SUSTAINABLE REFRIGERATION BASED ON THE SOLAR ADSORPTION CYCLE

G. BRITES[(a)], J. COSTA[(a)], V. COSTA[(b)]
[(a)] ADAI-LAETA, Mechanical Engineering Department, Coimbra University, P 3030-788 Coimbra, Portugal. email: goncalo.brites@adai.pt, webpage: http://www.adai.pt
[(b)] Mechanical Engineering Department, Aveiro University, P 3810-193 Aveiro, Portugal.

ABSTRACT

A solar adsorption refrigerator, with 1 m^2 of solar collector area, using the pair silica-gel+water, was built to demonstrate the feasibility of this refrigeration technology under typical Portuguese weather conditions. The experimental results refer to the summer of 2011, and were successful as the solar refrigerator was able to keep the refrigerated cabinet at temperatures near 0°C for consecutive days of good weather conditions, although the performance obtained was lower than initially expected. A numerical model was developed and simulations were conducted to investigate how to improve the performance of the solar refrigerator.
This technology cannot yet compete with the electrically powered compression vapor refrigeration systems. However, since it only requires solar radiation as energy source, and uses only environmentally friendly materials, it can be interesting in the future, to counterbalance the scarcity of fossil fuels and preserve the environment.

1. INTRODUCTION

Solar adsorption refrigeration is based on the adsorption properties of some common materials like silica-gel, activated carbon or zeolite. For example, silica-gel could adsorb water vapor until about 40% of its weigh, releasing the heat of adsorption to the environment. When heated, the silica-gel beads will release the vapor molecules, returning to the initial state without loss of capacity. This characteristic makes adsorbent materials useful to build a cooling machine, because in a closed system, when silica-gel is adsorbing water vapor, pressure decreases and liquid water present inside the system can be evaporated, producing a chilling effect. To work properly, all the air or other gases inside the system must be evacuated, leaving only water and water vapor.
Other less common adsorption pairs, some based in chemical reactions, were also investigated. Table 1 presents the performance obtained in some previous investigations concerning solar adsorption refrigeration, and it is notorious that the performance obtained in terms of the parameter COP_{solar} is quite low, ranging from 0.04 to 0.27. Nevertheless, the energy source is completely free and clean (solar energy), and these refrigerators are completely independent of any other source of energy because they have no moving parts. The parameter COP_{solar} represents the ratio between the cold effect produced, Q_{evap} [J], and the amount of solar radiation available in the plane of the collector, Q_{solar} [J], as stated in Equation 1.

$$COP_{solar} = \frac{Q_{evap}}{Q_{solar}} \tag{1}$$

In order to quantify Q_{evap} it is necessary to measure the mass of water condensed $m_{water,cond}$ [kg] (which is equal, on average, to the mass of water evaporated during the cycle), multiply by the latent heat of evaporation, L_{evap} [J/kg], and subtract some sensible heat when the condensed water, stored in the condensed reservoir, enters the evaporator, which usually is at 0°C.

$$COP = \frac{m_{water,evap} L_{evap} - m_{water,cond} c_{P,water} (T_{cond} - T_{evap})}{Q_{solar}} \tag{2}$$

Table 1 – Performance of some solar adsorption refrigerators, from the literature.

Author and year	Adsorbent-adsorbate	Country	COP_{solar}
Mayor and Dind, 2002	Silica-gel - water	Switzerland	0.10 to 0.15
Hildbrand *et al*., 2004	Silica-gel - water	Switzerland	0.20
Li and Wang, 2003	Activated charbon - methanol	China	0.132
Leite *et al.*, 2004	Activated charbon - methanol	Brasil	0.085
Khattab, 2006	Activated charbon - methanol	Egypt	0.1558
Li and Wang, 2002	Activated charbon - methanol	China	0.07 to 0.27
Li *et al.*, 2004	Activated charbon - methanol	China	0.12 to 0.15
Li *et al.*, 2003	Activated charbon - methanol	China	0.25 to 0.30
Lemmini and Errougani, 2005	Activated charbon - methanol	Morocco	0.04 to 0.08
Iloeje *et al.*, 1995	Calcium chloride - ammonia	Nigeria	0.12 to 0.14
Erhard *et al*., 1996	Strontium chloride - ammonia	Germany	0.05 to 0.08
Martín, 2006	Activated charbon - methanol	Spain	0.08 to 0.10
Ahmed *et al.*, 2011	Activated charbon - methanol	Egypt	0.07 to 0.11
El Fadar *et al.*, 2009	Activated charbon - methanol	Morocco	0.18

The solar adsorption refrigerator investigated, represented in Figure 1, uses the adsorbent – adsorbate pair silica-gel + water, and has three main components: the flat collector/adsorber, the condenser and the evaporator. There is also a small reservoir to store the water condensed during the day. The working principle is very simple: during the day the adsorbent is regenerated with solar energy, releasing water vapor, which is condensed and accumulated in the condensed reservoir, and the valve between the reservoir and the evaporator is kept closed. During the night, the valve below the reservoir is kept open, liquid flows into the evaporator, the adsorbent cools down and starts adsorbing water vapor; the adsorption heat is released through the collector plate to the ambient, the system pressure decreases and water evaporates in the evaporator, causing the cooling effect inside the refrigerated cabinet. It is desirable that this process produces a substantial amount of ice inside the evaporator, storing enough cold to keep the refrigerated cabinet at low temperature for one or two days if clouds block the solar radiation and temporarily prevent the system to work properly. Care must be taken to avoid the condensation in the evaporator, which would rise the temperature in the cold cabinet, and for this reason there is a valve between the water reservoir and the evaporator that must be closed during the day and open during the night.

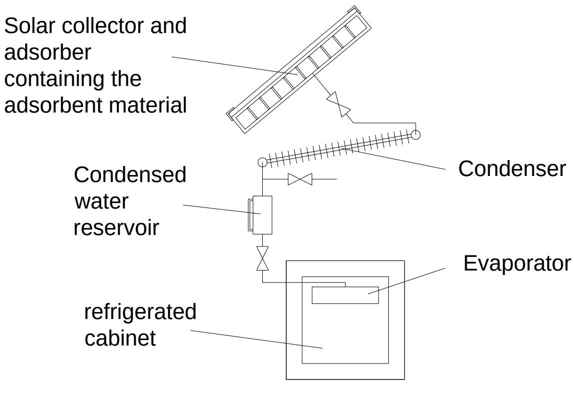


Figure 1 – Schematic diagram of the solar adsorption refrigerator.

2. EXPERIMENTAL RESULTS

A prototype of a solar adsorption refrigerator with 1 m^2 of collector area, working with the pair silica-gel + water, was built and tested with typical summer conditions in Coimbra (center of Portugal). The plane collector has a square shape, and consists of an insulated flat box that contains the adsorber and a 5 mm clear glass on the top. Figure 2 shows the interior of the adsorber, which contains 10 cells of adsorbent, separated by aluminum fins. An aluminum foil was used to contain the adsorbent, avoiding direct contact with the adsorber plate – later on it was suspected that this was not a good option, as this aluminum foil could have increased the thermal resistance between the adsorber plate and the adsorbent material, which decreases the system´s performance. The silica-gel type A beads are compressed against the absorber plate by a system of

shelves and compression springs. The solar collector has a tilt angle of 40°, a good option for Coimbra, and was placed facing south.
The other components are a finned condenser cooled by natural convection, a small condensate tank, some valves and an evaporator, made of stainless steel, placed inside the refrigerated cabinet. Figure 3 presents pictures of the solar adsorption refrigerator and the refrigerated cabinet with the door open, being visible the evaporator box.
The refrigerator was instrumented with seven thermocouples, a pressure sensor and a pyranometer in order to record the data necessary for the characterization of the adsorption cycle and to describe its operation.

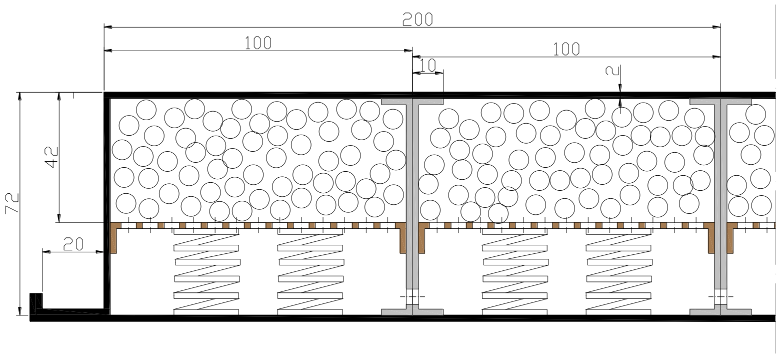


Figure 2 – Sketch of the adsorber box, showing the aluminum fins, the shelves to push silica-gel beads against the collector plate and compression springs. Dimensions in [mm].

Figure 3 – Pictures of the solar adsorption refrigerator and the placement of the evaporator inside the refrigerated cabinet.

To simulate a refrigeration load, 4 bottles of 1.5 L water each, initially at the ambient temperature, were placed every evening inside the refrigerated cabinet, replacing the similar bottles placed on the day before. Figure 4 shows the measurements made for one adsorption cycle, where it can be seen that the adsorber plate reached a maximum temperature of 100ºC while the adsorbent reached only 80ºC, which could mean that there is a significant thermal resistance between the metal plate and the adsorbent material. At night, there is a substantial difference between the adsorbent temperature and the ambient temperature, suggesting that the cooling of the adsorbent could be optimized with some night ventilation. The evaporator temperature was always near 0ºC, but a slight linear increase of the evaporator temperature close to 19:00h suggests that all the ice reserve was melted. This is not too bad because by this time the adsorber is cooling and adsorption phase will start soon, producing new ice. There was another increase in the evaporator temperature, which corresponds to the time when the valve was opened, letting condensed water flow into the evaporator. A slight increase in the adsorbent temperature suggests that adsorption started at this instant, because some adsorption heat was released. The refrigerated load (6 kg of water) was successfully cooled to near the evaporator temperature in about 12 hours, and was kept refrigerated the whole day.
These results suggest that the ice reserve formed in one cycle may not be large enough to maintain the temperature of the refrigerated cabinet for consecutive days if the next day is cloudy, especially if a new refrigerated load is introduced every day.

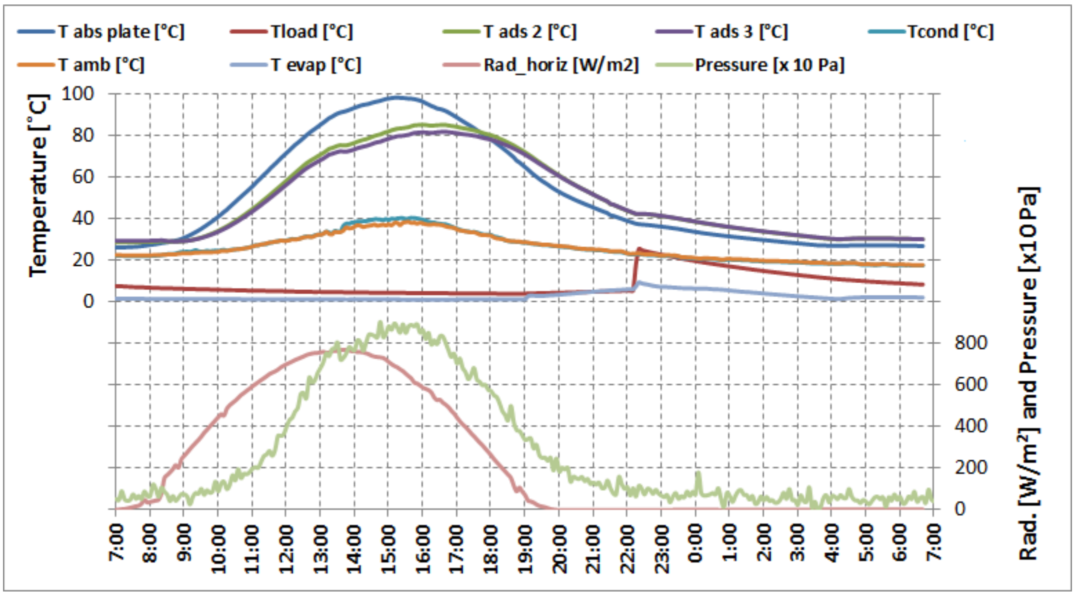


Figure 4 – Experimental results for the day 14-09-2011.

Figure 5 shows the adsorption cycle for the same day. The cycle apparently folows the theoretical cycle, and the content of water in the silica-gel changes between 0.04 and 0.09 kg of water by kg of silica-gel (dry). With 30 kg of silica-gel inside the adsorber, this means that we should have obtained 30x(0.09-0.04) = 1.5 kg of water condensed. Actually, the mass of water condensed was only 0.51 L, which means that the solar refrigerator is not working correctly and that it can and should be improved. The COP_{solar} obtained was only 0.056.
It was thought that the low performance obtained could be due to the presence of air or other gases inside the system, so a better vacuum pump was used aiming to completely evacuate the system from any residual air, and a slightly better performance was achieved, but results were still lower than expected. Figure 6 shows the results obtained after the better vacuum pump was used.
The causes for the low performance could also be related to the kind of siliga-gel used, because it was selected an equivalent type of silica-gel, with the same characteristic pore dimensions, instead of silica-gel type A from a recognized manufacturer. In fact, the siliga-gel used was not tested in order to confirm its properties.

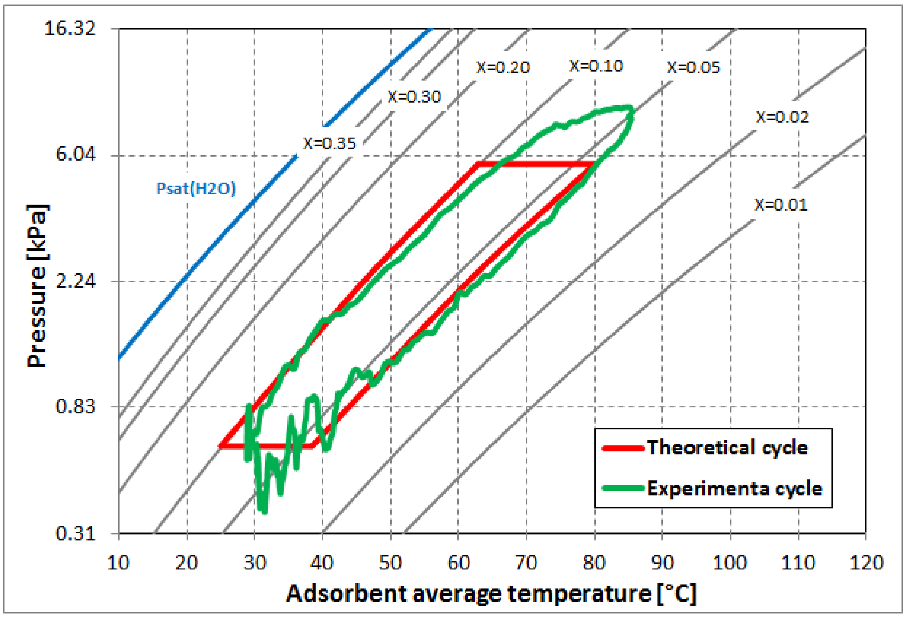
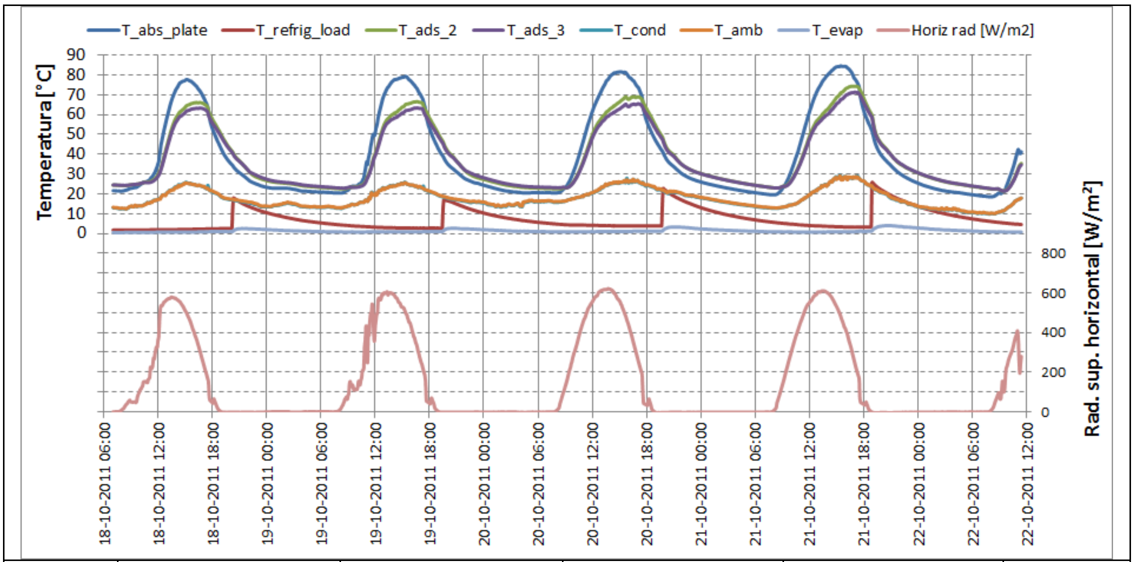


Figure 5 – Adsorption cycle for the data collected in 14-09-2011.



Q_{evap} [kJ]	699.8	1375.5	1509.7	1557.7	
Q_{solar} [kJ]	15119.0	18520.4	22252.9	21771.4	
M_{cond} [kg]	0.29	0.57	0.63	0.65	
COP_{solar}	0.0463	0.0743	0.0678	0.0715	

Figure 6 - Results for a 4 day test of the solar refrigerator.

3. OPTIMIZATION OF THE SOLAR REFRIGERATOR

A parametric study towards optimization was made involving the main factors influencing the performance of the solar refrigerator using a numerical model. The main equations of the model are described in the following paragraphs. The heat exchanged in the flat collector is obtained from:

$$\dot{Q}_{col} = A_c\left[S - U_L\left(T_{pm} - T_a\right)\right] \tag{3}$$

where S [W/m^2] is the radiation received by the absorber plate of the solar collector (radiation on the plane of the collector, corrected by the transmission coefficient of the glass and the absorption coefficient of the plate), and U_L [W/(m^2·ºC)] is the global heat transfer coefficient for a flat plate solar collector, obtained by the equation proposed by Duffie and Beckman (2006). The simplified form of the energy conservation equation, applied to the adsorber, is:

$$(\rho c_P)\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + (1-\varepsilon)\rho_{silica}\Delta H_{ads}\frac{dX}{dt} \tag{4}$$

In this equation, the properties ρ [kg/m^3], c_P [J/(kg·ºC)] and k [W/(m·ºC] are considered constants, and their values are obtained using a wheighted average according to the volume of each phase in the adsorber. ΔH_{ads} [J/kg] is the heat of adsorption and dX/dt [kg$_{water}$/(kg$_{silica\text{-}gel}$·s)] is the instantaneous rate of change of the water content adsorbed in the silica-gel, calculated by the LDF model as presented in Chua *et al.* (1999):

$$\frac{dX}{dt} = \frac{15D_e}{R_p^2}\left[X_{eq} - X(t)\right] \tag{5}$$

where $X(t)$ [kg$_{water}$/kg$_{silica\text{-}gel}$] represents the instantaneous value of the water content adsorbed in the silica-gel, X_{eq} [kg$_{water}$/kg$_{silica\text{-}gel}$] is the corresponding equilibrium water content, and D_e [m^2/s] is the effective mass diffusivity. The equilibrium water content for the silica-gel of type A, in $kg_{water}/kg_{silica\text{-}gel}$, is obtained using the Toth equation (Equation 6), according to Wang *et al.* (2004) :

$$X_{eq} = \frac{K_0 \cdot \exp[\Delta H_{ads} / (R_{vapor} T)] \cdot P}{\{1 + [K_0 / X_m \cdot \exp(\Delta H_{ads} / (R_{vapor} T)) \cdot P]^t\}^{1/t}} \quad (6)$$

The energy balance equation for the condenser is:

$$\frac{d(m_c c_{P,c} T_{cond})}{dt} = -\dot{Q} + \dot{m}_{water\ cond} \cdot \Delta h_{fg}(T_{cond}) \quad (7)$$

where the rate of heat rejected to the environment $\dot{Q}$ [W] is evaluated as:

$$\dot{Q} = U_c \cdot A_c (T_{cond} - T_{amb}) \quad (8)$$

For the refrigerated cabinet, the energy balance equation is:

$$\dot{Q}_{envelope} + \dot{Q}_{load} + \dot{Q}_{mcondensed} - \frac{dm_{evap}}{dt} \cdot L_{evap,liq} + \frac{dm_{ice}}{dt} \cdot L_{f,ice} = 0 \quad (9)$$

The heat gains through the cabinet envelope and the heat transferred from the refrigerating load is calculated by an equation similar to Equation (8). $\dot{Q}_{mcondensed}$ [W] is the sensible heat introduced in the evaporator when the condensed water stored in the reservoir is allowed to enter the evaporator (this happens only once in each cycle). The pressure is considered uniform inside the system in each timestep. During the heating and cooling phases, the pressure is calculated using the Clausius-Clapeyron equation:

$$\frac{\Delta H_{ads}}{R_{vapor} T^2} = \left(\frac{d \ln P}{dT} \right)_{X=const} \quad (10)$$

During desorption, the pressure is the saturation pressure at the condenser temperature; during the adsorption phase, the pressure is considered constant, and an averaged value obtained experimentally was used.

3.1 Results of the parametric study

The model of the solar refrigerator was validated with the obtained experimental data, and then it was used to perform the study for optimization of the solar refrigerator, considering the main parameters that influence its performance. Influence of the following parameters was studied in detail:

- Mass of silica-gel – it does not need to be changed
- Number of fins inside the adsorber – it was found that increasing the number of fins the performance could be increased. It was proposed to double the number of fins in the adsorber.
- Solar azimuth of the solar collector – instead of facing south, the collector should be facing with an azimuth of +40° (towards west). This makes it possible to increase the dessorption temperature, because the collector receives more radiation during the dessorption fase.
- Night cooling effect – the adsorber needs to be cooled during the night, to dissipate the heat of adsorption. The performance can be increased if ambient air can circulate between the

glass and the collector plate during the night. Special openings can be designed in the collector for this purpose.

- Thermal contact resistance between adsorbent and the plate collector – it was found during the validation of the model that the thermal resistance between the adsorbent material and adsorber plate is aproximately $1.5x10^{-1}$ m^2°C/W. This value is too high, comparing with experimental measurements obtained by Zhu and Wang, (2002). The possible explanation is the use of a thin aluminum foil to separate and contain the adsorbent from the metal plate. This aluminum foil should be removed or replaced by a graphite foil.
- Evaporation area – the water free surface inside the evaporador should be increased to facilitate the evaporation and to avoid the blocking of the evaporator surface with ice.
- Collector paint – the absorber surface of the solar collector was painted with an ordinary black paint. A black carbon paint should be used to maximize the absorption of solar radiation and the night cooling by radiation to the sky.

Running the simulation again, with all parameters optimized, once at each time, results of an optimized cycle are shown in Figure 7. The optimized refrigerator maximizes heat exchanges, allowing a much wider variation of the water content in the silica-gel, which represents more water condensed and evaporated, and higher cooling effect and better *COPsolar*. The simulation results predict 2.50 kg of water condensed, which gives a COP_{solar}=0.28. This is far better than the obtained experimental results, whose COP_{solar} was only about 0.08.

4. CONCLUSIONS

Adsorption refrigeration is nowadays a proven concept, with many successful prototypes built worldwide.

It seems very difficult to improve the system performance beyond COP_{solar} of 0.25 – 0.30, but it must be retained that a really free and clean (solar) energy is used, so the challenge is not necessarily to search for higher efficiencies but to solve problems like significant first costs, the high weight, the operation in cloudy days and the improvement of the refrigerator design. Further research is needed in order to build and test the optimized and reliable solar adsorption refrigerator at an acceptable cost, as well as to adapt its design to practical applications.

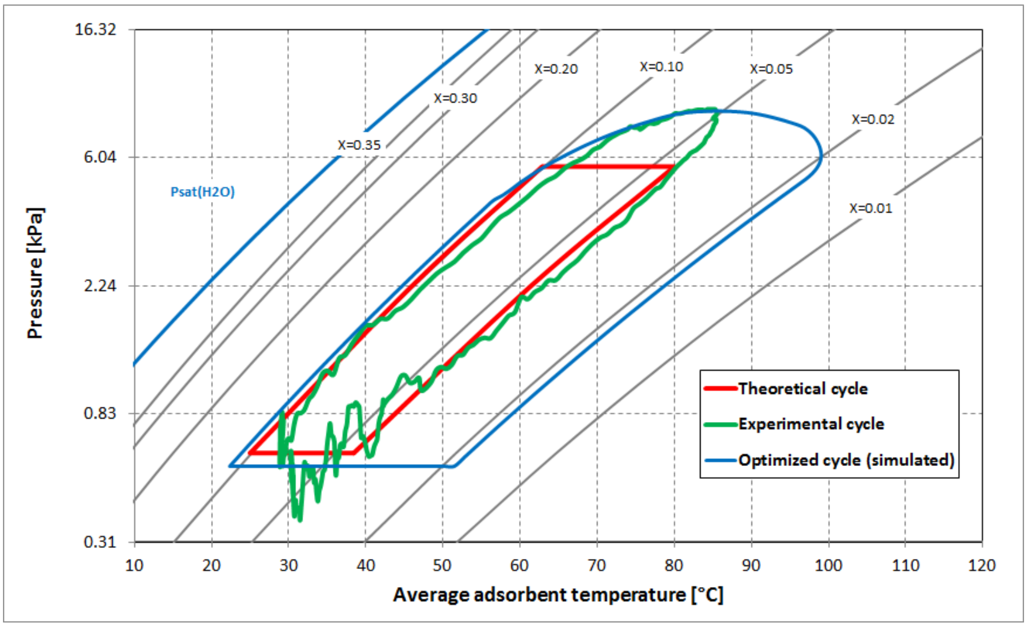


Figure 7 – Comparison between theoretical cycle, experimental cycle and cycle with optimized solar adsorption refrigerator.

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