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Citation for published version:
Freni, A, Santori, G, Sapienza, A, Frazzica, A, Vasta, S, Maggio, G, La Rosa, D, Brancato, V, Palomba, V & Gulli', G 2016, Solar Powered Solid Adsorption System for Cold-Storage Applications. in Proceeding of 16th CIRIAF Congress. Assisi (Italy), 16th CIRIAF Congress - Sustainable Development, Environment and Human Health Protection, Assisi, Italy, 7/04/16.

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Proceeding of 16th CIRIAF Congress

Assisi, Italy. April 7-9, 2016

16th CIRIAF National Congress

Sustainable Development, Human Health and Environmental Protection

Solar Powered Solid Adsorption System for Cold-Storage Applications

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Abstract: This paper presents the prototype of a novel solar-powered adsorption chiller system for cold storage. Field tests carried out for several months showed that the prototype is able to store up to 1.7 MJ, with a solar Coefficient Of Performance (COPs) of about 0.1, which is in line with the current state-of-the-art in the field. The possibility to replace methanol with the less toxic and corrosive ethanol as working fluid was successfully demonstrated by ethanol adsorption measurements on activated carbon Chemviron SRD 1352-3 and subsequent thermodynamic modelling. The schematics of a second-generation prototype was proposed, with improved core-components design and control strategy, to guarantee a 30% size reduction and a 20% performance increase.

Keywords: adsorption chiller; solar-powered; ice-making; cold-storage; activated carbon; ethanol; methanol; thermodynamic model; prototype.

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1. Introduction

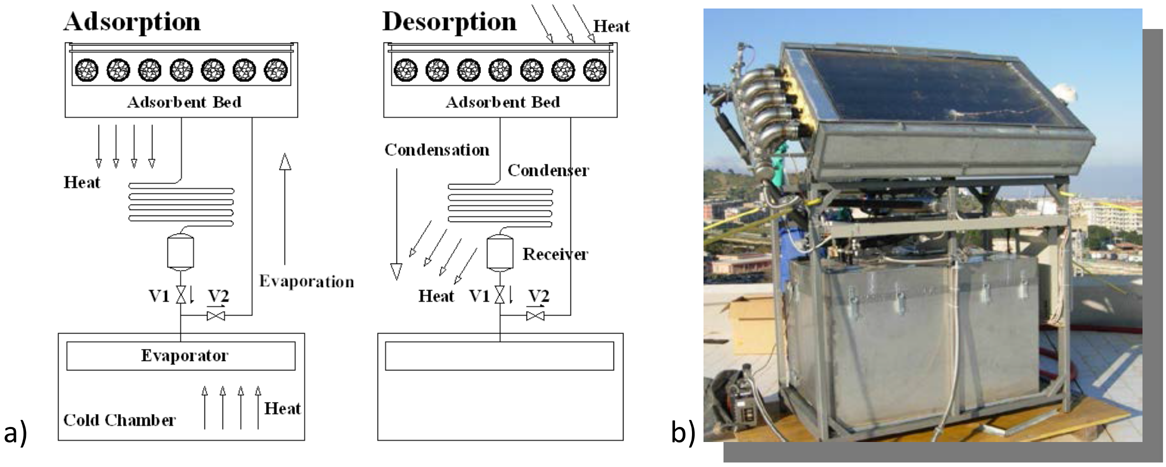
Adsorption cold storage systems powered by solar heat are devices that could prove a great help in sustaining the cold chain in third-world countries. Indeed, many rural areas of the world produce ample food supplies but there are considerable losses due to lack of refrigeration facilities. The use of such devices could be extended also in supporting humanitarian aid actions for vaccines storage.

The operating principle of this technology is based on the reversible – and thermally activated – adsorption of vapour (water, ammonia, methanol) on a porous media (zeolite, silica gel, activated carbon). Details on working principles of adsorption cooling systems can be found elsewhere [1]. Compared with absorption refrigeration, utilization of an adsorption cooling system sounds particularly attractive when a low temperature heat source, such as waste heat or solar energy, is available [2]. Accordingly, the current R&D focused on the development of adsorption solar-powered chillers to be used for ice-making or food storage [3]. Many off-grid solar refrigerator devices were realized and successfully tested in rural areas where solar radiation is widely available [4-6], thus demonstrating the feasibility of this technology. Recently, a novel solar powered adsorption cold storage system operating with the activated carbon/methanol adsorption pair was developed by the authors and preliminary tested in [7]. Results of testing showed that the prototype is able to store up to 1.7 MJ, with a solar Coefficient Of Performance (COPs) of about 0.1, which is in line with the current state-of-the-art in the field. Notwithstanding the encouraging results, still large room for further efficiency improvement exists, especially in terms of power density enhancement. In this paper, the mean features of the realized prototype are briefly introduced. Afterwards, the possibility to replace methanol with the less toxic and corrosive ethanol as working fluid was studied by thermodynamic modelling based on author's experimental adsorption data measured for the activated carbon/ethanol working pair. Finally, the schematic of a second-generation prototype, with improved core-components design and control strategy, is proposed.

2. Prototype description

Schematic and practical realization of the solar powered solid adsorption system are presented in Fig. 1a, b. The prototype operates with a 24-hours intermittent cycle and consists of the following main components: a solar collector, in which the adsorbent (activated carbon) is embedded; an air-cooled condenser for the adsorbate (methanol) phase transition; an evaporator placed inside an insulated box where the cooling effect is achieved. During the daytime, the solar energy received by the collector allows the methanol desorption from the activated carbon. The methanol vapour is condensed via the condenser into a receiver. When the desorption phase is completed, the liquid methanol collected into the receiver is passed to the evaporator through an automatic valve. Overnight, the activated carbon adsorbs methanol from the evaporator.

Figure 1. Schematic (a) and practical realization (b) of the solar powered solid adsorption system for cold storage.



A "high activation" carbon (Chemviron Carbon Ltd.; grain size: 0.6-1.7 mm) was selected as adsorbent of methanol. The activated carbon was loaded inside a tube bundle, which was integrated with a double glass flat-type solar collector having an exposed area of 1.2 m^2. The tubes containing the activated carbon were coated with a high absorptivity and low-emissivity adhesive layer in order to maximize the absorbed solar energy and reduce thermal energy losses. The integrated system “adsorber/solar collector” was installed inside an insulated metallic housing equipped with shutters that can be opened during the adsorption phase, allowing dissipation of the adsorption heat to the ambient. Moreover, the tilt angle of the adsorber/solar collector can be adjusted in order to set the optimal inclination of the solar collector, in relation to the location of the installation site. The air-cooled condenser consists of several finned tubes connected to a cylindrical receiver for collection of the condensate methanol. When the desorption phase is completed, the liquid methanol collected into the receiver is passed to the evaporator through an automatic valve. The evaporator consists of several finned tubes organized in two interconnected levels and is located inside a highly insulated box where the cooling effect is achieved by natural convection and that can be opened to insert/remove the substance to be cooled. All components have been realized in stainless steel AISI 304. A number of pressure and temperature sensors was installed, allowing to monitor the evolution of the ad/desorption cycle. The system was equipped with a data acquisition and control system. A specific software realized in LabVIEW environment allows to operate the ice-maker automatically.

Table 1 resumes the main features of the prototype.

Table 1. Main features of the solar powered solid adsorption system for cold storage.

Solar collector:	
Exposed area	1.2 m^2
Selective surface	SolMax Foil (α = 95-99%; ε = 4-10%)
Tube bundle	5 tubes DN 60 x 1.73 m + 5 tubes DN 60 x 1.63 m
Total surface	3.7 m^2
Adsorbent material	SRD 1352-3 Chemviron Carbon Ltd.
Adsorbent mass	20 kg
Grain size	0.6-1.7 mm
Condenser:	Air-cooled, 7 finned tubes DN 16, length 1 m Cylindrical receiver (DN100, 6.5 liters)
Total surface	4.08 m^2
Evaporator:	18 finned tubes DN 25, length 1 m in 2 interconnected levels
Total surface	18.45 m^2
Insulated box:	
Internal volume	1000 x 640 x 500 mm = 0.32 m^3
External volume	1.3 m^2
Insulation material	Polyurethane foam

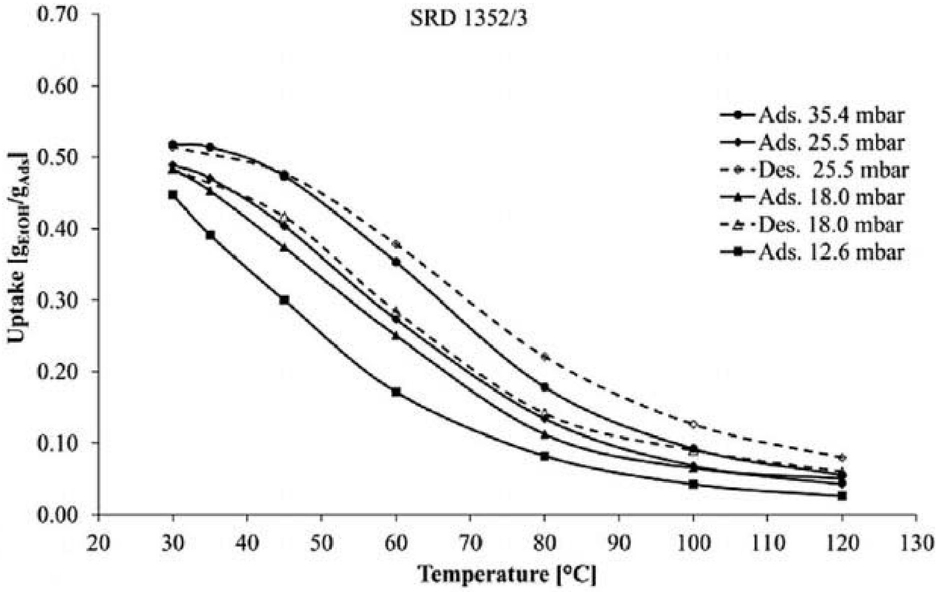
The prototype was installed on the roof of the CNR-ITAE building, in Messina (38° 11’ latitude N). Field tests carried out for several months showed that the prototype is able to store up to 1.7 MJ, with a solar Coefficient Of Performance (COPs) of about 0.1, which is in line with the current state-of-the-art in the field. Additionally, after field testing the following major issues were found: i) some internal corrosion problems due to the methanol employment, ii) some components were oversized (namely the liquid methanol receivers), while the air-cooled condensed appeared to by undersized, affecting the system performance.

3. Evaluation of activated carbon/ethanol as working pair

To increase the overall reliability of the system and therefore reduce the need for maintenance, the possibility to replace methanol with the less corrosive ethanol as a refrigerant has been evaluated. In order to calculate the achievable performance, the experimental adsorption data for the activated carbon/ethanol working pair have been measured and used into a specifically developed mathematical model, presented below.

Ethanol adsorption measurements were performed by a thermo-gravimetric system specifically designed for this scope. For each test, 7-8 g of adsorbent material were used. Prior to all the measurements, the samples were dried in an oven at 150 °C for at least 12 h to determine their dry mass (reference mass). After drying, the sample was put in a nickel crucible in the testing chamber and then evacuated by a vacuum pump for at least 6 h at 120 °C. Then the valve between the test section and the evaporator was opened and adsorption started. The measurements were conducted under isobaric conditions at four different ethanol pressures: 12.6 mbar (–3 °C), 18.0 mbar (2 °C), 25.5 mbar (7 °C), and 35.4 mbar (12 °C). Seven different equilibrium points were measured between 30 °C and 120 °C. Figure 2 reports the achieved results, demonstrating that the activated carbon shows a monotonic increase of the uptake with the decrease of temperature, up to 0.52 g_{EtOH}/g_{ads}. A so large ethanol adsorption capacity is very attractive for practical utilization of this working pair in Adsorption Heat Transformers. In addition, it exhibits a limited hysteresis effect between adsorption and desorption branches.

Figure 2. Ethanol/activated carbon SRD 1352-3 ad/desorption equilibrium isobars.



4. Thermodynamic analysis

The model used to calculate maximum expected efficiency of the system is a thermodynamic type and it is based on energy balances for the adsorbent reactor, evaporator and condenser. Moreover, equation to calculate the overall efficiency of the solar collector η_{solar} and the average desorption temperature have also been implemented in accordance with Ref. [8].

The main governing equations are:

$$COP_{solar} = \frac{\text{useful effect}}{\text{available solar radiation}} = \frac{Q_e}{(Q_{ri} + Q_d)/\eta_{solar}} \tag{1}$$

$$COP_{\text{thermodynamic}} = \frac{\text{useful effect}}{\text{available heat}} = \frac{Q_e}{Q_{ri} + Q_d} \tag{2}$$

where

$$Q_{ri} = Q_{s1} = \int_{T_A}^{T_B} [c_{p_{eq}}(W,T) + c_{p_{met}} m_{met}] dT \qquad \text{with} \rightarrow \; W = W_2 \tag{3}$$

$$Q_d = Q_{s2} + Q_h \tag{4}$$

$$Q_{s2} = \int_{T_B}^{T_C} [c_{p_{eq}}(W,T) + c_{p_{met}} m_{met}] dT \qquad \text{where} \rightarrow \; W = W(T) \tag{5}$$

$$Q_h = \int_{W_2}^{W_1} \Delta H(W) dW \tag{6}$$

$$Q_e = Q_e^* + Q_w \tag{7}$$

$$Q_e^* = \Delta W \; L(T_e) \tag{8}$$

$$Q_w = c_{p_{ref}} \; \Delta W \; (T_e - T_c) \tag{9}$$

Overall performance have been described by means of COP_{solar} and $COP_{thermodynamic}$, indicating the efficiency of the system comprising the solar collector, and the coefficient of performance of the adsorption cooling cycle, respectively. As already mentioned, the optical efficiency of the solar collector has been calculated based on the approach reported in [8]. Several simulations have been performed for each day of the year and the corresponding solar coefficient of performance (COP_{solar}) was evaluated. The results below show the main output of the model for weather conditions typical for the middle of July. In such a conditions, considering the very low thermal conductivity of the adsorbent material, the thermal efficiency of the solar collector is reduced to 0.36 and the maximum desorption temperature is 91 °C. Accordingly, the solar *COP* (COP_{solar}) decreases, compared to the thermodynamic value ($COP_{thermodynamic}$), in accordance with equations (1) and (2).

Figure 3 reports a typical thermodynamic cycle (T_{ads}=20 °C, T_e=–5 °C, T_c=40 °C, T_{des}= 95°C) of the simulated system on the P-T Clapeyron diagram, showing an attractive ethanol uptake variation along the cycle Δw=15 wt.% .

Figure 3. Thermodynamic cycle of the simulated system on a Clapeyron diagram.

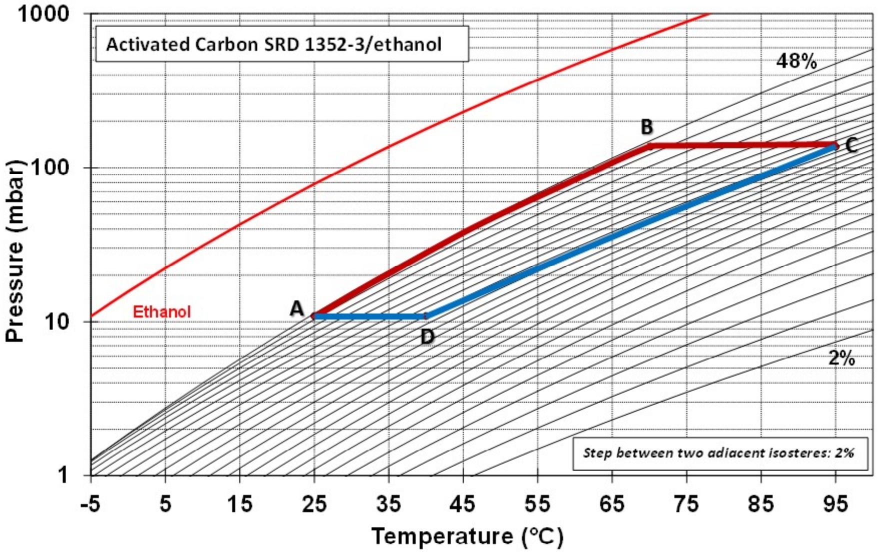
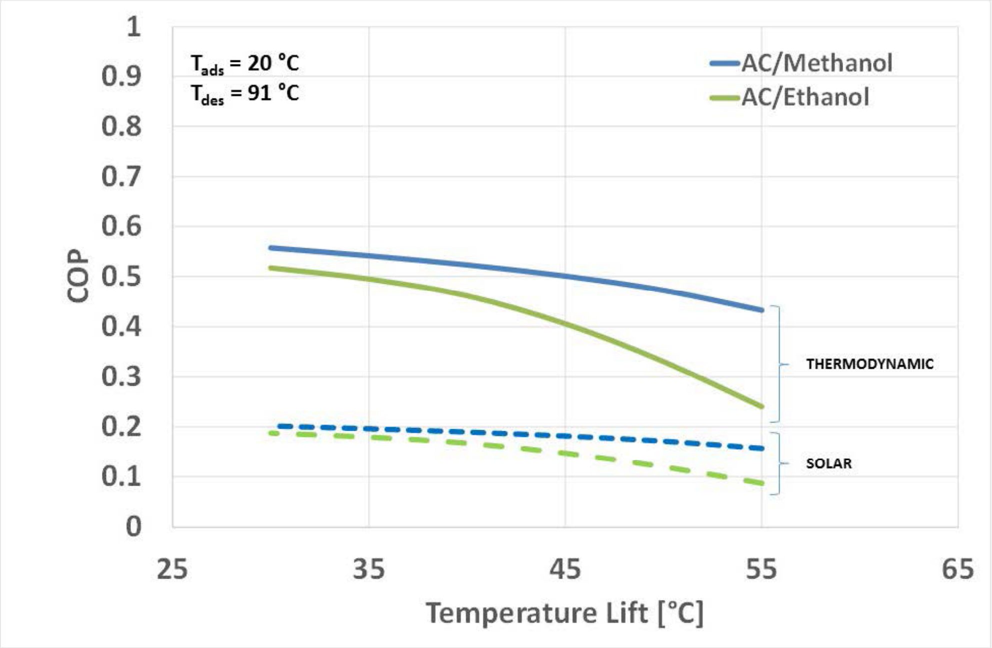


Figure 4 shows the modelling results in terms of solar and thermodynamic COP comparison between activated carbon using methanol and ethanol as a refrigerant. The results achieved clearly indicate that the AC/ethanol pair can guarantee comparable performance provided that the temperature lift between evaporation and condensation phases is lower than 40 °C.

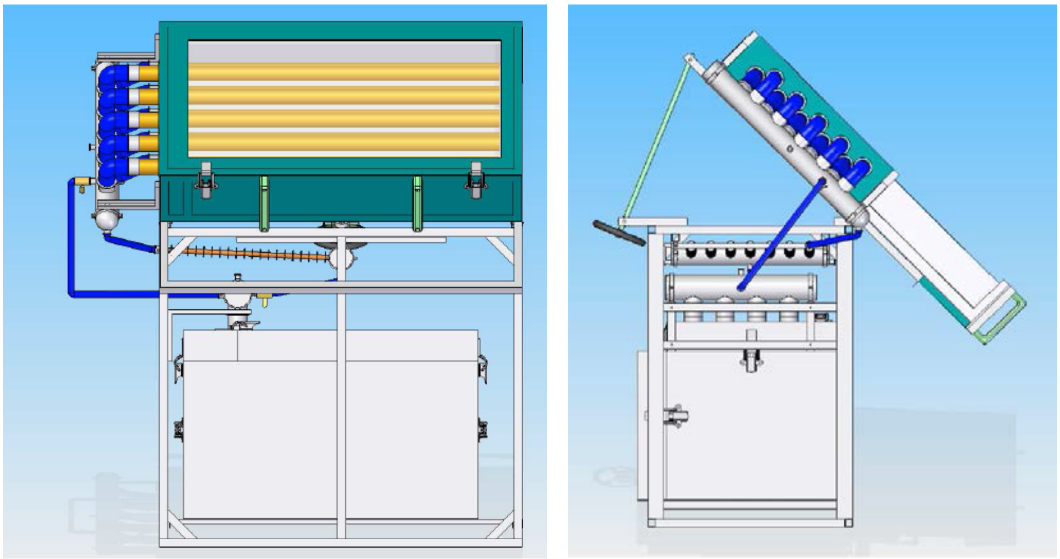
Figure 4. COP comparison between working pairs using methanol and ethanol as a refrigerant.



5. Schematic of the second generation prototype

Figure 5 shows the schematic of the second-generation prototype employing ethanol as working fluid and with improved core-components design.

Figure 5. The second generation prototype: front (on the left) and side (on the right) view.



Specifically, the following improvements have been adopted:

1) the size of the refrigerant receivers was noticeably reduced;
2) the heat exchange area of the air-cooled condenser was increased;
3) the inclination of the condenser was increased, to facilitate the flow of the condensed refrigerant to the receiver;
4) the thickness of evaporator and condenser finned tubes was reduced.

Moreover, special attention has been paid on control system and management with the aim of guaranteeing a stand-alone application in easily movable single-room containers, for practical application in remote rural areas.

Overall, the second generation prototype can guarantee a 30% size reduction and a 20% performance increase with respect to the first prototype. Therefore, next efforts of the research and development should be addressed towards the realization of a competitive product at the pilot or pre-commercial stage.

6. Conclusions

In this work we proposed the design of a more efficient solar powered solid adsorption system for cold-storage applications employing the activated carbon/ethanol working pair. Ethanol adsorption measurements over activated carbon Chemviron SRD 1352-3 were performed by a thermo-gravimetric system, showing that the investigated adsorbent is able to reversibly adsorb up to 0.52 g_{EtOH}/g_{ads}. Thermodynamic modelling demonstrated that ethanol can be efficiently used instead of methanol provided that the temperature lift between evaporation and condensation phases is lower than 40 °C. On the basis of such results, we proposed the schematic of a second generation prototype, with improved core-components design and control strategy, which allowed to guarantee a 30% size reduction and a 20% performance increase.

Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})
COP	coefficient of performance
$L(T)$	latent heat (J kg^{-1}), at the temperature T
m	mass (kg)
Q	heat per unit mass of adsorbent (J kg^{-1})
T	temperature (K)
W	uptake (kg kg^{-1})
ΔH	adsorption enthalpy (J kg^{-1})
ΔW	uptake variation (kg kg^{-1})

Subscripts

A,B,C,D	phase indicator of the thermodynamic cycle
c	condenser
eq	equivalent (i.e., referred to adsorbent plus adsorbate)
e	evaporator
met	metal

Acknowledgments

This work was partially supported by Italian Ministry of University and Research within the project: “Progetto Bandiera RITMARE” (SubProject SP2 - Technologies for Sustainable Fishing).

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