



# Hybrid thermochemical cycle for cold and electricity cogeneration: experimental analysis of the process behavior and expander-reactor coupling

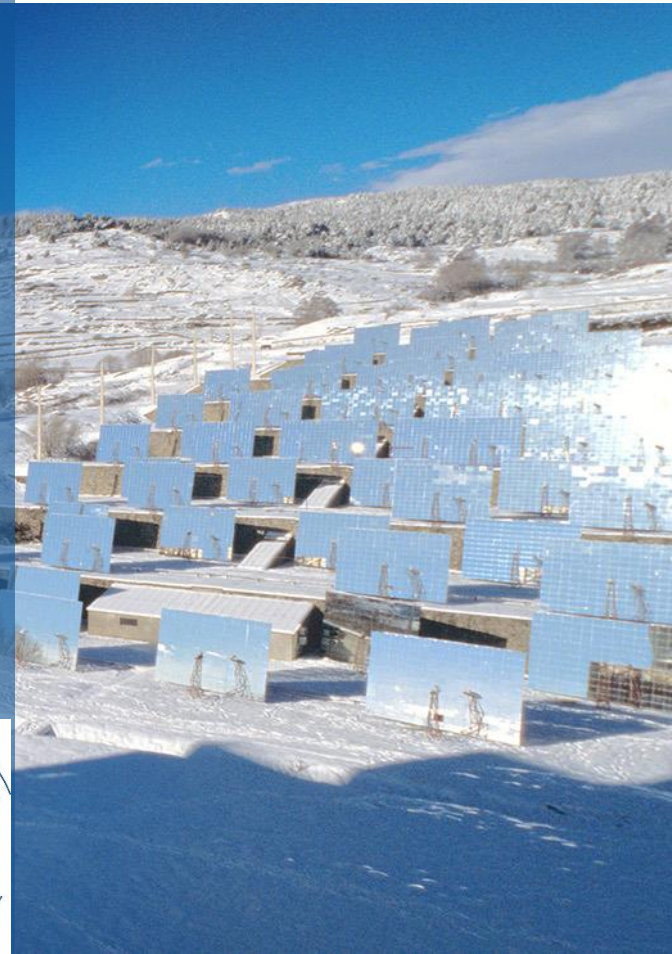


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*ThermHyVal project*

**36<sup>th</sup> International Conference on  
Efficiency, Cost, Optimization,  
Simulation and Environmental impact of  
energy systems.**

**LAS PALMAS DE GRAN CANARIA - SPAIN**  
Laboratoire PROcedes, Matériaux et Energie Solaire



# Table of contents

1. Introduction
2. Hybrid thermochemical process: concept and functionality
3. Experimental prototype: concept validation
4. Results & coupling analysis in different operating conditions
5. Numerical modeling
6. Conclusion



# Introduction

*Waste heat – Recovery technologies*



# Recovery technologies



Heat waste availability

- Experiencing a growth
- At low ( $< 100\text{ }^{\circ}\text{C}$ ), medium ( $< 600\text{ }^{\circ}\text{C}$ ) and high ( $> 600\text{ }^{\circ}\text{C}$ ) temperature
- Environmental damage contribution

Heat to heat / cold

- Recuperators
- Regenerators
- Absorption refrigeration systems...

Heat to electricity

- Organic Rankine Cycle
- Kalina cycle
- Thermoelectric generators

# Recovery technologies



Heat waste availability

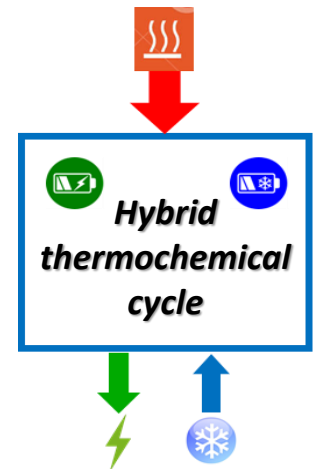
Heat to heat / cold

- Recuperators
- Regenerators
- Absorption refrigeration systems...


Heat to electricity

- Organic Rankine Cycle
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As the industrial sector could operate in an intermittent behavior, processes involving the recovery and storage of heat waste to meet energy demands attract attention.



→ Hybrid thermochemical process: recovery – storage – production



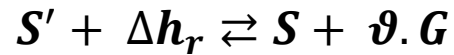
# Thermochemical cycles

*Hybrid concept – functionality*



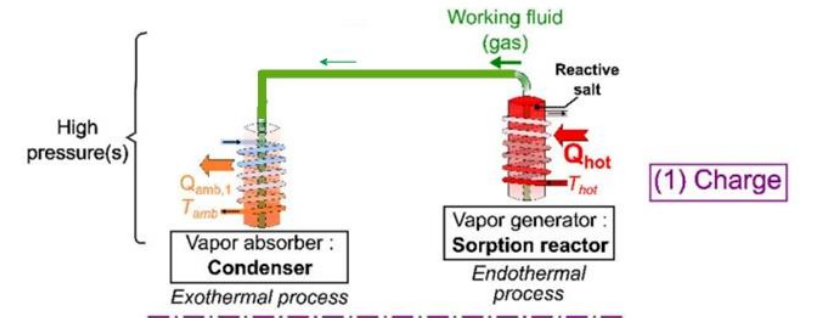
# Hybrid thermochemical cycle

- Based on a reversible chemical reaction: decomposition & synthesis phases.

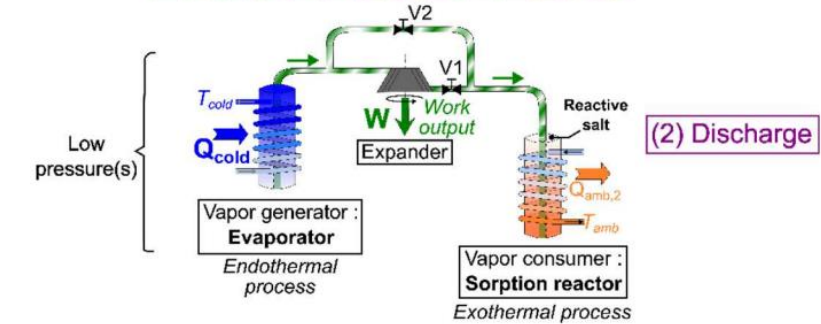


- The hybrid thermochemical process aims to:
  - Recover heat at low and medium temperatures (< 250 °C)
  - Offer a storage at ambient conditions
  - Valorize the heat into cold
  - Valorize the mass (enthalpy) flow of gas into mechanical work
- Ammoniated salts, especially chlorides, are known solids that undergo thermochemical processes, since they are:
  - Stable with interesting thermodynamic properties
  - Abundant variety
  - Mono-variant equilibrium (P-T):

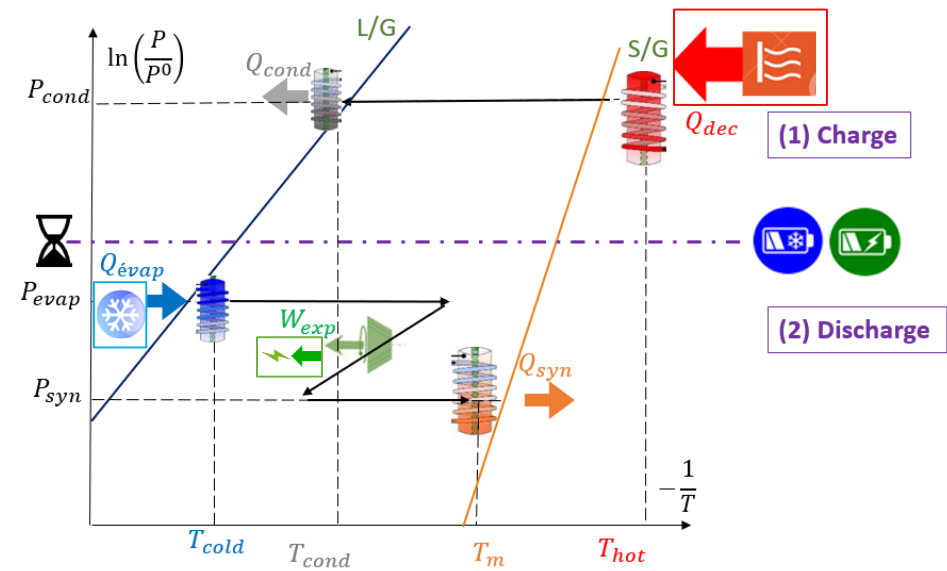
$$\ln\left(\frac{P}{P^0}\right) = -\frac{\Delta h_r}{RT} + \frac{\Delta s_r}{R}$$



(1) Charge



(2) Discharge



(1) Charge

(2) Discharge



# Concept validation

*Developed prototype – Experimental proof of concept*





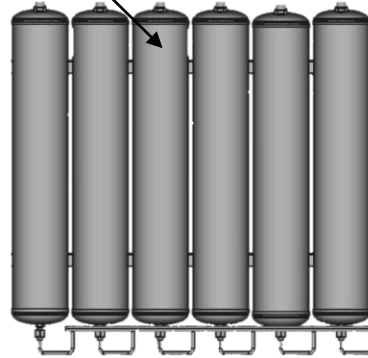
# Experimental prototype



**Liquid ammonia storage tank**  
 $V_{\text{tank}} = 36 \text{ l}$

**Plate condenser**

$A_{\text{cond}} = 0.276 \text{ m}^2$   
 HTF : water  
 $(15^\circ\text{C} \leq T_{\text{HTF}} \leq 30^\circ\text{C})$

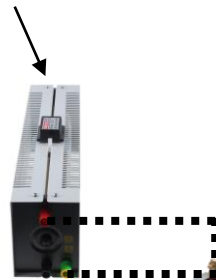


**Reactor**  
 $V_{\text{react}} \approx 0.15 \text{ m}^3$   
 HTF : mineral oil  
 $(40^\circ\text{C} \leq T_{\text{HTF}} \leq 180^\circ\text{C})$



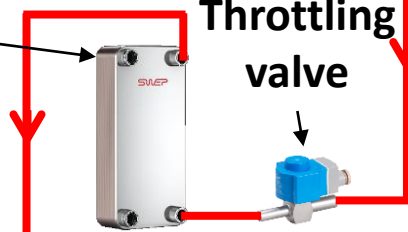
**Baffles**

**Electrical rheostat**  
 $0 \leq R_{\text{elec}} \leq 100 \text{ Ohm}$



**Plate evaporator**  
 $A_{\text{evap}} = 0.414 \text{ m}^2$   
 HTF : glycolic water  
 $(-10^\circ\text{C} \leq T_{\text{cold}} \leq 25^\circ\text{C})$

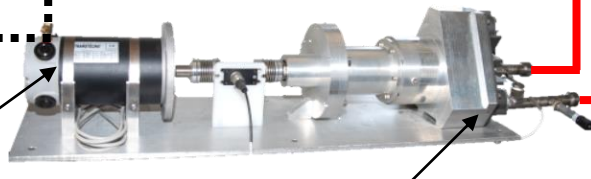
**Throttling valve**



**Reactor tubes**

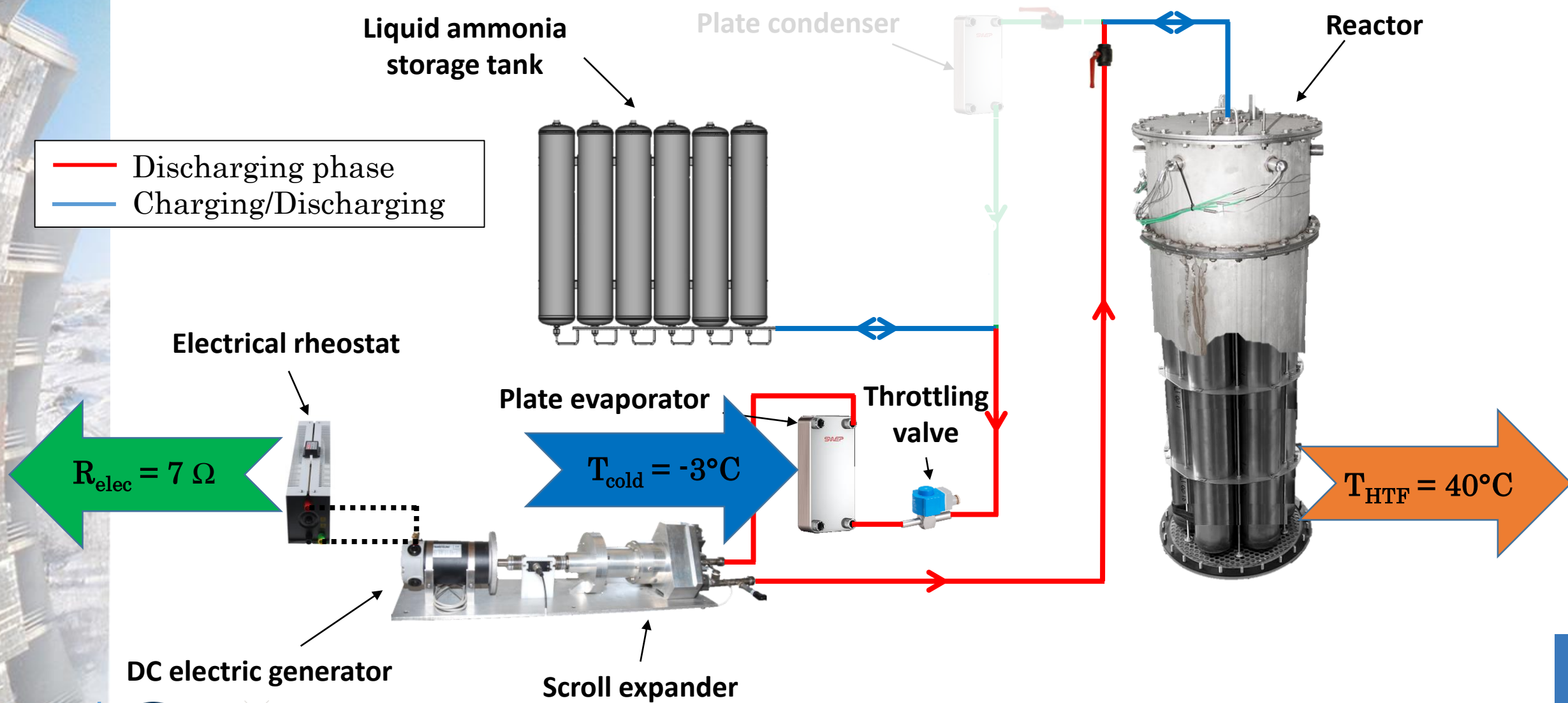
$D_{\text{ext}} = 0.114 \text{ m} ; L = 1 \text{ m}$   
 Reactants :  $\text{MnCl}_2(2/6)\text{NH}_3$   
 29 kg of  $\text{MnCl}_2$   
 23.45 kg of  $\text{NH}_3$  (cycled)

**DC electric generator**

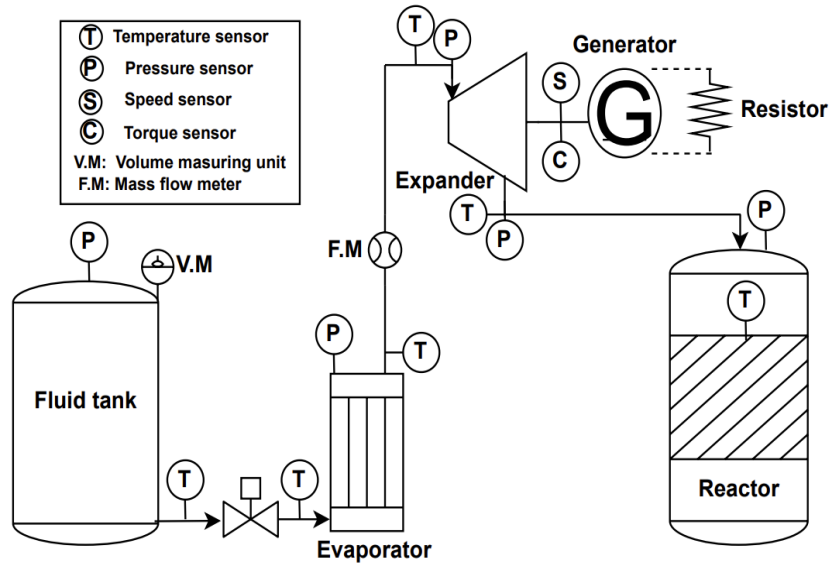


**Scroll expander**  
 $\dot{W}_{\text{nom}} = 1 \text{ kW}_{\text{mec}}$   
 $\omega_{\text{nom}} = 3600 \text{ rpm}$

# Nominal experimental operating parameters



# Proof of concept

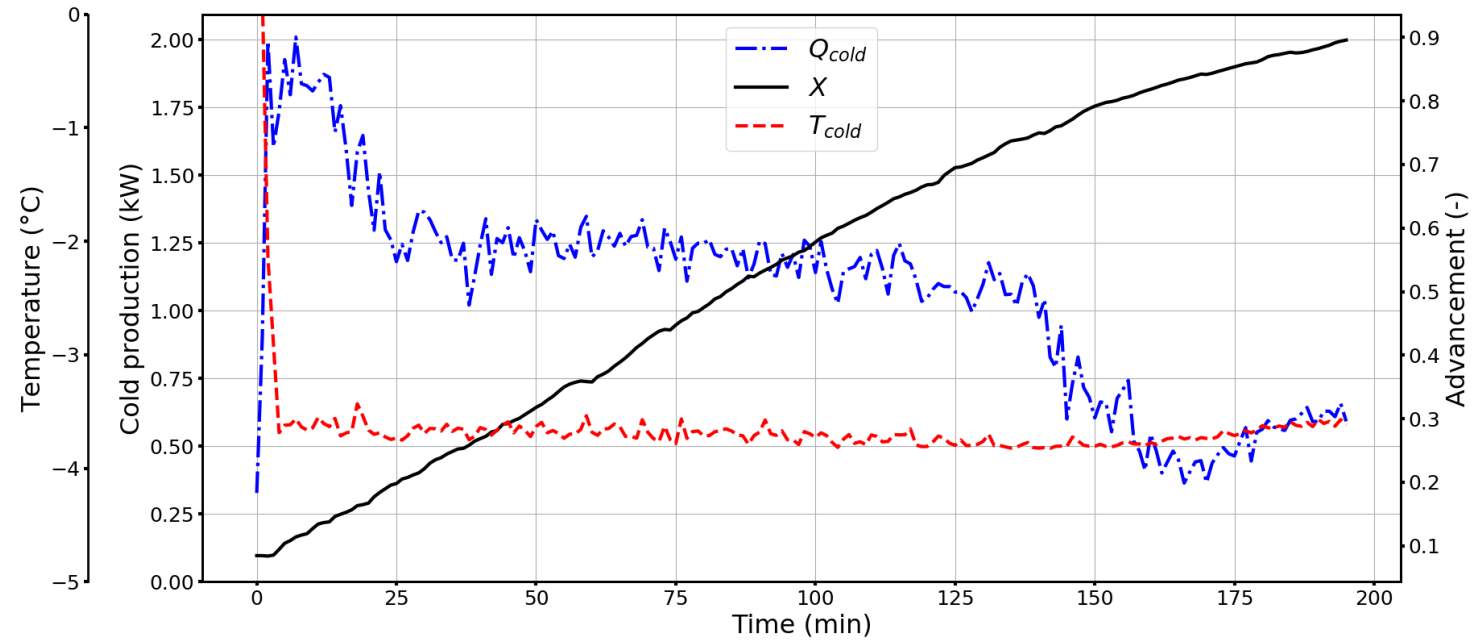


Cold production power of 1.25 kW at -3 °C during the synthesis reaction

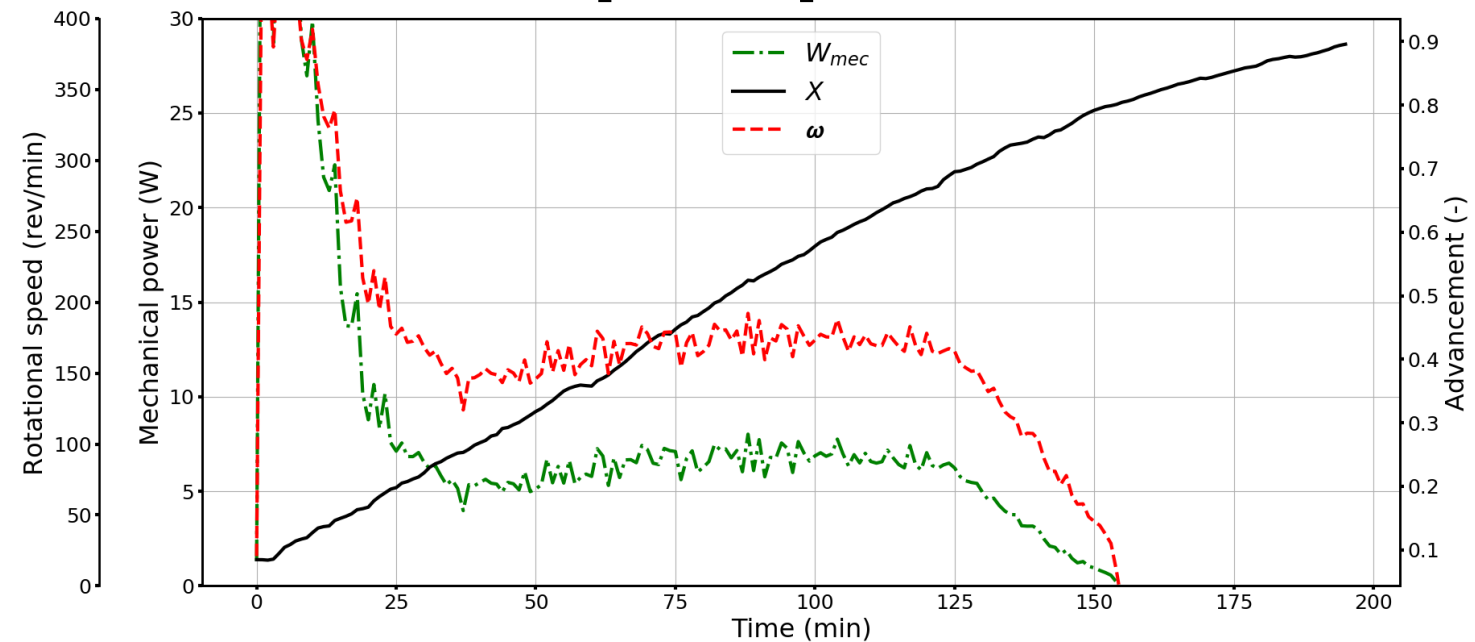
<< Hybrid concept validation >>

Continuous production of the expander, 8 W mechanical power at 200 rpm

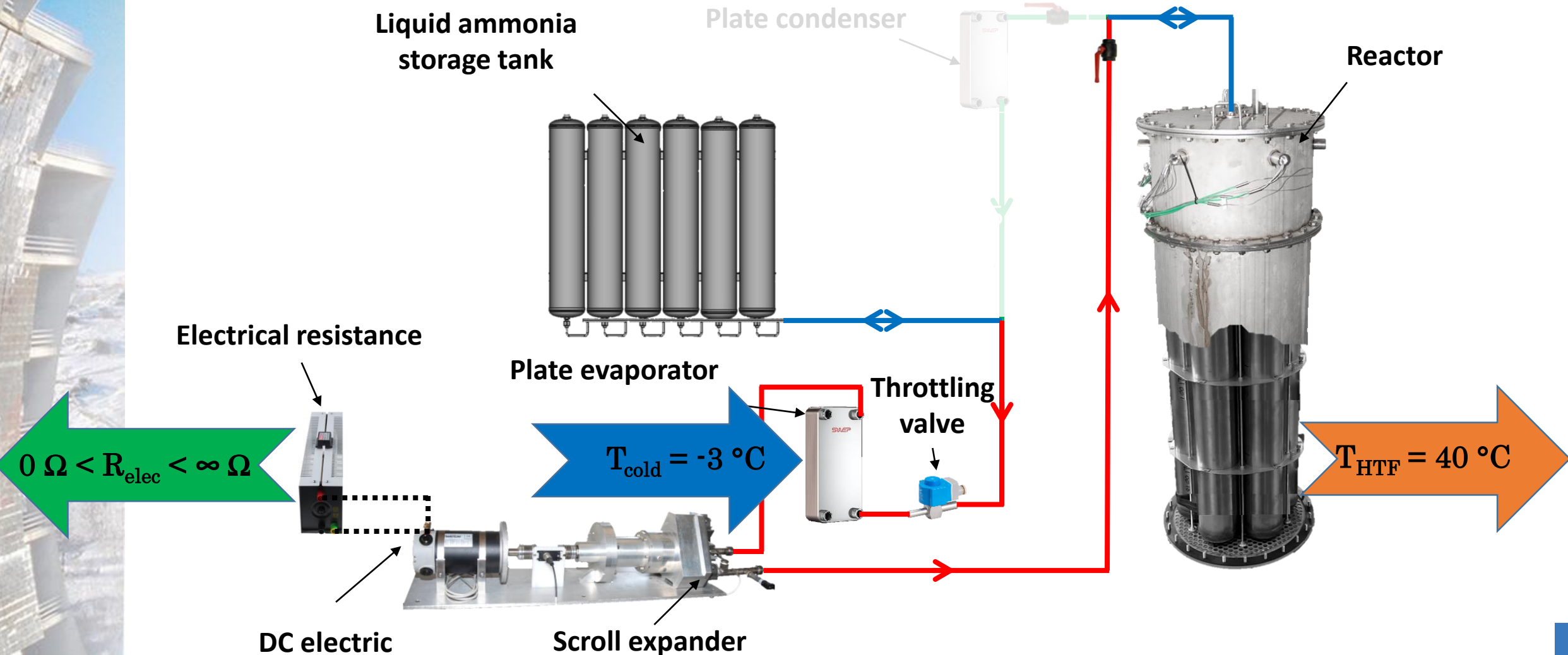
## Evaporator's production



## Expander's production

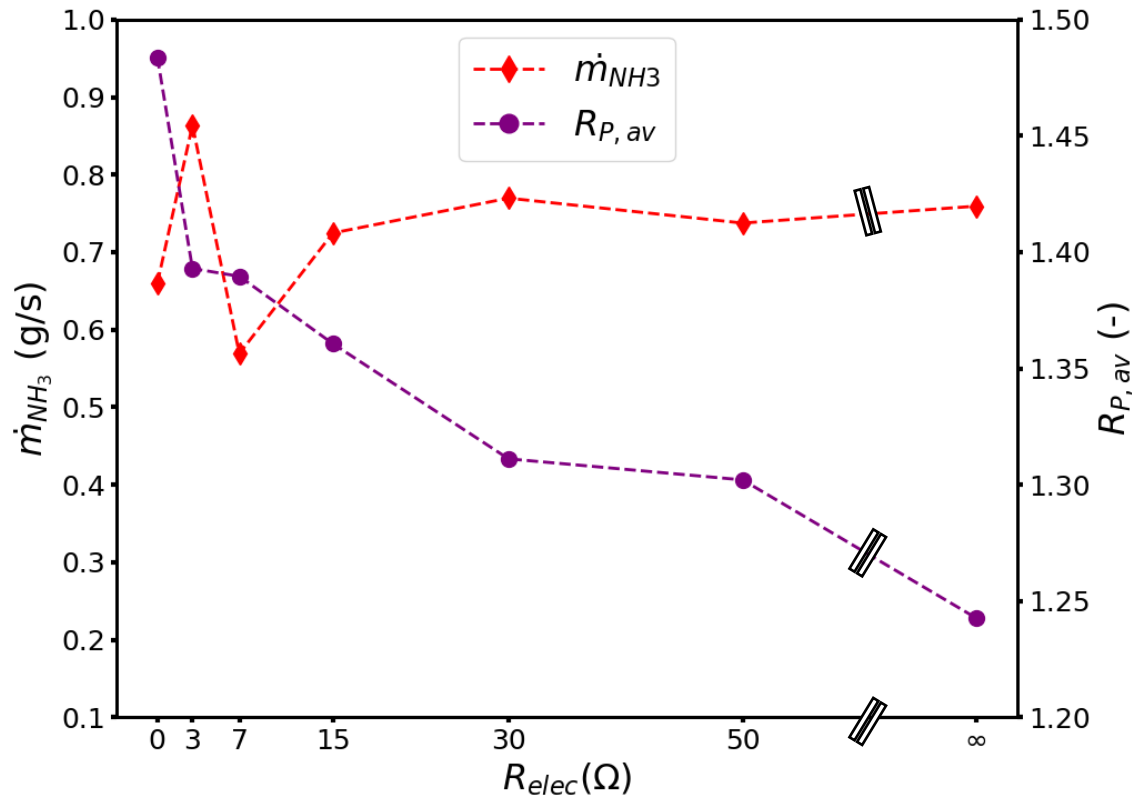


# Sensitivity to electrical charge



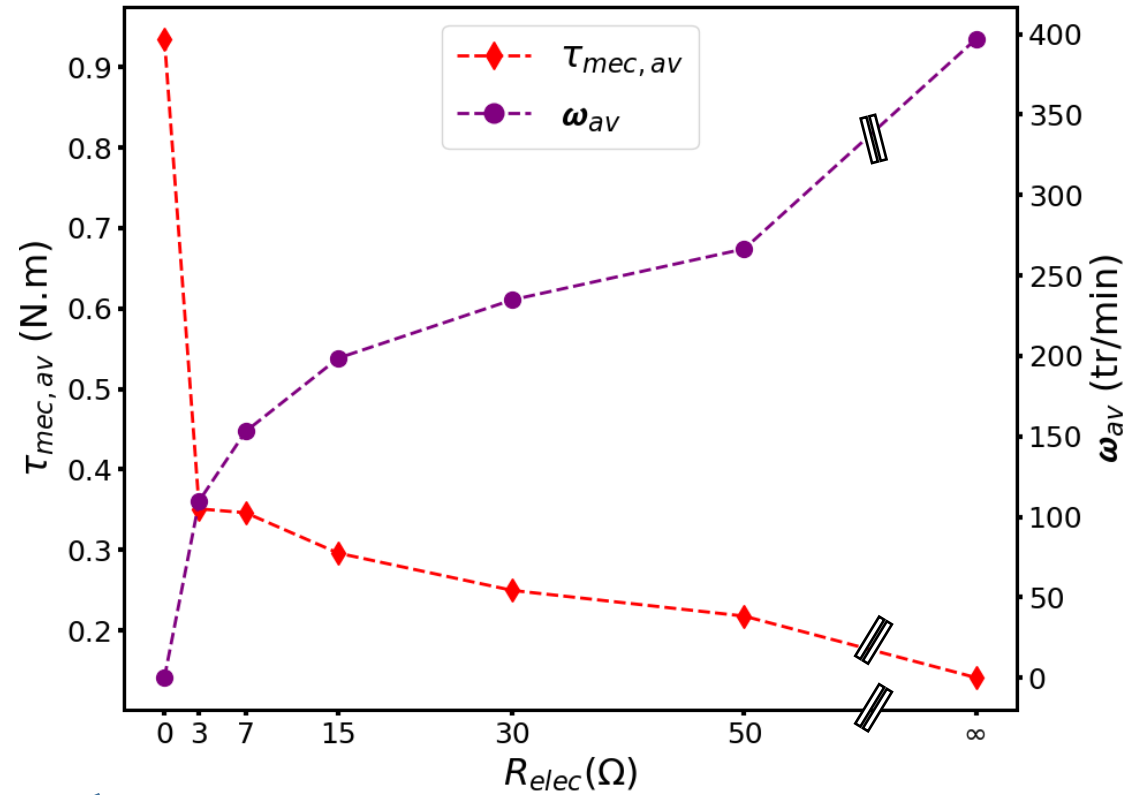
*Average treatment of results (0.2 < X < 0.8)*

# Results – with the increase of $R_{elec}$



No clear difference in the measured mass flow rate of  $NH_3$

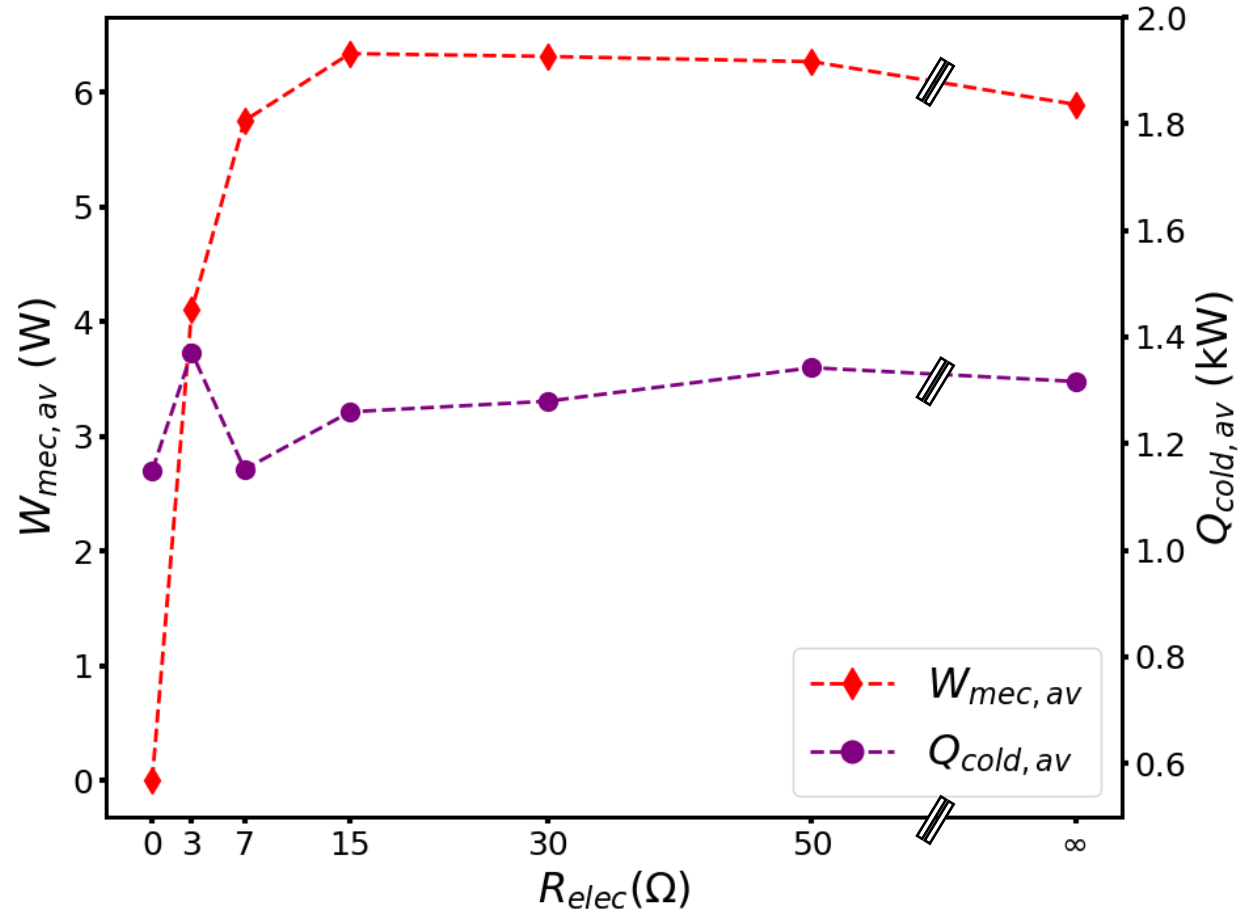
Decrease in the pressure ratio  $R_p$



Increase in the rotational speed (expander)

Decrease in the torque force (expander)

# Results – with the increase of $R_{elec}$

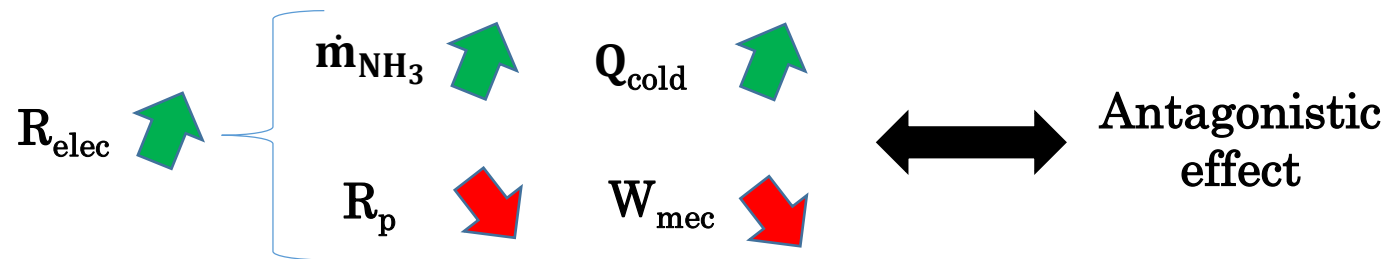
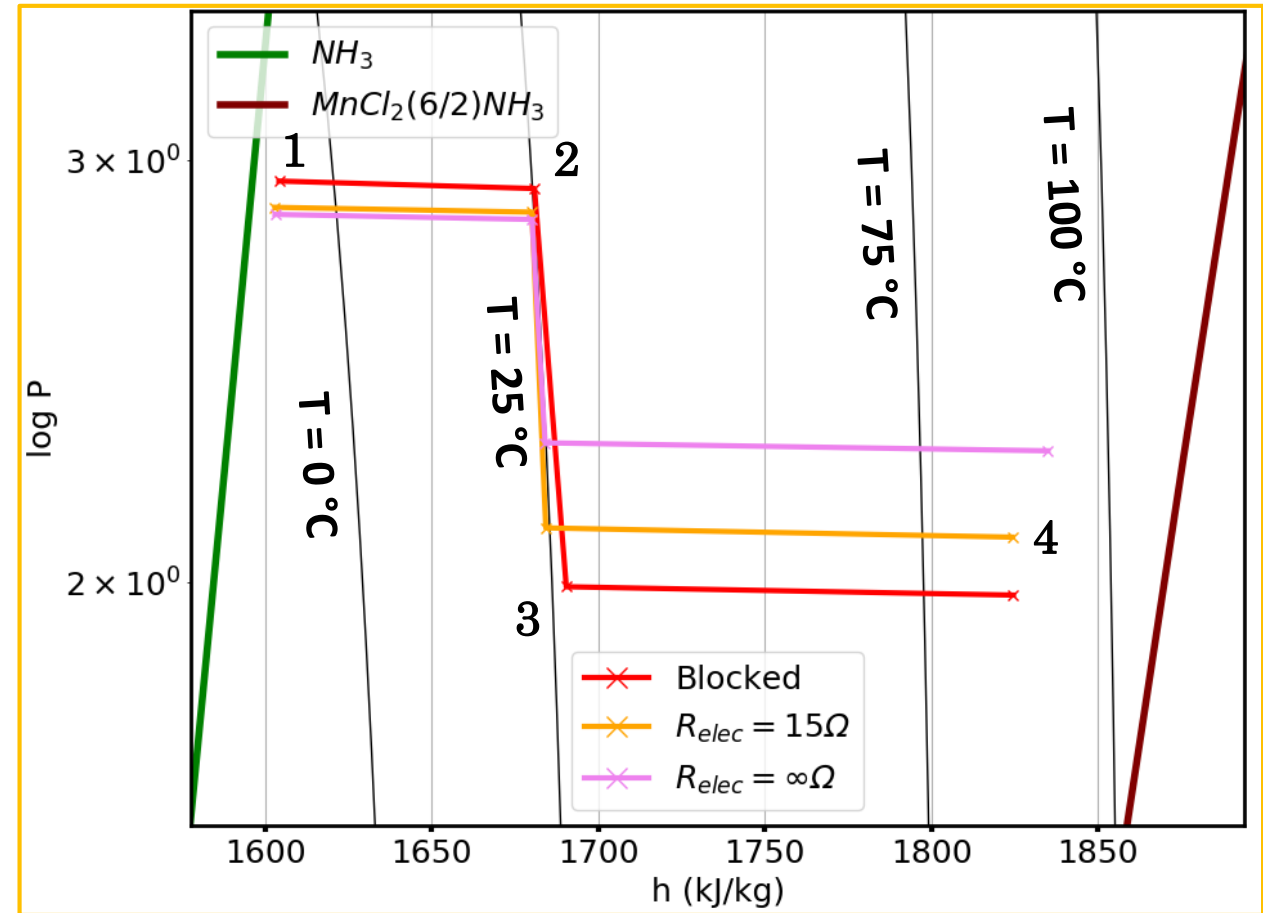
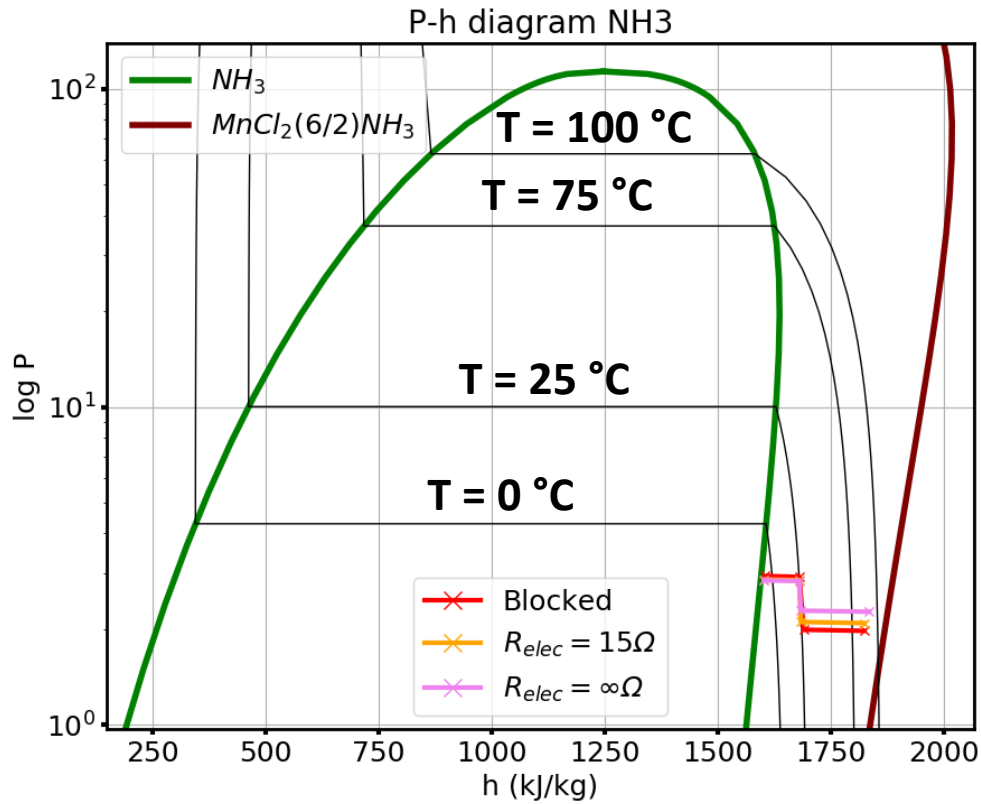


No significant effect of the electrical charge on the cold power.

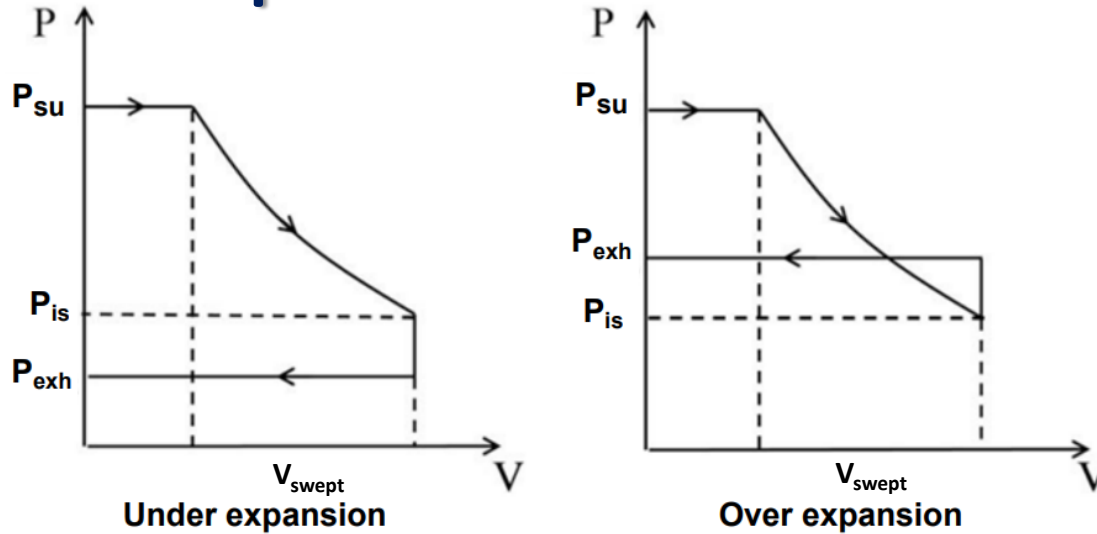
An optimum in the mechanical power of 6.4 W of the expander is noticed at 15 ohm.

# Coupling analysis

1: Evaporator / 2: Expander inlet  
3: Expander outlet / 4: Reactor



# Expander's performance



For an isentropic expansion, with a volumetric ratio  $R_v = 3.5$

$$\left(\frac{P_{is}}{P_{su}}\right)^{\frac{1}{\gamma}} = \frac{1}{R_v}$$


$$\eta_v = \frac{\dot{m}_{swept}}{\dot{m}_{meas}} = \frac{\rho * \omega * V_{swept}}{\dot{m}_{meas}}$$

$R_{elec} = 0 \Omega$		$R_{elec} = 15 \Omega$		$R_{elec} = \text{inf } \Omega$	
$P_{exh} = 1.98$ bar	$P_{is} = 0.3$ bar	$P_{exh} = 2.08$ bar	$P_{is} = 0.3$ bar	$P_{exh} = 2.26$ bar	$P_{is} = 0.3$ bar

Maximum  $R_p$  ←————→ Minimum  $R_p$

- An over expansion performance in the expander
- Weak volumetric efficiency of the expander, around  $\eta_v = 15 \%$
- The reactor's cooling is an important coupling key performance





# Numerical analysis of the coupling

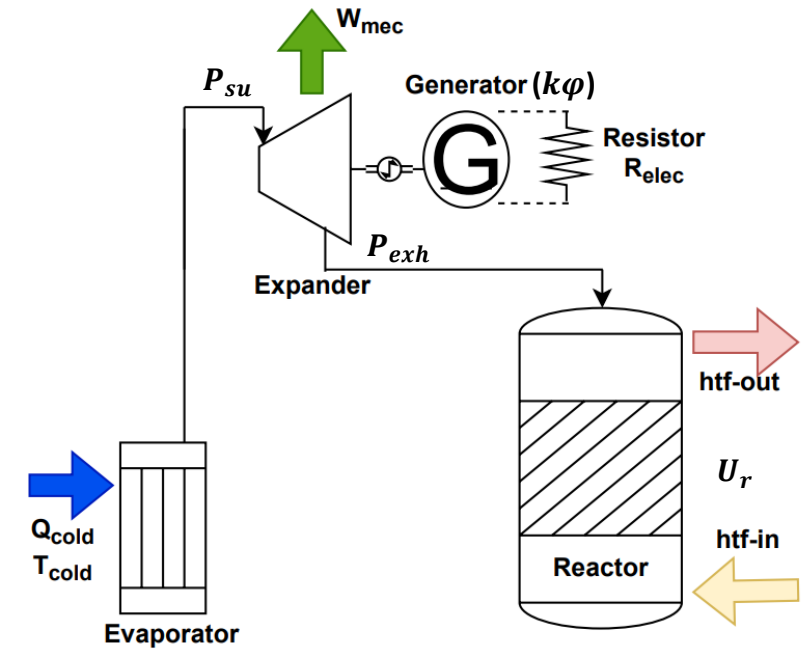
Evaporator – Expander – Generator – Reactor



# Coupling equations

## Hypotheses:

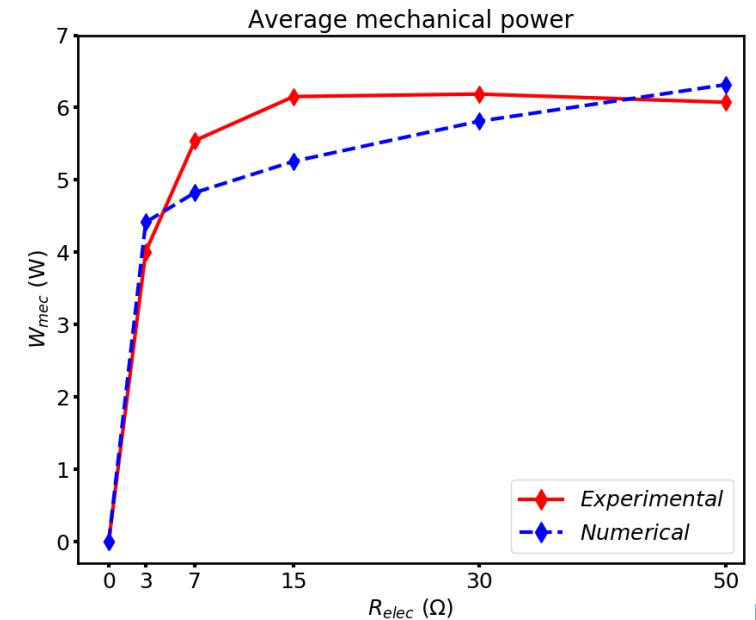
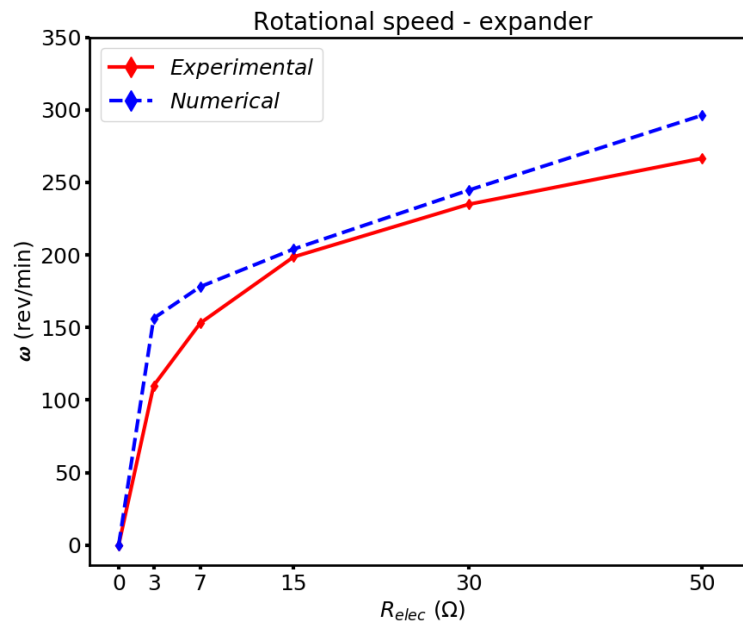
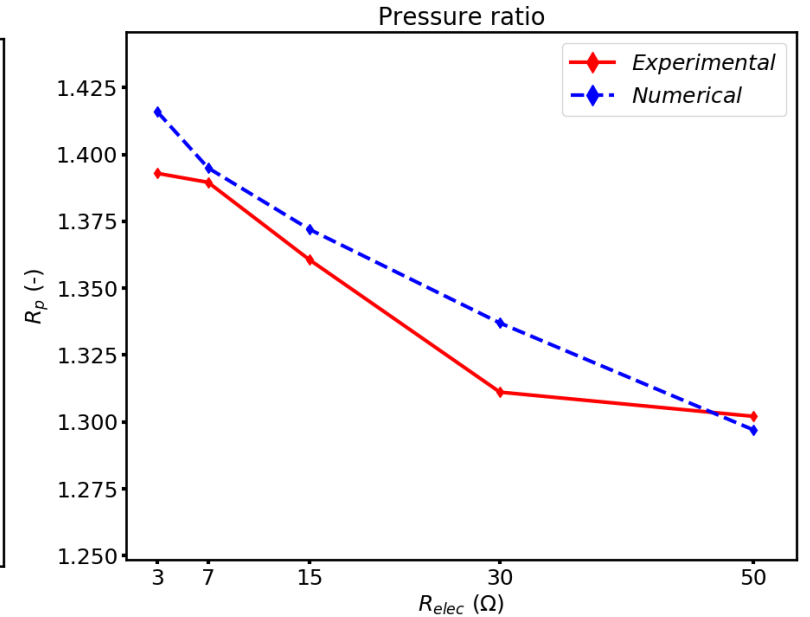
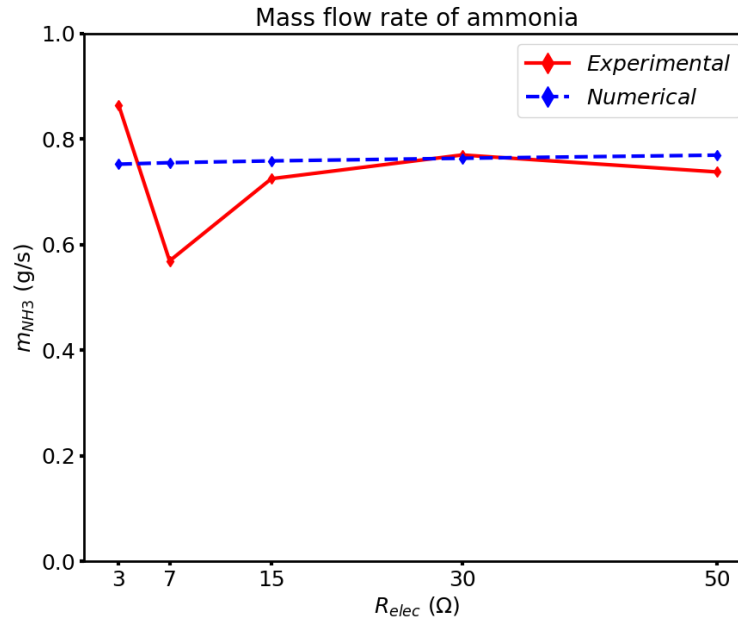
- Steady state
- Reaction's advancement: 50%
- Homogeneous temperature & pressure in the reactor
  - Constant isentropic efficiency of the expander
  - Constant adiabatic expansion coefficient



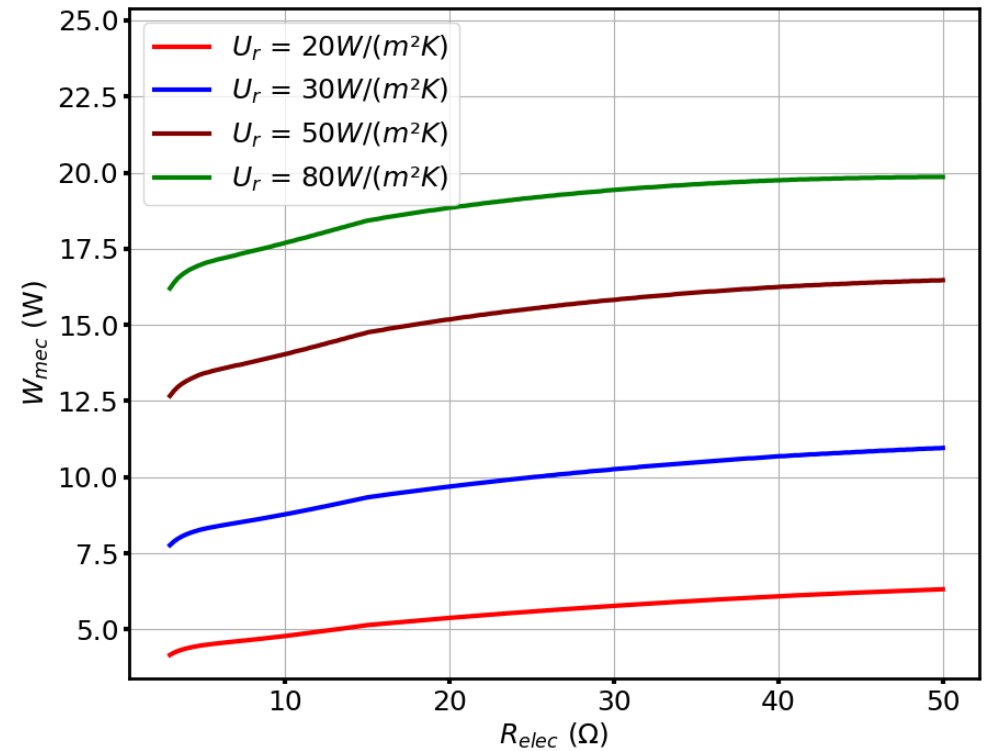
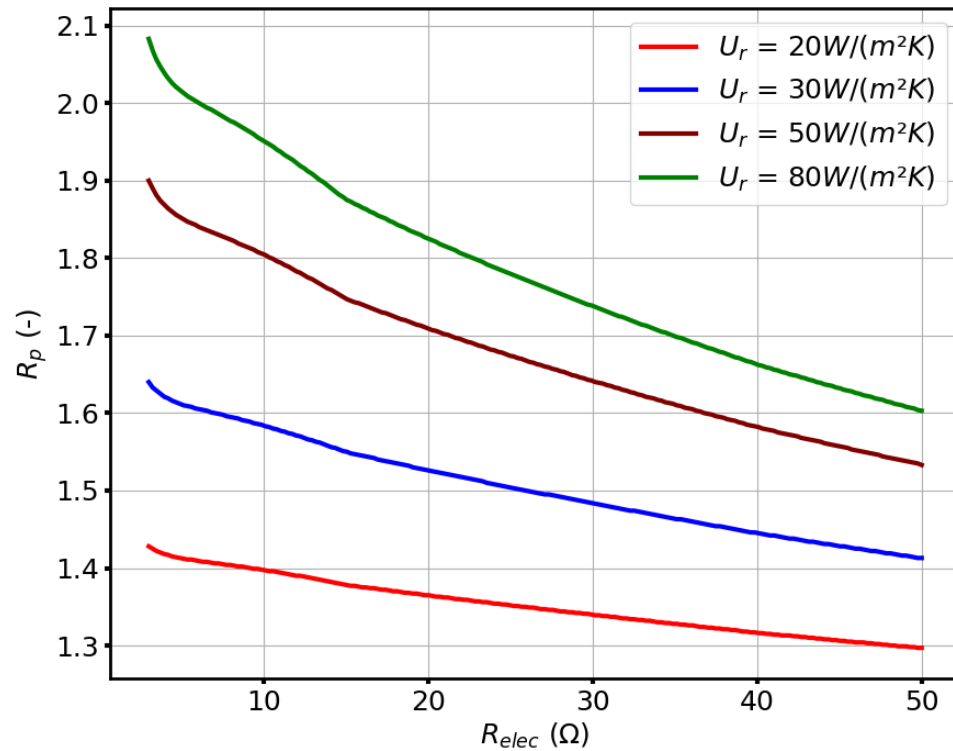
Variables	Equations
Supply pressure	$P_{su} = P_{sat}(T_{cold})$
Exhaust pressure	$P_{exh} = f_1(T_{htf,r}^{in}, \dot{m}_g, U_r)$
Mechanical power	$W_{mec} = f_2(\dot{m}_g, P_{su}, P_{exh})$
Rotational speed	$\omega = f_3(W_{mec}, k\varphi, R_{elec})$
Torque force	$\tau_{mec} = f_4(W_{mec}, k\varphi, R_{elec})$

# Numerical results validation

Identified parameters	Value
$K_{cin}$	<b>0,00015</b> (s <sup>-1</sup> )
$U_r$	<b>20</b> (W/m <sup>2</sup> K)
$T_{cold}$	<b>-3°C</b>
$T_{htf,r}^{in}$	<b>40°C</b>
$k\phi$	$f(R_{elec})$
$K_{leak}$	<b>1,11 * 10<sup>-6</sup></b> m <sup>3</sup> /s.Pa <sup>0,5</sup>



# Numerical parametric analysis



- The increase in  $U_r$  leads to:
- Higher pressure ratio at the expander
  - Higher mechanical power

# Conclusion



# Conclusion

- The concept of hybridization of thermochemical cycles is proved experimentally.
- The cycle's behavior is analyzed in different operating conditions: sensitivity to electrical charge.
- The variation of  $R_{elec}$ , fixing  $T_{cold}$ , shows an optimum in the mechanical production.
- An important internal leakage in the expander is detected, where the reached volumetric efficiency is about 15%.
- A steady state numerical model is developed. Validations with the experimental results lead to parametric analysis of the coupling.
- A better heat transfer coefficient at the reactor's level enhances the mechanical production.



***Thanks for your  
attention***



***Questions ?***

