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**Citation for published version:**
Santori, G, Brandani, S, Santamaria, S, Sapienza, A & Freni, A 2014, 'A stand-alone solar adsorption refrigerator for humanitarian aid' Solar energy, vol. 100, pp. 172-178. DOI: 10.1016/j.solener.2013.12.012

**Digital Object Identifier (DOI):**
10.1016/j.solener.2013.12.012

**Link:**
Link to publication record in Edinburgh Research Explorer

**Document Version:**
Peer reviewed version

**Published In:**
Solar energy

Published in:
Santori, G.; Brandani, S.; Santamaria, S.; Sapienza, A.; Freni, A.
Solar energy, Vol. 100, 01.02.2014, p. 172-178.

# A stand-alone solar adsorption refrigerator for humanitarian aid

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**Abstract**
Solar adsorption ice makers are devices which could prove a great help in sustaining the cold chain in third world countries. The use of such devices could be extended also in supporting humanitarian aid actions for vaccines storage. However, further development and optimization of the system design are still required. In this paper a new, versatile, solar driven ice maker operating with the activated carbon/methanol adsorption pair has been developed and tested. The field tests carried out on February and March 2013, showed that the prototype is able to produce up to 5 kg of ice, with a solar Coefficient Of Performance ($COP_s$) of about 0.08, and to preserve it for whole next day. The overall dimensions of the realized prototype are 1.7x1.5x0.95 m. Solar radiation is collected by a solar collector with an exposed area of 1.2 $m^2$.

**Keywords:** Adsorption ice maker; Experimental test; Stand alone refrigerator; Solar cooling;

## Introduction

Every day thousands of children die also because of vaccination-preventable diseases (You et al., 2012). Immunization is a milestone for the economic development and poverty reduction in the third world countries. Following this believe, UNICEF has promoted the Global Alliance for Vaccines and Immunization (GAVI). The GAVI Alliance aims at saving children's lives and protecting people's health by increasing access to immunisation in poor countries (GAVI Alliance, 2011).

The largest difficulty affecting the impact of every immunization programs consists in keeping stored the vaccines at the right temperature until the administration.

The majority of vaccines have to be kept between 2°C and 8°C preventing any crossing of these limits (WHO-UNICEF, 2005). Such conditions can be easily kept storing ice in a highly insulated boxes. For this reason research in ice making technology could be an important impact on vaccines savings, increasing the number of vaccines available for administration and consequently reducing mortality.

The countries needing of such kind of humanitarian aid usually have not a fully-developed electrical grid, therefore the traditional vapour compression refrigeration systems have to be driven by internal combustion engines. This involves a series of drawbacks and problems concerning fuel supply and maintenance.

Despite the situation described above, the majority of the third world countries benefit of high power solar radiation. These features make the third world countries particularly attractive for solar adsorptive cooling.

Nowadays, thermally-driven adsorption cooling systems have been extensively studied and can be considered as a viable alternative to traditional electric-driven vapour compression systems (Critoph and Zhong, 2005). Their operating principle is based on the reversible adsorption of vapour (water, ammonia, methanol) on a porous media (zeolite, silica gel, activated carbon). Exhaustive details

concerning the adsorption heat transformers and their applications can be found elsewhere (Cacciola and Restuccia, 1999).
This technology sounds particularly attractive when an high amount of low temperature heat is available, such as solar energy (Wang et Oliveira, 2006).
Accordingly, the current R&D is focused on the development of adsorption and absorption solar-powered chillers to be used for icemaking or food storage (Dieng and Wang, 2001; Luo et al., 2005). Many off-grid solar refrigerator devices have been realized and successfully tested in rural areas where solar radiation is widely available (Anyanwu and Ezekwe, 2003; Buchter et al., 2003; Erickson, 2009; Hildbrand et al., 2004; Lemmini and Errougani, 2007; Li et al., 2004; Leite et al., 2007), demonstrating the feasibility of this technology. However, further development and optimization of the system design are still required in order to realize compact, cheap and efficient units with the aim to make them more market-attractive.
This paper presents a new solar-powered adsorption ice maker using the working pair activated carbon (adsorbent) and methanol (adsorbate). The prototype was designed on the basis of the result of a mathematical model developed and optimized in previous works (Freni et al., 2008; Maggio et al., 2009; Vasta et al., 2008). This paper represents an experimental follow up of that previous activity.
The prototype has been developed with the aim to study the influence of some different, modifiable aspects (i.e. heat transfer surfaces areas, type of adsorbent, adsorbent mass and adsorbent grain size) on the overall performance. Therefore the versatility of the prototype, its main strength, permits an overall sensitivity analysis, useful for the development of optimized units.
In the first part of the paper, the operating principle and the design criteria are described. Afterwards experimental results of two typical operational days under winter/spring Mediterranean conditions are provided.

## Operational phases of the solar powered adsorption ice maker

The conceptual scheme of an adsorption ice-maker is presented in Fig. 1. The machine operates with a 24-hours intermittent cycle and consists of the following main components: a solar collector, in which the adsorbent (activated carbon) is integrated, an air-cooled condenser for the relative adsorbate (methanol) phase transition and an evaporator placed inside an insulated box where cold is produced.
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 and then flows into the evaporator. During this process, valves V1 and V0 depicted in the scheme are opened, while valve V2 is closed. Overnight, the positions of valves V0, V1 and V2 are inverted. As a consequence, the activated carbon adsorbs methanol from the evaporator, where the useful cooling effect is produced. If liquid water is placed inside the insulated box, it can be converted into ice. The heat of condensation and of adsorption are released to the ambient during the day/night cycle.

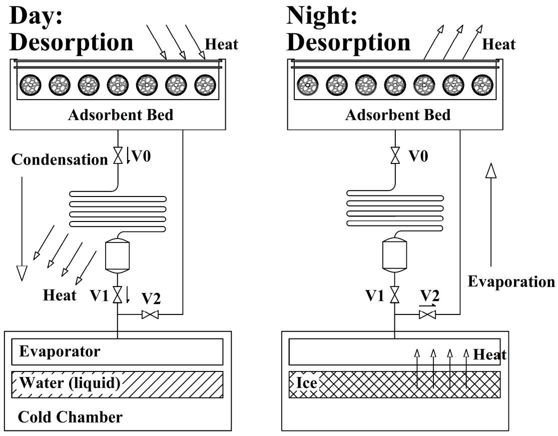


Figure 1: Operational phases of an intermittent solar adsorption ice maker

## Realization of the prototype

The most important part of the system is the adsorbent bed where the pressure gradients, resulting from its thermal conditions, drive the vapour transfer through the other components. Adsorbent bed consists of a tube bundle made of 10 pipes where about 20 kg of adsorbent are loaded.
Activated carbon SRD 1352/3 (origin Coconut Shell, manufactured by Chemviron Carbons Ltd.) (Tamainot-Telto et al., 2009) has been suitably selected to work in pair with methanol. Its grain size ranges between 0.6 and 1.7mm. These values should make the interparticle diffusion resistances reduced to guarantee a sufficient mass transport through the tube length. The adsorbent bed is integrated with a flat-type solar collector with an exposed area of 1.2 $m^2$. The advantage of this configuration is the compactness of the component and the reduction of the heat transfer resistances from solar collector to the activated carbon. The tubes are coated with a high absorptivity and low-emissivity layer in order to maximize the absorbed solar energy and reduce thermal energy losses. Fig. 2 shows the integrated system "adsorber/solar collector", installed inside an insulated metallic housing. This is equipped with shutters that can be opened during the adsorption phase, allowing the adsorption heat dissipation from the activated carbon to the external ambient. Moreover, the tilt angle of the adsorber/solar collector can be adjusted in order to set its optimal value on the basis of the installation latitude and of the time of year.
The present adsorber can be partially disassembled for tests with a variable number of tubes and material mass in order to understand the sensitivity of these parameters on the machine performance. In addition, this design allows the refilling the tubes with different adsorbent materials for a screening on the more suitable material for ice making, its optimal grain size, etc.

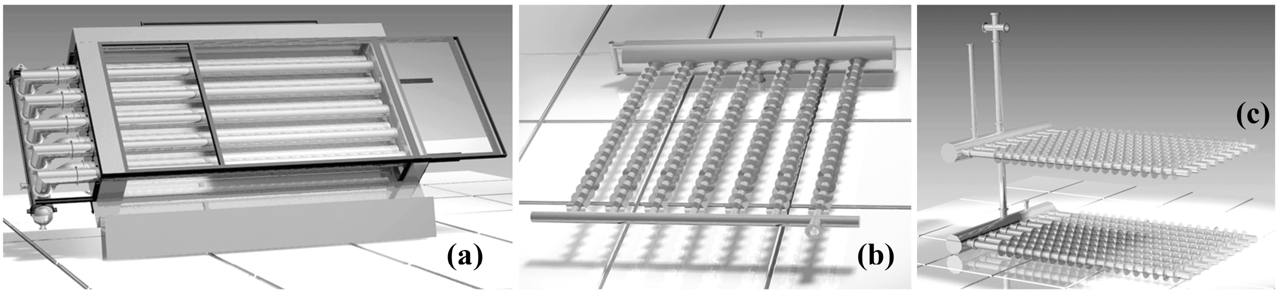

Figure 2: Schematic of the adsorber/solar collector (a), condenser/receiver (b), evaporator (c)

The specifically designed air-cooled condenser consists of seven finned tubes connected to a cylindrical receiver for collection of the condensate methanol (Fig. 2). When the desorption phase is completed, the liquid methanol collected into the receiver is passed to the evaporator through an automatic valve.
The evaporator (Fig. 2) consists of eighteen finned tubes organized in two interconnected levels. This configuration offers large heat exchange surface and high heat transfer rate. All finned tubes convey the refrigerant to two cylindrical collectors. The tubes can be partially disassembled from the collectors for sensitivity analysis purposes.
The evaporator 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 (food, medicines, water). In the presented tests, water to be iced has been located in four bins. In one of these a thermocouple is devoted to monitor the temperature evolution during the tests.
Regarding the construction material, stainless steel AISI 304 has been selected as most suitable metal to avoid corrosion problems on the methanol used as refrigerant (Hu, 1998).
Fig. 3 shows a 3D computerised view of the prototype and the real apparatus equipped with the auxiliary devices. The three main components previously described, mounted on a proper metallic framework, are suitably interconnected by a pipe system and a set of vacuum valves. The system is equipped with pressure (piezoresistive) and temperature sensors (thermocouple type T, class1), with

accuracy respectively of ±2 mbar and ±0.5°C. They allow to monitor the evolution of the ad/desorption cycle as well as of the most relevant operational variables. A pyranometer for the measurement of the global radiation is also installed on the same plane of the solar collector.

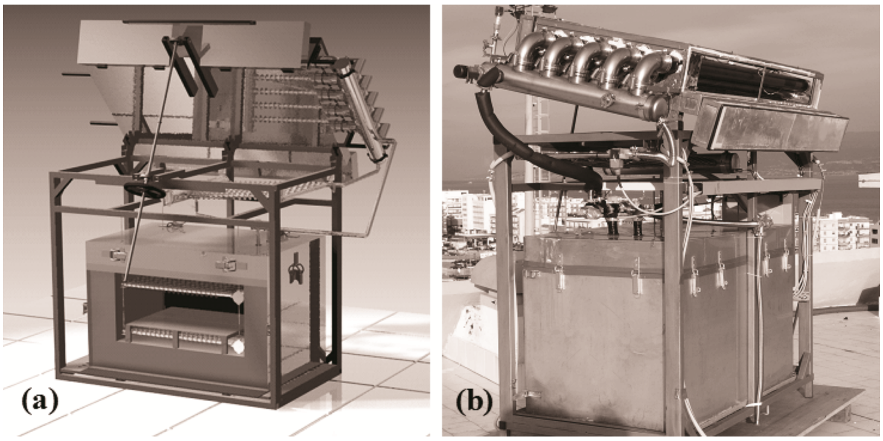


Figure 3: The solar-powered adsorption ice maker in a rendering design (a) and a real (b) view

All sensors and automatic valves have been interfaced with a data acquisition and control system. A specific software developed in Labview® environment, allows to operate the ice maker automatically. The overall dimensions of the machine are approx. 1.7x1.5x0.95 m, while the total weight is about 500 kg. The main features of the prototype are reported in Table 1.

Table 1: Main features of the ice maker.

| | |
|---|---|
| **Solar Collector** | |
| Exposed area | 1.2 $m^2$ |
| Selective surface: | SolMax Foil (α= 95-99%; ε= 4-10%) |
| Tube bundle | 5 tubes DN 60x1.73m + 5 tubes DN 60x1.63 m |
| Total Surface | 3.7 $m^2$ |
| Adsorbent material | SRD 1352/3 Chemviron Carbons Ltd |
| Adsorbent Mass | 20 kg |
| Grain size | 0.6-1.7 mm |
| **Condenser** | Air-cooled , 7 finned tubes DN 16, length 1 m<br>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 $m^3$ |
| Insulation material | Polyurethane foam |

## Experimental results and discussion

The prototype is installed on the roof of the CNR-ITAE building in Messina (38° 11' latitude N). In order to maximize the collected solar energy, the prototype is oriented towards south with an angle of inclination of about 38°. A complete adsorbent evacuation to flush out air and residual gases has been performed using a vacuum pump for 8 h and heating the carbon in a sunny day until to reach a maximal temperature of about 95°C. 7 liters of methanol have been loaded in the system. This quantity represents an optimal value, obtained using the developed model. It is able to produce the cooling effect required as well as to produce a constant reservoir in the evaporator of almost 2 litres, useful to promote the evaporation process.

The presented field tests have been performed during two typical days, respectively on 11 February 2013 (winter season) and on 20 March 2013 (spring season). The climatic operational conditions are reported in Fig. 4. The solar energy provided is quite similar, even though a slightly higher cloudiness is recorded on the March test. The ambient temperatures range between a minimum difference of 0.3°C during the night and a maximum difference of 4.3°C during the day. These features of the selected days make them useful for comparison purposes about the influence of the condensing temperature on the performance of the system. Table 2 resumes the phases scheduling of the thermodynamic cycles performed.

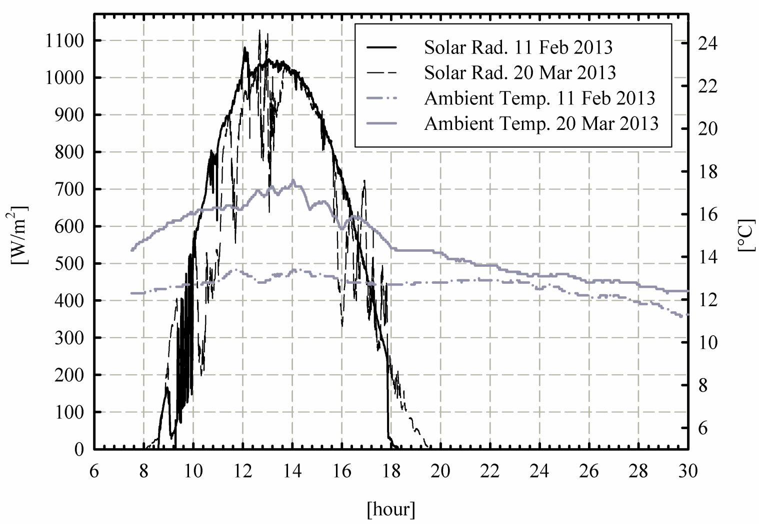


Figure 4: Climatic conditions in Messina during 11 February 2013 and 20 March 2013

Table 2: Scheduling of the phases of the thermodynamic cycles performed

| | Start time of the operational phase | Solar Radiation [W/m$^2$] |
|---|---|---|
| **11 February 2013 (Sunrise: 6:54; Sunset: 17:30)** | | |
| Isosteric heating | 7:30 (+0:36 sunrise) | 0 |
| Desorption[1] + cold box opening | 9:30 (+2:36 sunrise) | 145 (at 9:30); 1081 (Peak) |
| Isosteric Cooling + water substitution | 18:30 (+1:00 sunset) | 0 |
| Adsorption[2] | 19:15(+1:45 sunset) | 0 |
| **20 March 2013 (Sunrise: 6:00; Sunset: 18:10)** | | |
| Isosteric heating | 7:00 (+1:00 sunrise) | 0 |
| Desorption | 9:30 (+3:30 sunrise) | 225 (at 9:30); 1024 (Peak) |
| Cold box opening | 10:40 | 430 |
| Isosteric Cooling+ water substitution | 18:40(+0:30 sunset) | 80 |
| Adsorption | 20:00(+1:50 sunset) | 0 |

[1] valve V1 open, V2 closed
[2] valve V1 closed, V2 open

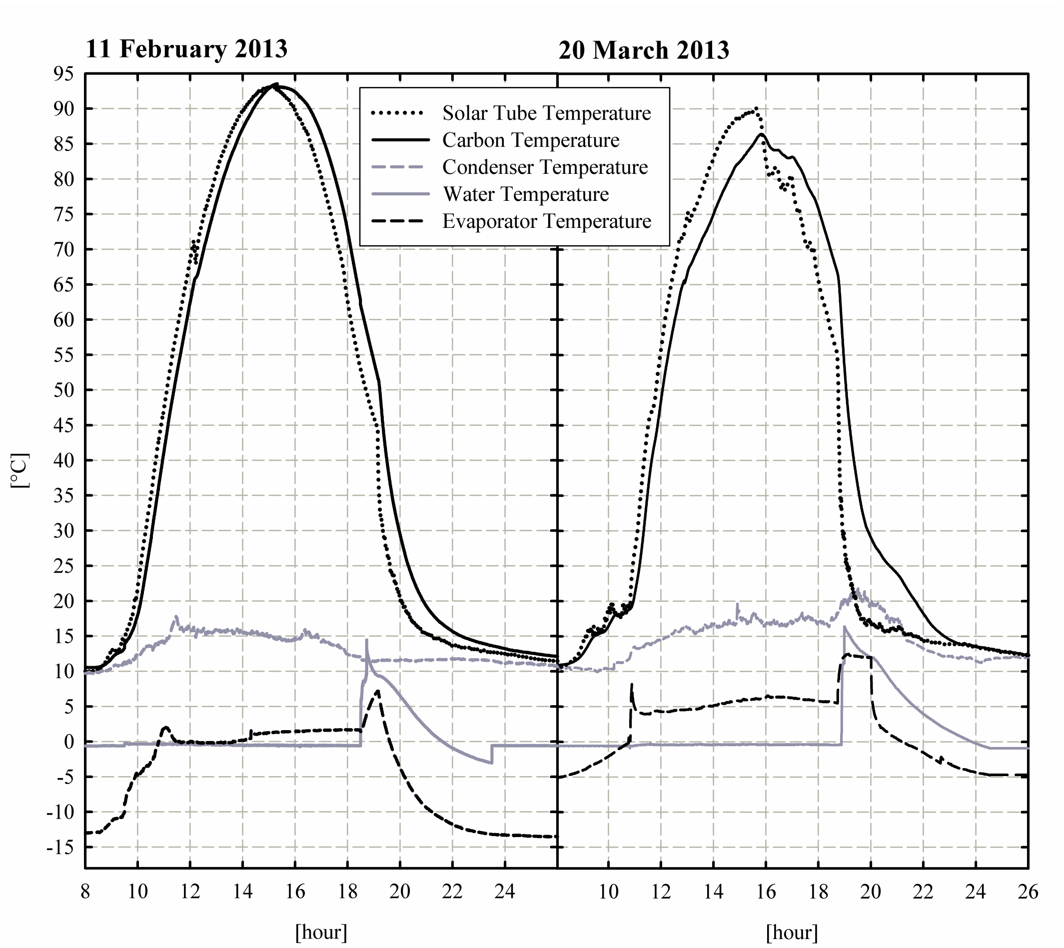

Figure 5: Dynamic profile of the operational temperatures of the system in 11 February 2013 and 20 March 2013

During the diurnal time, the solar radiation is effectively captured allowing to reach high temperatures on the adsorbent grains in both the days. It can be seen from Fig.5 that carbon temperature rises steadily until to achieve its maximum, near to 93°C and 85°C respectively on February and March test. These values guarantee a sufficient desorption of refrigerant, especially in the first case. The time shift between the tube temperature and the activated carbon temperature reflects the thermal inertia of the adsorbent bed, giving a measure of the system heating dynamics and of the efficiency in the solar tubes/adsorbent material heat transfer. About 6 hours are requested to reach the maximal tubes temperature while another hour is needed to get the adsorbent temperature peak.
At the end of the isosteric heating phase the cold box is opened to check the quantity of ice produced during the previous night. Since air at ambient temperature replaces the cold one inside the box, an increase of evaporator temperature is observed. This increase is not registered in the ice temperature profile thanks to its high latent heat of fusion and to the good cold box thermal insulation. In fact the ice temperature remains constant equal to around 0°C until the start of isosteric cooling, which is the moment of the ice substitution with fresh water. At the same time a steep increase of the evaporator temperature occurs as the barely warm condensed refrigerant moves from the condenser to the evaporator.
During the night time (adsorption phase) the external temperature permits to cool down the adsorbent bed promoting the methanol adsorption and the consequent useful cooling effect in the cold box.
The evaporator temperature (measured on the external surface of the heat exchanger) decreases respectively to -13.6°C on 11 February and -5.3°C on 20 March allowing the cooling of the air

closed in the box and the subsequent ice production (Fig. 6). These minimal temperature values are reached in about 5 hours since the beginning of the adsorption phase. This confirms the sufficient heat transfer performance of the evaporator. In the presented test 5 kg and 4.6 kg of ice have been produced and suitably preserved for all the next day.
The solar Coefficient Of Performance ($COP_s$) of 0.08 on 11 February and of 0.063 on 20 March are obtained. The $COP_s$ is defined in eq. (1).

$$COP_S = \frac{Q_e}{Q_t} = \frac{Q_{sw}+Q_L+Q_{si}}{Q_t} = \frac{m_w c_{pw}\Delta T_w + m_i \Delta L + m_i c_{pi}\Delta T_i}{A\int_0^t I(t)dt} \quad (1)$$

It is the ratio between the useful cooling effect $Q_e$ and the daily collected solar energy $Q_t$ , incident on the solar collector surface. The $Q_e$ value is a sum of the sensible heat and the latent heat of liquefaction of the water. The global performance of the prototype are summarized in table 3.

Figure 6: Ice produced in the bins

Table 3 Performance of the ice maker

| Day | 11 February 2013 | 20 March 2013 |
|---|---|---|
| Solar Radiation Energy [kJ] | 28664 | 26961 |
| $COP_{solar}$ [1] | 0.08 | 0.063 |
| Daily ice production [kg] | 5 | 4.6 |
| Maximal Carbon Temperature [°C] | 93.0 | 86.4 |
| Average Ambient Temperature[2] [°C] | 13.0 | 16.2 |
| Minimal Evaporator Temperature [°C] | -12.4 | -5.7 |

[1] $COP_{solar}$ is calculated as reported in (Vasta et al., 2008)
[2] Considering only the diurnal period affecting the desorption phase

Results show the meaningful influence of the total radiation captured as well as of the diurnal ambient temperature. Decreasing by 7 % the first parameter as well as increasing by 3°C the second one, the overall system performance show a reduction about equal to 20%. In fact the solar radiation affects the maximum adsorbent temperature reached, influencing the driving force for the desorption stage. In general higher desorption temperatures are desirable and-this could be obtained reducing the thermal inertia of bed. The diurnal ambient temperature is another important operational parameter because it affects the methanol condensation rate. Operating at slightly higher ambient temperature then the design ambient temperature, coupled with a slight decrease in the desorption temperatures, leads to a plentiful decrease in the machine performance.
First tests conducted in real operating conditions highlight as a great care should be taken in the system design, tailoring the components on the local climate of the installation, in order to develop high performance units.
Optimized condensers should be designed in climate with high diurnal average ambient temperature, while areas with partially cloudy weather need solar collectors able to capture efficiently the solar radiation and to store it powerfully in the absorbed heat.

## Conclusions

In this paper a novel experimental solar-powered adsorption ice maker, employing the working pair activated carbon/methanol, is presented. The prototype has been designed after an accurate optimization based on a mathematical model. The latter was specifically developed with the aim of performing experimental sensitivity analyses both on the components features and on climatic conditions.

The first outdoor field tests, performed at CNR-ITAE in Messina (~38° latitude N), show that the system in its basic configuration is able to produce up to 5kg of ice per day with a solar COP of 0.08. The produced ice is suitably stored for all the following day, when a new cycle start. This confirms the possibility to employ this technology for vaccines or foods conservation in remote areas.

Furthermore the test have confirmed that the technology is compliant with the requirements of the main humanitarian organizations in supporting aid operations.

The results suggest that great care must be taken in the design of the machine components about the operational weather conditions. In fact the performance drop when the machine is operated with slightly higher diurnal temperatures or less solar irradiation. Future activities concern a deeper sensitive analysis aiming at identify the most relevant construction parameter where to focus the optimization efforts. On the basis of this study a new, more compact and market-attractive prototype can be developed.

## Acknowledgements

This work has been partially founded by Rotary International Districts 2030, 2040, 2050, 2070, 2080, 2090, 2100, 2110, 2120.

## Nomenclature

| | |
|---|---|
| $COP_s$ | solar coefficient of performance |
| $Q_e$ | useful effect (heat of cooling) [J] |
| $Q_t$ | solar energy incident on the surface of the solar collector [J] |
| $Q_{sw}$ | sensible heat of cooling of the water [J] |
| $Q_L$ | latent heat of liquefaction of water [J] |
| $Q_{si}$ | sensible heat of sub-cooling for the ice [J] |
| $m_w$ | mass of water in the bins [kg] |
| $c_{pw}$ | specific heat of water in ambient conditions [J/(kg K)] |
| $T_w$ | water temperature [K] |
| $m_i$ | mass of ice [kg] |
| $\Delta L$ | latent heat of liquefaction [J/kg] |
| $c_{pi}$ | specific heat of the ice in ambient conditions [J/(kg K)] |
| $T_i$ | temperature of the ice [K] |
| $I(t)$ | global solar radiation incident on the tilted plane of the solar collector [$W/m^2$] |
| $A$ | incident surface of the solar radiation [$m^2$] |

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