condenser heat transfer fluid at 12 °C imposing a condensation pressure of 7 bars. This experiment was repeated twice under the same conditions for reproducibility tests. Then, the decomposition operating conditions were changed (by decreasing the reactor's inlet temperature) to analyse the evolution of the reaction kinetics at different deviations from the thermodynamic equilibrium conditions. Figure 8 presents the advancement of the reaction for these 6 decomposition phases. It is noteworthy that X equals 1 in the event of complete synthesis of the salt ( $MnCl_2.6NH_3$ ), and X equals 0 in the event of total decomposition of the salt ( $MnCl_2.2NH_3$ ).



*Figure 8- Evolution of the advancement of the decomposition reaction for different deviations from equilibrium* 



The first three decomposition reactions, carried out in the same conditions, leading to a temperature deviation from the equilibrium of the salt of 43 °C ( $\Delta T_{eq} = T_{htf,R,in} - T_{eq}(P_R)$ ), have identical evolution of the advancement demonstrating the reproducibility of the decomposition phase. For the three other decomposition reactions where the inlet temperature of the condenser heat transfer fluid remains at 12 °C and the deviation from the salt's equilibrium decreases to  $\Delta T_{eq,4} = 33$  °C,  $\Delta T_{eq,5} = 23$  °C and  $\Delta T_{eq,6} = 13$  °C: as expected, the reaction's rate becomes slower when the deviation from equilibrium decreases. For instance, at the time when the first three decompositions were finished (X  $\rightarrow$  0 i.e., at 350 min), the reaction's advancement was still at X = 0.1, X = 0.3 and X = 0.43 for the 4<sup>th</sup>, 5<sup>th</sup> and 6<sup>th</sup> reactions, respectively.

3- Discharging phase with an open circuit electrical generator

The heat transfer fluid inlet temperature at the evaporator is fixed at 10 °C, the reactor's temperature setpoint is 35 °C and the expander freely rotates with no electrical load. The reaction's advancement and cold production profiles of this experiment are shown in figure 9, and the expander's rotational speed, pressure ratio, and mechanical production are shown in figure 10.

Before the start of the synthesis phase, the solid reactant is kept at low temperature (35  $^{\circ}$ C) and therefore the pressure in the reactor is low. At the beginning of the synthesis phase (when the reactor is connected to the evaporator through the expander) the reactor sorbs a high flow of ammonia by maintaining a high-pressure difference with the evaporator which results in a peak of cold and mechanical power. Due to the exothermic synthesis reaction, the solid reactant rises in temperature and pressure, reducing the pressure difference across the expander and the sorbed ammonia flow rate is modulated so that the heat of reaction can be dissipated by the coolant. A change in the slope of the advancement and an increase in the cold production are noted after 50 minutes. The cold power production increased from 1.5 kW to 2.5 kW (as average values) and the saturation temperature of ammonia decreased to -5 °C. During the whole discharging phase, the expander is rotating and performing mechanical work (figure 10). In the first 50 mins, the expander rotates freely at 450 rpm producing around 4 W of mechanical work. After, the expander accelerates to around 800 rpm and produces around 10 W of mechanical power. This acceleration in the reaction that favours the production at the second period of the synthesis reaction is referred, as a first hypothesis, to a variable thermal exchange at the level of the reactor where the heat transfer fluid evacuates weakly – but increasingly – the heat of the synthesis reaction.



Figure 9- Cold power, cold temperature and advancement of the chemical reaction over time during the discharging phase





Figure 10- Expander's rotational speed, mechanical power and pressure ratio over time during the whole synthesis phase

4- Discharging phase experiments with fixed evaporating pressure and variable electrical charges

For these experiments, the evaporator's heat transfer fluid inlet temperature is fixed at 10 °C, and the reactor's setpoint is 35 °C. During the first experiment, the expander was blocked mechanically. An electrical resistor of 7  $\Omega$  is coupled to the electrical generator in the second experiment, 57  $\Omega$  in the third, 100  $\Omega$  in the fourth, and an infinity resistor (open circuit) in the fifth experiment. The advancement of the synthesis reaction for each experiment is plotted in figure 11. An inflection point in the curves of advancement is noted where the slope of the advancement profiles increases after 50 minutes. Behind this inflection point, all the advancement curves are bounded by the curves of the blocked and the open circuit conditions, where the faster advancement corresponds to an open circuit condition and the lowest to a blocked expander. This acceleration appears also in the production of cold at the level of the evaporator, where the similar profiles of cold production increase from 1.5 kW to 2.5 kW as shown in figure 12, and no significant effect of the electrical charge is shown by these experiments on the cold production for a maximum difference of 0.5 kW between the boundaries of the cold powers.



At the level of the expander, during the second period of the discharging phase, the volumetric flowrate of ammonia scores the highest value of  $V_5 = 2.75 \text{ m}^3/\text{hr}$  for the experiment done in open circuit electrical conditions at the generator (figure 13). While the resistance value



decreases, the volumetric flowrate decreases where a maximum of 2.5, 2.3, 2.25 m<sup>3</sup>/hr are achieved for experiments with electrical resistance of 100, 57 and 7  $\Omega$  respectively. The blocked expander experiment achieved a maximum of 1.8 m<sup>3</sup>/hr during the second period of the discharging phase. This high-volume flow rate of ammonia that circulates in the expander when it is blocked reveals a strong internal leakage flow in the expander which limits significantly the performance of the latter in the operating conditions of these experiments (low speed of rotation compared to the nominal). Beside the volumetric flowrate results, the pressure ratio at the expander's extremities is also evaluated by the change in electrical resistance at the generator's level. The minimum pressure ratio  $T_p$  is obtained in experiment 5 where the generator is in an open circuit condition. Decreasing the value of the electrical resistance results in higher pressure ratios as shown in figure 14. For instance,  $T_p$  increases from 1.25 to 1.3, 1.35, and 1.6 – as maximum values – while decreasing the resistance value from infinity to 100, 57, and 7  $\Omega$  respectively. Similarly,  $T_p$  increases to 1.8 when the expander is blocked. This weak pressure difference at the extremities of the expander results from the mass coupling between the expander and the reactor as already discussed in the part 2 of this document.



Furthermore, the dynamic rotational speed and the torque force are also affected by the variation of the electrical resistance. While the expander was freely rotating (open circuit conditions), the rotational speed  $\boldsymbol{\omega}$  reached a maximum of 800 tr/min. Once decreasing the electrical charge to 100, 57 and 7  $\Omega$ , the maximum rotational speed decreases to 600, 500 and 300 tr/min respectively, and the blocked expander has no rotation. Contrary, the maximum torque force **T** in the same period of the reaction is at its maximum of 1.2 N.m for a blocked expander and decreases to 0.6, 0.3, 0.2 and 0.1 N.m when increasing the electrical resistance to 7  $\Omega$ , 57  $\Omega$ , 100  $\Omega$  and infinity. These evolutions of the torque forces and rotational speeds at the expander, which vary inversely while changing the electrical resistance, affect the production of mechanical work and thus the expander's efficiency ( $\eta_{exp}$ ) – obtained between 0.15 and 0.2 – that are calculated as follows:

$$\dot{W}_{mec} = \frac{2\pi.\,\boldsymbol{\omega}.\,\mathbf{T}}{60}$$



$$\eta_{exp} = \frac{\dot{W}_{mec}}{\dot{m}_g. \left(h_{ex}^{in} - h_{ex}^{out,is}\right)}$$

where,  $\dot{W}_{mec}$  is the mechanical power of the expander in W,  $\boldsymbol{\omega}$  is the rotational speed in tr/min, **T** is the torque force in N.m,  $\eta_{exp}$  is the efficiency of the expander,  $\dot{m}_g$  is the mass flowrate of ammonia in kg/s,  $h_{ex}^{in}$  and  $h_{ex}^{out,is}$  are the inlet enthalpy and outlet isentropic enthalpy at the extremities of the expander respectively in J/kg.



During these experiments, the effects of the electrical resistances are shown on the behaviour of the expander. These effects on the operating conditions of the expander are summarized in table 1. The analysis of these results shows a concave evolution of the maximum mechanical power with the evolution of the electrical resistance. An optimum is obtained for these experiments with a load between 57 Ohm and the blocked expander.

Experiment	Electrical resistance (Ω)	<b>ω</b> <sub>max</sub> (rev/min)	T <sub>max</sub> (N.m)	Ŵ <sub>max</sub> (W)
1	-	0	1.2	0
2	7	350	0.6	22
3	57	500	0.3	16
4	100	600	0.25	15
5	00	800	0.1	10

Table 1- Maximum rotational speed, torques and mechanical power of the expander for different electrical resistances

#### Conclusions

A hybrid thermochemical concept to valorise low or mid-grade heat in cold and mechanical power is analysed numerically and developed experimentally. A prototype involving MnCl<sub>2</sub>NH<sub>3</sub>(6/2) ammoniated salts and a 1 kWe scroll expander was mounted. First, the reproducibility and kinetics of the cycles were checked for several operating conditions of the reactor. In a second step, the hybrid process with the expander was exploited. A first cycle was done with no electrical charges at the generator's level to validate the concept of the integration of an expander in a thermochemical process. Other experiments were followed where the evaporating conditions were fixed and the electrical resistance at the generator was varied. These experiments showed the effect of the electrical charge on the performance of the expander: by the increase of the electrical charge (electrical potential difference at the generator), the expander rotates faster with lower coupled torque forces applied by the generator. These variations in the behaviour of the expander with the generator affected the mechanical power production and the efficiency of the expander. A presence of an important internal leakage in the expander is observed, reducing the performance of that latter. Furthermore, the synthesis reaction has shown an acceleration, which could be attributed to a possible hypothesis that suggests a weak and gradually improving heat evacuation performance at the reactor level.

More experiments are in progress to better understand the coupling between the elements of the hybrid thermochemical cycle. Several experimental protocols are to be done, such as fixing the electrical resistance at the generator and varying the evaporating pressure to analyse the behaviour of the expander in such conditions. The numerical dynamic model of the cycle is set to be validated with the experimental results to head finally towards sensibility studies, energetic and exergetic studies and analysis of the components irreversibilities, along with a global performance optimization of the cycle.

#### Acknowledgments

This work has been financially supported by the French National Research Agency (ANR) for the purpose of the ThermHyVal project under contract ANR-20-CE05-0036 (https://anr.fr/Projet-ANR-20-CE05-0036) and by a prematuration program of the French National Centre for Scientific Research (CNRS).

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