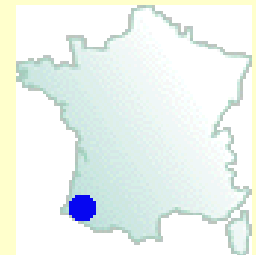


Numerical parametric study for different cold storage designs and strategies of a solar driven thermoacoustic cooler system

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Presentation plan

- Context
- Prototype description
- model
- Simulation conditions
- Results and discussions
- Conclusions and perspectives


World refrigeration context

- The major part of the refrigeration production is provided by electrically driven vapor compression machines
- 15% of the world electricity production is consumed for refrigeration
- Increase in the number of units in operation over the coming years

To ensure the refrigerating production while responding to environmental challenges, the future cooling machines

- should not be primary energy intensive
- should use environmentally friendly refrigerants

TACSOL ANR project

Numerous possible combinations between solar thermal collectors and heat driven cooling machines 
Solar cooling equipment seems to be an interesting alternative

The coupling of a solar concentrator with a heat driven thermoacoustic refrigerator is a promising technology :

- no moving part
- environmentally friendly gas as working fluid

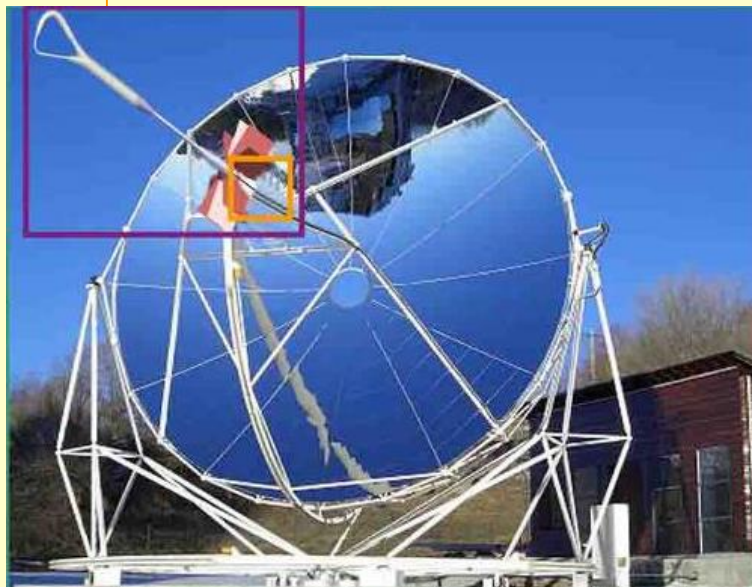
→ TACSOL project



Design and study of a solar driven thermoacoustic refrigerator
Modelling – Simulation – Experimental test

Prototype description

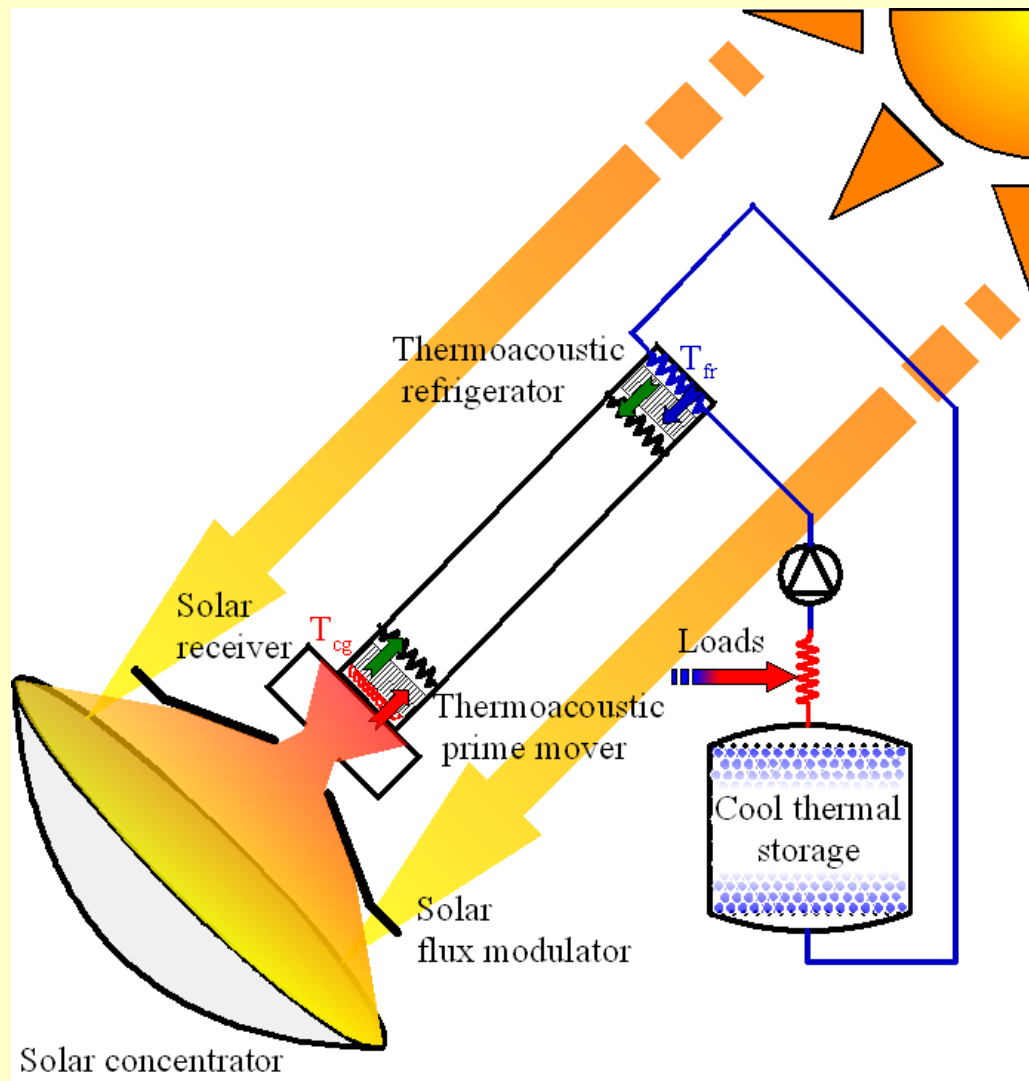
1 kW scale solar thermodriven thermoacoustic refrigerator



solar dish concentrator

$$A_{\text{useful apert conc}} = 10 \text{ m}^2$$

$$P_{\text{frigo max}} \approx 1 \text{ kW}$$



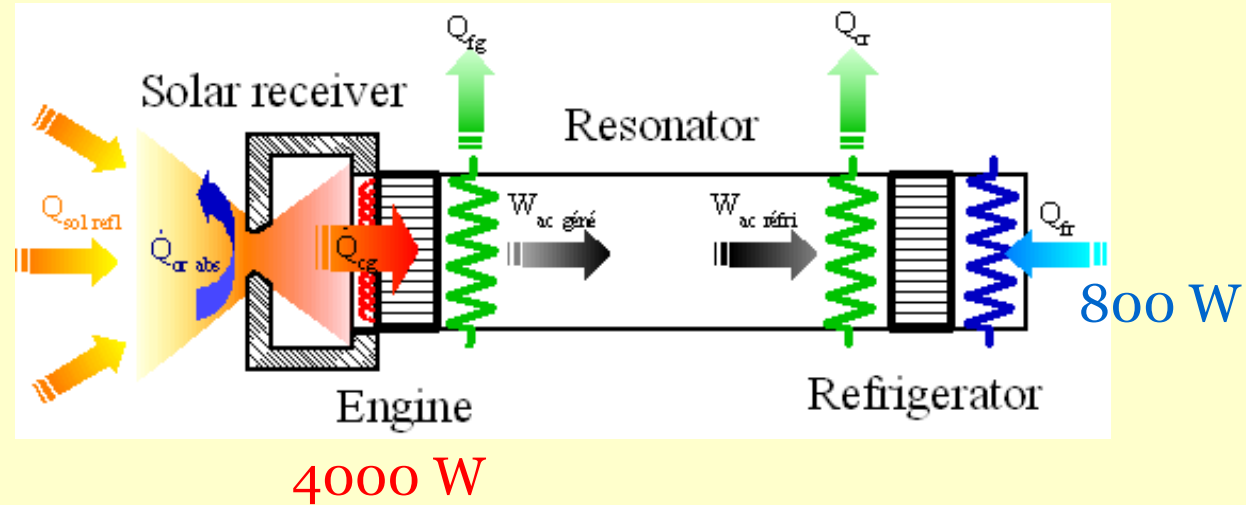
Thermoacoustic machine

- Tri-thermal machine:

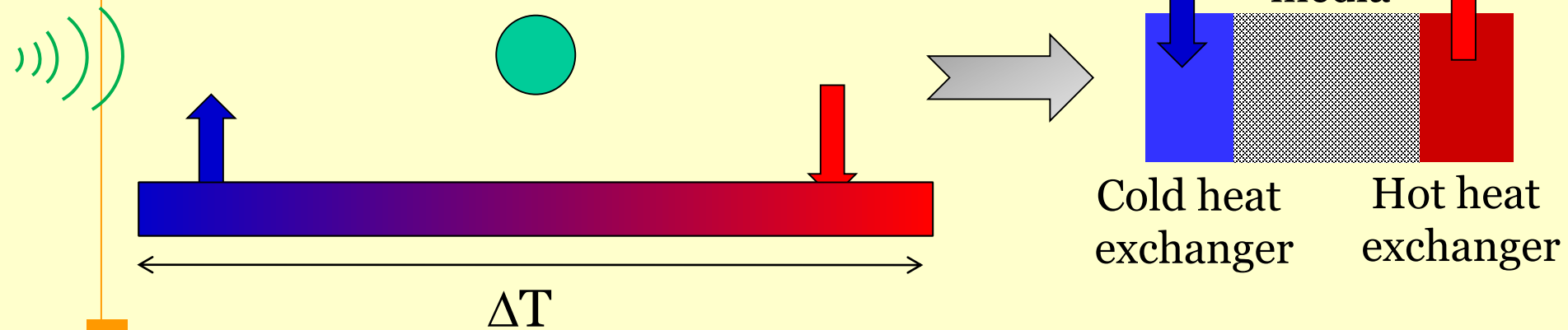
$$T_{cg} \approx 500 \text{ }^{\circ}\text{C}$$

$$T_{\text{medium}} \approx 20 / 35 \text{ }^{\circ}\text{C}$$

$$T_{fr} \approx -20 / -30 \text{ }^{\circ}\text{C}$$



- Thermoacoustic effect in the refrigerator:
(sound waves are pressure waves)



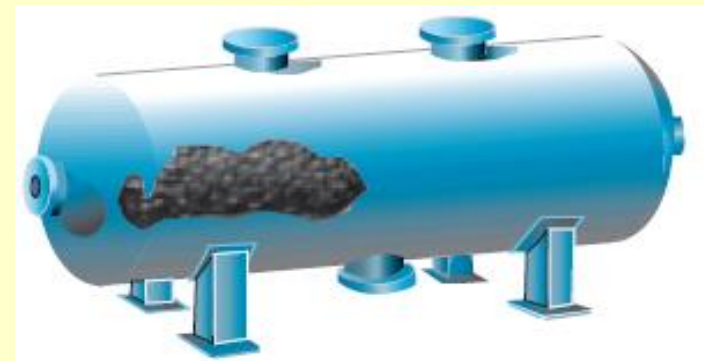
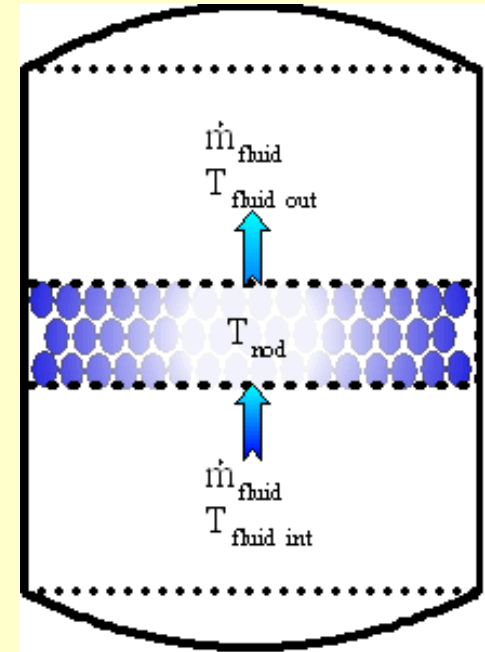
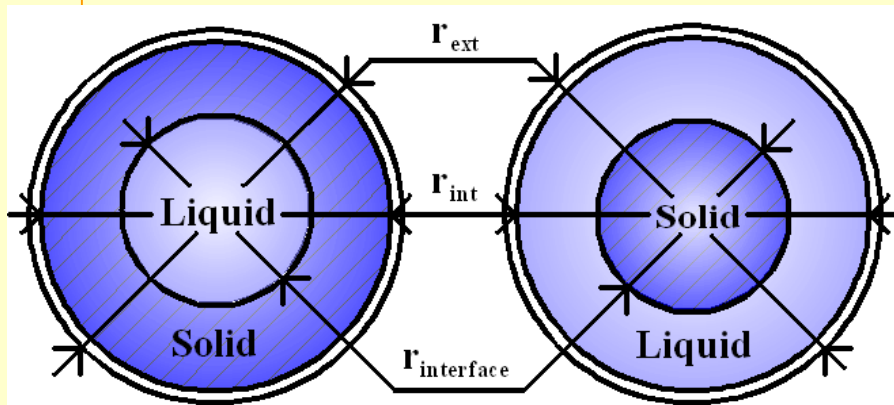
Cold energy storage

Technology: Encapsulated PCM

PCM: eutectic solution of H₂O-NaCl

$T_{\text{melt}} = -21,3 \text{ } ^\circ\text{C}$

Tank volume = 0,2 m³



Collected solar flux:

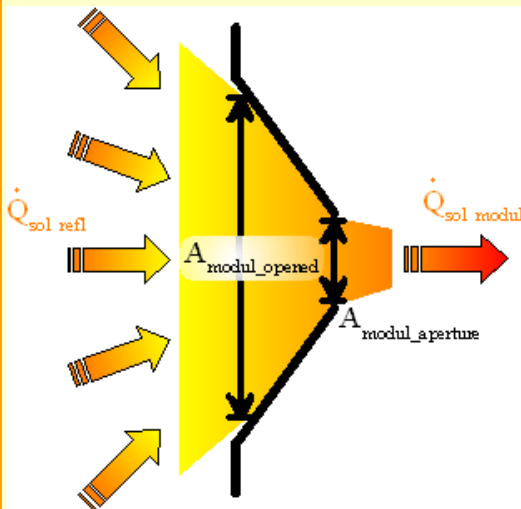
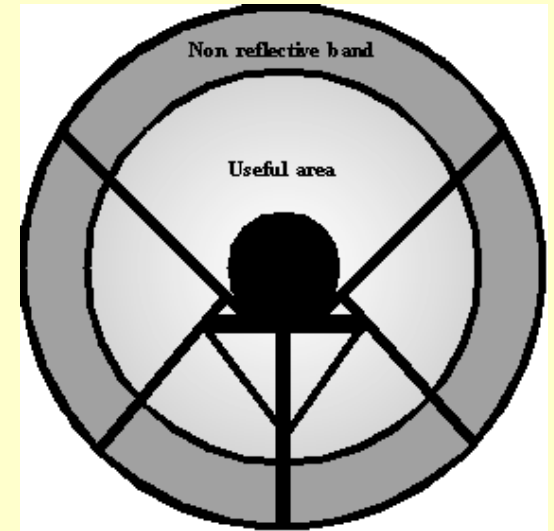
$$\dot{Q}_{sol_collect} = A_{collector_aperture} \cdot DNI$$

DNI = Direct Normal Irradiation

Reflected solar flux:

$$\dot{Q}_{sol_reflect} = A_{collector_useful} \cdot \chi \cdot DNI$$

χ = mirror reflectivity



Modulated solar flux:

$$\dot{Q}_{sol_modul} = \dot{Q}_{sol_reflect} \frac{A_{modul_aperture}}{A_{modul_opened}}$$

Absorber cavity and generator hot exchanger model

Energy balance:

$$\frac{dU_{cavity+hg}}{dt} = \dot{Q}_{sol_abs} + \dot{Q}_{loss_cavity} + \dot{Q}_{hel-wall_hg}$$

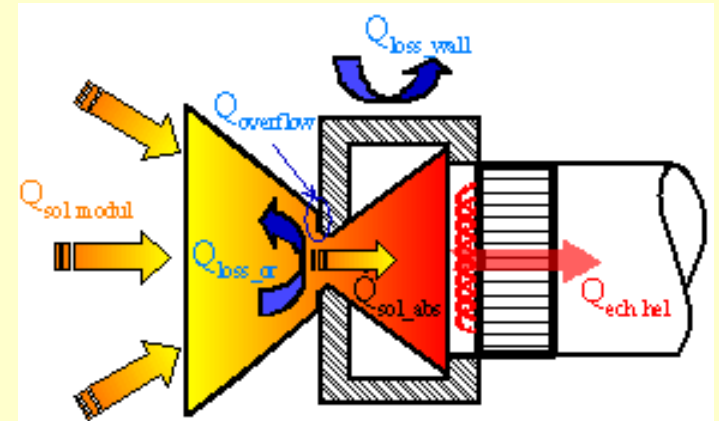
With:

Absorbed solar power

$$\dot{Q}_{sol_abs} = \dot{Q}_{sol_modul} \cdot (1 - \tau_{overflow})$$

Cavity thermal losses

$$\dot{Q}_{loss_cavity} = \dot{Q}_{loss_or} + \dot{Q}_{loss_lateral_wall} + \dot{Q}_{loss_back_wall}$$



Three other thermoacoustic heat exchanger model

Convective heat transfers between the heat exchanger walls and the fluids

Energy balance:

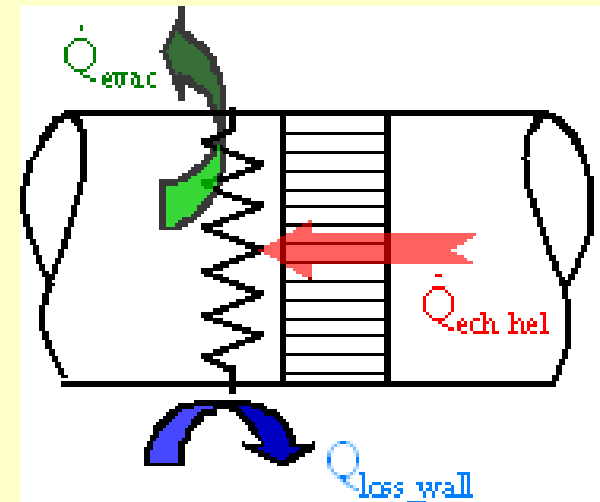
$$\left\{ \begin{array}{l} \frac{dU_{wall_exch}}{dt} = \dot{Q}_{fluid-wall_exch} + \dot{Q}_{hel-wall_exch} + \dot{Q}_{loss_exch} \\ \frac{dU_{fluid_exch}}{dt} = \dot{Q}_{wall-fluid_exch} + \dot{m}_{fluid_exch} (h_{fluid_input_exch} - h_{fluid_output_exch}) + \dot{Q}_{visco_exch} \end{array} \right.$$

With:

$$\dot{Q}_{fluid-wall_exch} = \alpha_{fluid-wall} \cdot A_{fluid-wall} (T_{fluid} - T_{wall_exch})$$

$$\dot{Q}_{visco_exch} = \Delta P_{exch} \frac{\dot{m}_{fluid_exch}}{\rho_{fluid}}$$

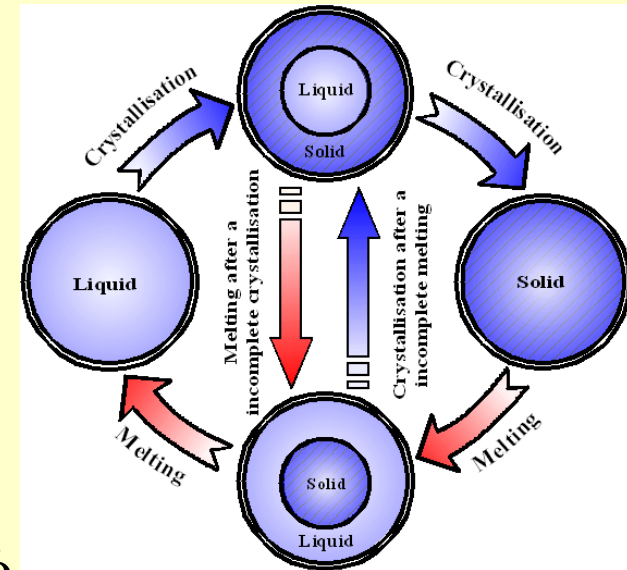
Viscous dissipation term



Cold energy storage

Assumptions

- The flow in the tank is axial and incompressible;
- Variation of temperature of the heat transfer fluid occurs only along the axial direction, the temperature is independent of the radial position;
- Heat transfer by conduction is neglected in the heat transfer fluid;
- Kinetic and potential energy changes are negligible;
- The tank is divided in several control volumes according to the height ;
- The nodules are considered as exchangers. The energy flux exchanged is proportional to the difference of temperature between the fluid and the interior of the spherical nodule;
- The **supercooling** phenomenon is taken into account.
- The pressure losses are considered for the flow inlet and outlet, the flow diffusers and the nodule bed thank to local coefficients of pressure drops.



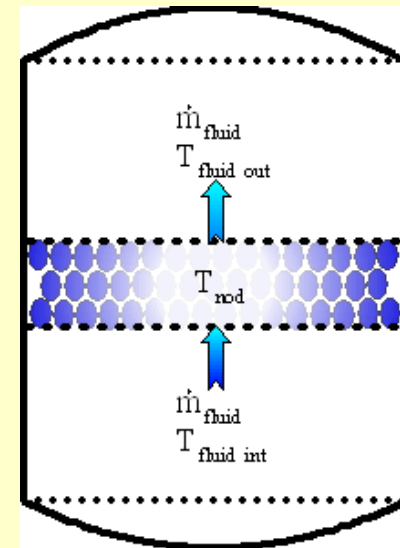
Energy balance equations :

$$\frac{dU_{nod,i}}{dt} = m_{nod} \frac{du_{nod,i}}{dt} = \dot{Q}_{nod-fluid,i}$$

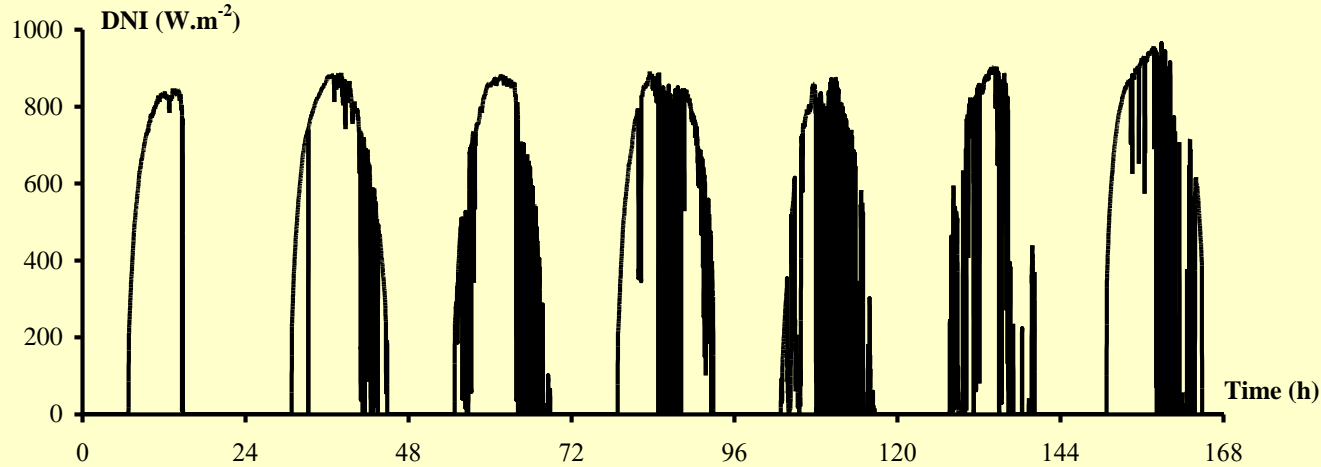
$$\frac{dU_{fluid}}{dt} = \dot{m}_{fluid} (h_{fluid\ in} - h_{fluid\ out}) + \sum_{i=1}^{N_{nod}} \dot{Q}_{nod-fluid,i} + \dot{Q}_{visco_storage}$$

With:

$$u_{nod,i} = \begin{cases} u_{ref} + C_{v_{PCM\ solid}} (T_{nod,i} - T_{ref}) & \text{if } x_{nod,i} = 1 \\ u_{ref} + C_{v_{PCM\ solid}} (T_{melt} - T_{ref}) + (1 - x_{nod,i}) L & \text{if } 0 < x_{nod,i} < 1 \\ u_{ref} + C_{v_{PCM\ solid}} (T_{melt} - T_{ref}) + L + C_{v_{PCM\ liq}} (T_{nod,i} - T_{ref}) & \text{if } x_{nod,i} = 0 \end{cases}$$



Simulation conditions



Typical DNI at Odeillo (France) measured in July

Main simulation parameters :

Solar concentrator aperture area (m^2)	13.5	Hot heat exchanger mass (kg)	30
Shadow area on the concentrator (m^2)	3.5	Ambient heat exchanger mass (kg)	1
Reflectivity of the concentrator	0.92	Cold heat exchanger mass (kg)	1
Cavity orifice diameter (m)	0.1	Electrical power of the heater (W)	350
Solar overflow rate	0.1	PCM nodule diameter (mm)	77

Simulation conditions

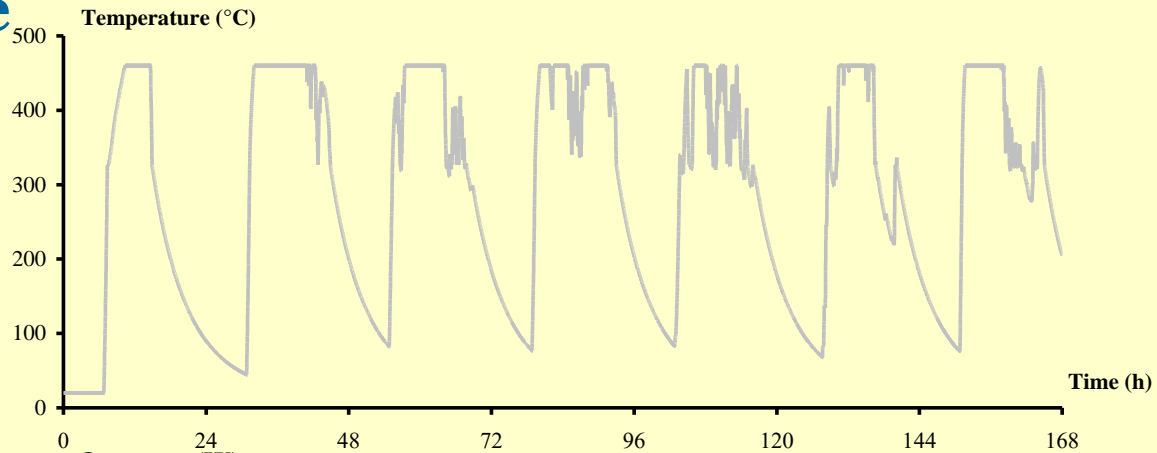
	Standard case	Variation for parametric study
Tank volume (m ³)	0.2	0.15 and 0.25
Masse flow rate (kg.s ⁻¹)	0.1	0.05 and 0.2
PCM melting temperature (°C)	-21.3	-18.8 and -26.2

Solar flux modulator regulation: $T_{cg} \leq 500^{\circ}\text{C}$

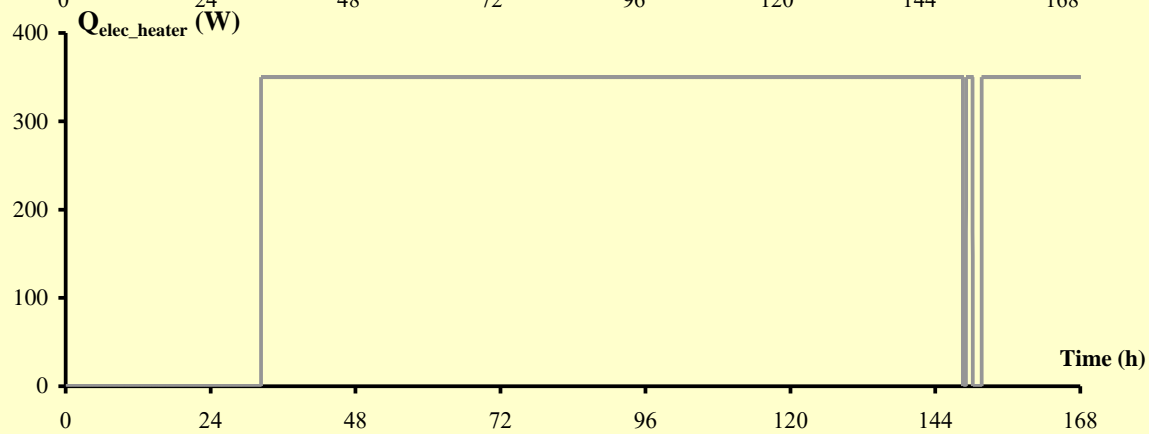
Loads regulation: $Q_{loads} = 350 \text{ W}$ if $T_{fluid} < -18^{\circ}\text{C}$ and $t > 30 \text{ h}$

Standard case

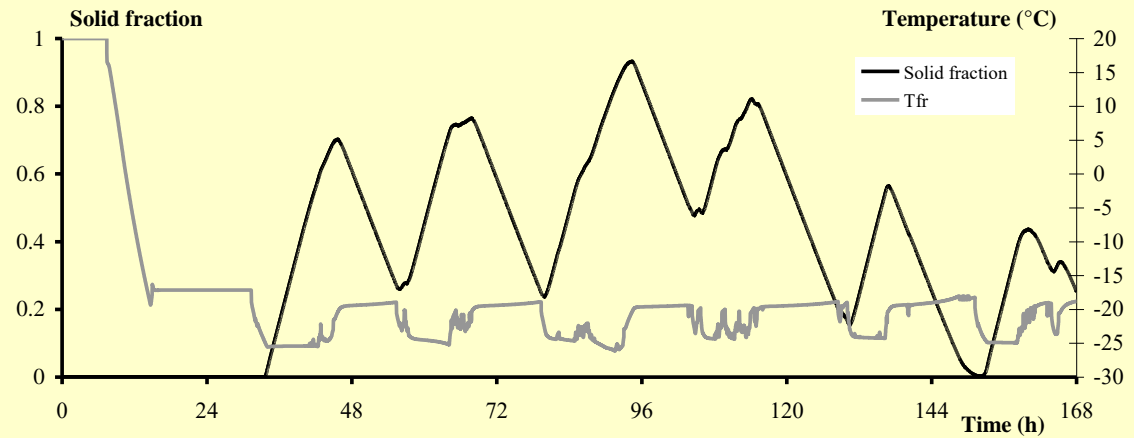
Temperature of the generator hot exchanger



Electrical power of the fluid heater

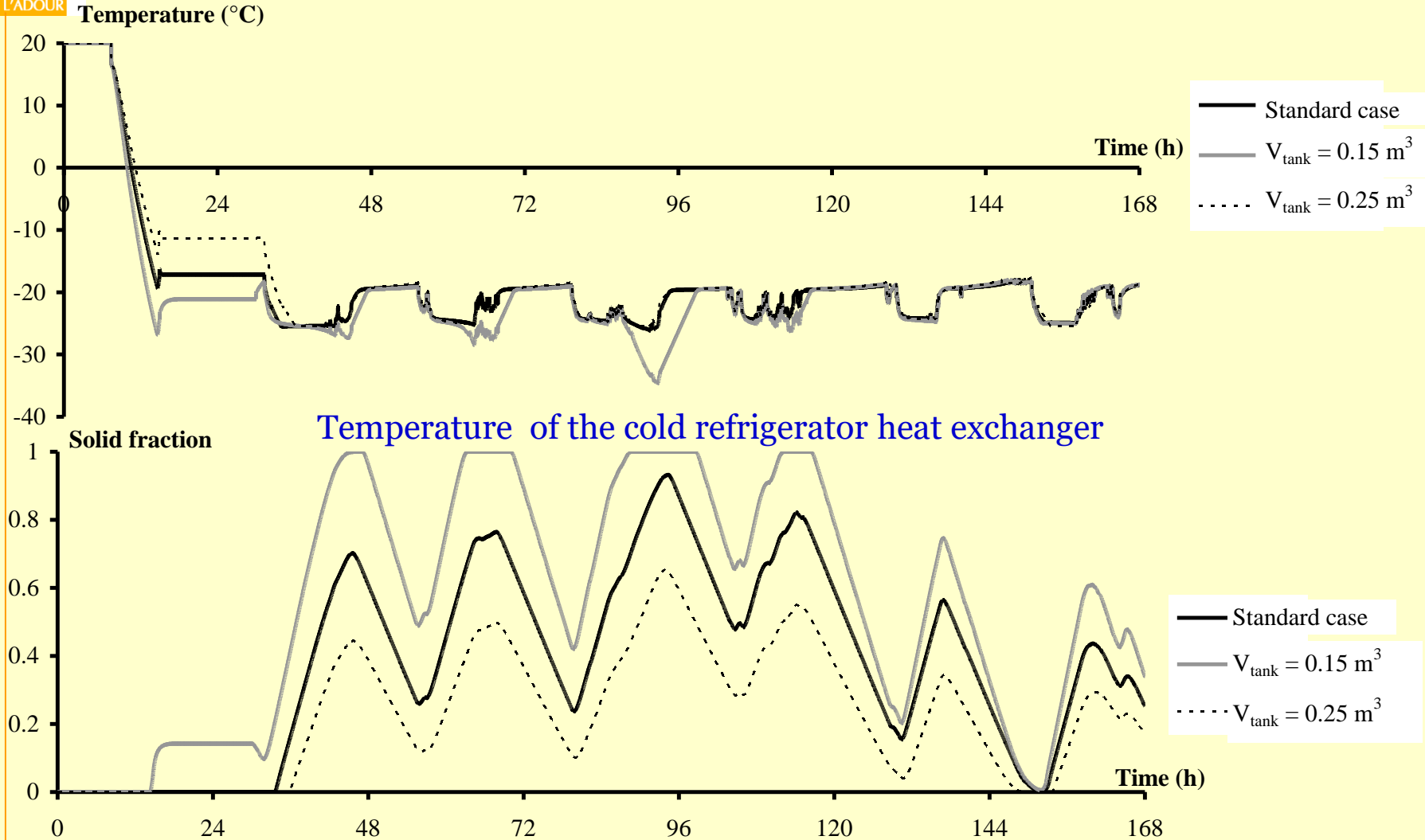


Solid fraction in the storage tank nodules and temperature of the refrigerator cold exchanger



Parametric study

Variation of the storage volume:

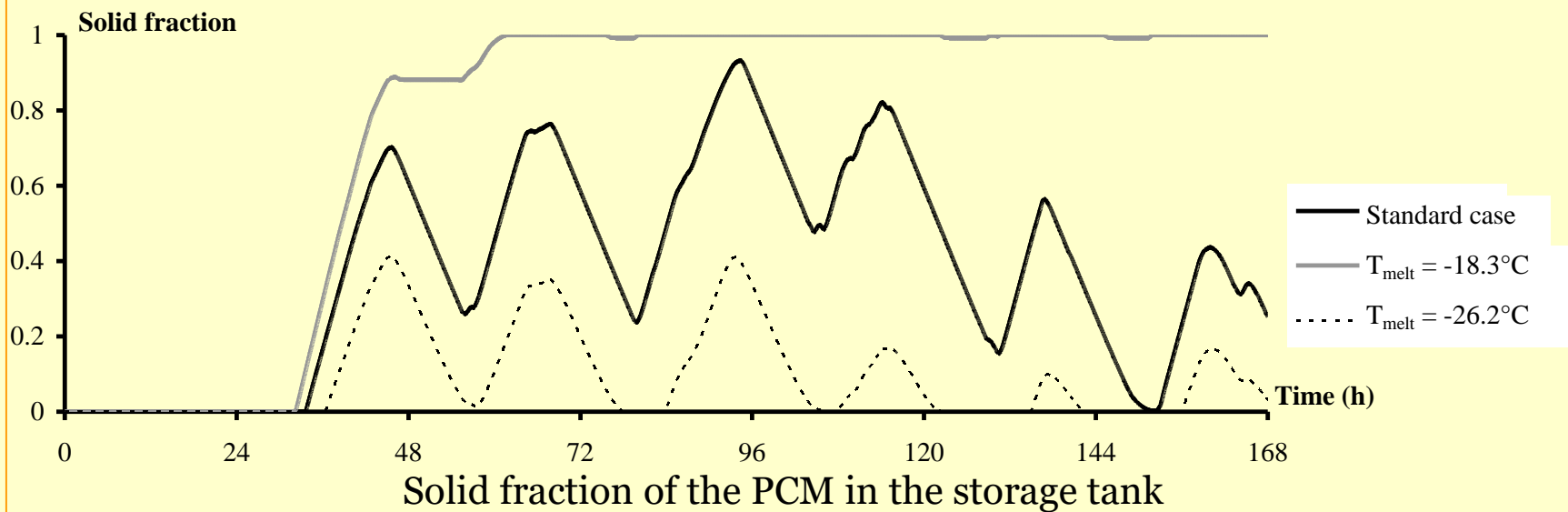
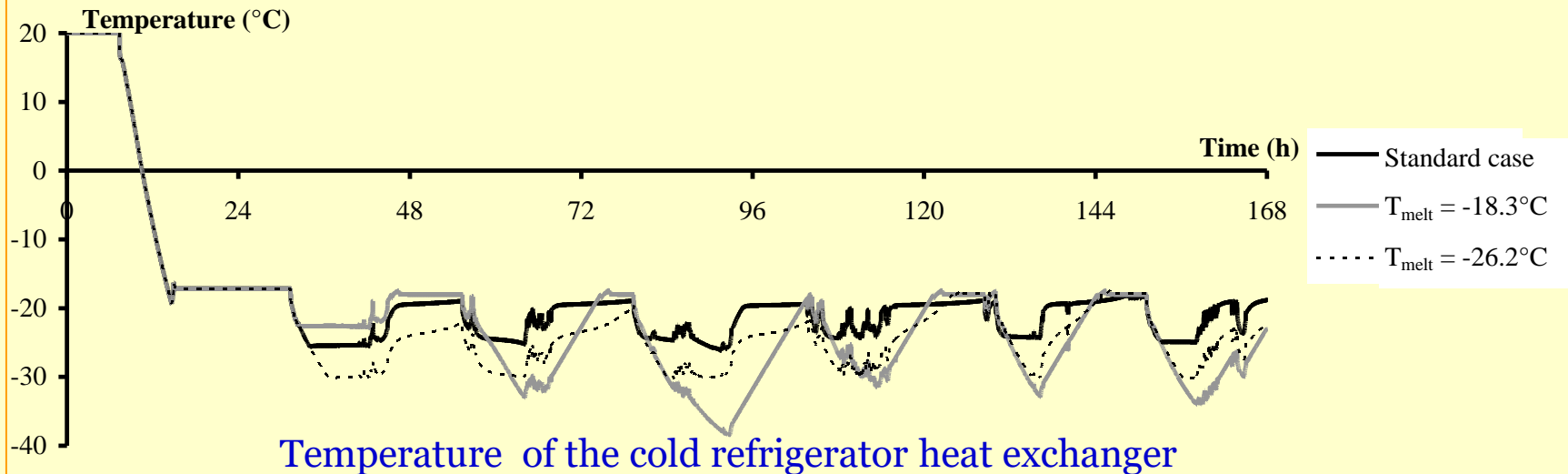


Temperature of the cold refrigerator heat exchanger

Solid fraction of the PCM in the storage tank

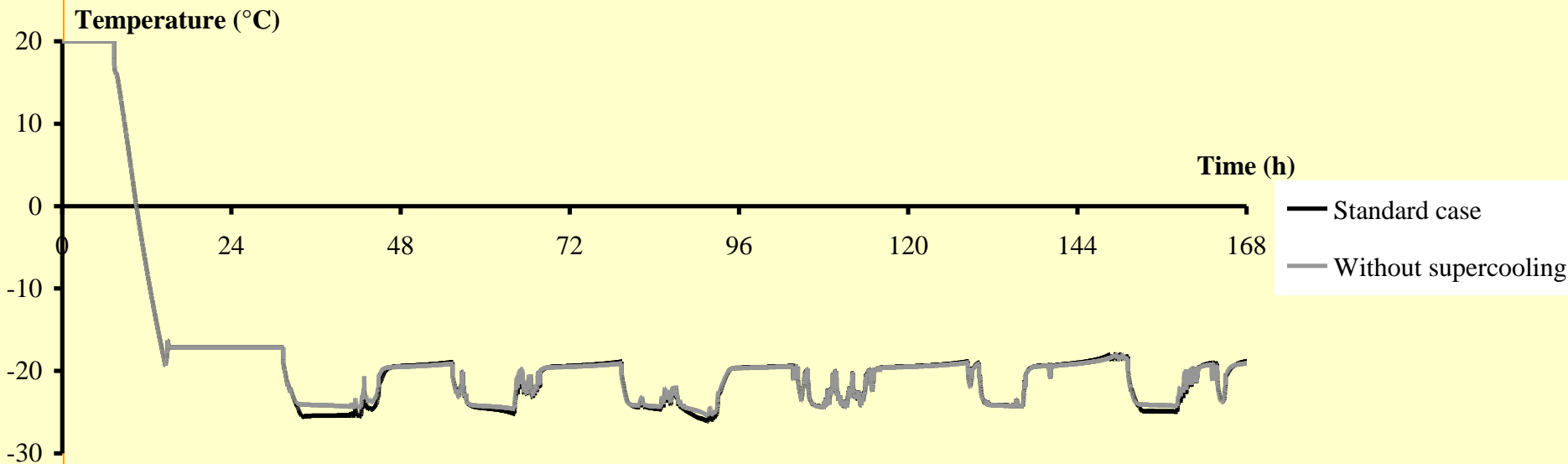
Parametric study

Variation of the melting temperature of the PCM:



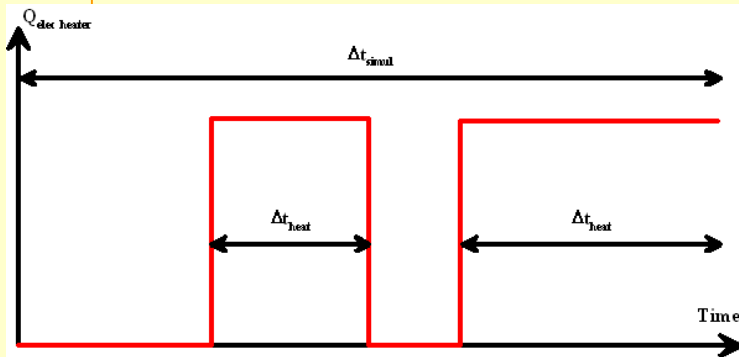
Parametric study

Impact of the supercooling effect:

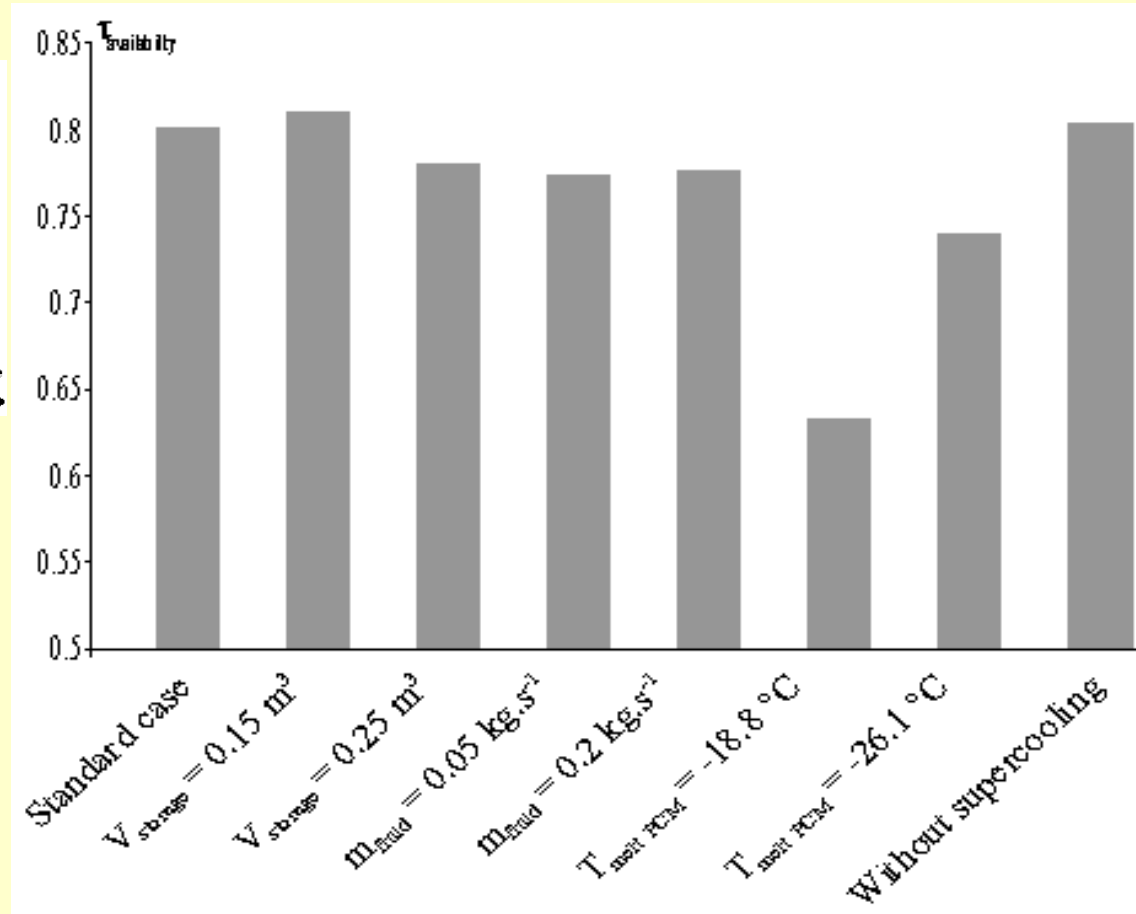


Temperature of the cold refrigerator heat exchanger

- Availability rate:



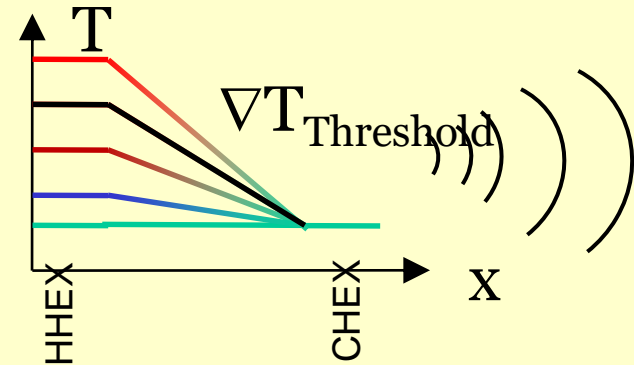
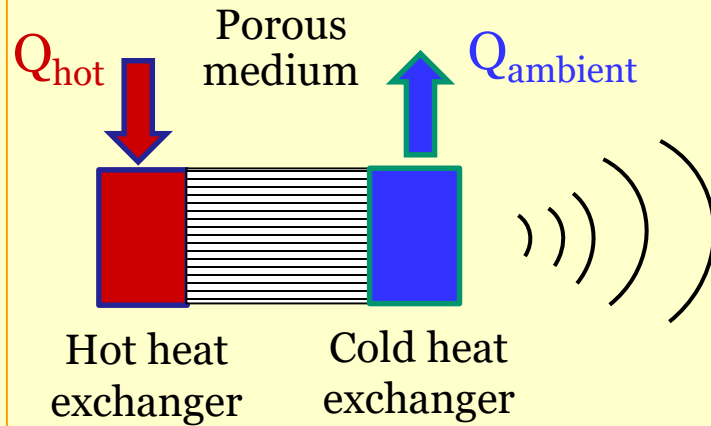
$$\tau_{\text{availability}} = \frac{\sum \Delta t_{\text{heat}}}{\Delta t_{\text{simul}}}$$



Conclusion & Perspectives

- A model of a solar driven thermoacoustic refrigerator coupled to a latent cold storage has been developed
- The impacts of the main design and control parameters of the cold storage have been studied
- A prototype has been designed and is under construction
- The experimental study will begin next September in Odeillo (France)

Thermoacoustic generator



Threshold mechanism

Hot HEX heating and Cold HEX at T_{amb} → Temperature gradient establishment in the porous medium

Critical temperature gradient reached → Thermoacoustic wave generation

Hot heat flux increase → Changes temperature gradient → Higher acoustic wave intensity