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Design Of A Solar Adsorption Ice-Making Machine In Antsiranana, Madagascar

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Abstract - This work presents the first experimental demonstration of a locally built solar adsorption ice-making machine in Madagascar, using the activated carbon AC-35 / methanol pair in Antsiranana. Two experimental tests carried out in May 2023 produced up to 2,47 kg (3,53 kg/m²/day) and 2,84 kg of ice (4,06 kg/m²/day) respectively, both exceeding the Mhiri & El Golli (1996) reference of 3,05 kg/m²/day despite regeneration temperatures below the nominal value. These results are based on a complete thermodynamic study and the sizing of a prototype founded on the Dubinin-Astakhov (D-A) model, with the analytical calculation of adsorbed masses ($x_{max} = 0,2194\ kg/kg, x_{min} = 0,0447\ kg/kg, \Delta m = 0,1747\ kg/kg$) and the construction of the Clapeyron thermodynamic cycle. Operating temperatures are established under worst-case conditions from twelve years of climatic data from Antsiranana : $T_a = 26,45\ °C, T_c = 31,9\ °C, T_e = -6\ °C\ and\ T_g = 110\ °C$. The thermal balance gives $Q_f = 1\ 382\ 970\ J$ for a nominal production of 3 kg of ice per day, $Q_c = 2\ 810\ 556\ J$, a $COP_{th} = 0,492$ consistent with the literature range for this pair (0,38–0,55, Passos and al. 1986), and a $COP_s = 0,235$ in the upper range of solar adsorption refrigeration. The hexagonal aluminum-zinc sheet adsorber ($e = 0,35\ mm$, $Bi = 2,2 \times 10^{-5} \ll 1$) constitutes a constructive innovation suited to local manufacturing, with a moderate thermal penalty of $\Delta COP_{th} = -0,036$ relative to copper. These results confirm the technical viability and reproducibility of solar adsorption refrigeration under Madagascar's climatic conditions.

Keywords : solar refrigeration, adsorption, AC-35 activated carbon, methanol, ice machine, COP_{th}, COP_s.

1. INTRODUCTION

Given climate change and the depletion of conventional energy resources, solar energy stands out as an inexhaustible and clean alternative whose exploitation is particularly relevant in Antsiranana, a city in northern Madagascar that benefits from exceptional sunshine of 4,5 to 7,2 kWh/m²/day, yet where much of the population still lacks access to electricity. Solar adsorption refrigeration systems, which operate without moving parts or electricity consumption through an intermittent day-night cycle, offer a solution well suited to this off-grid context. Since the foundational work [1] (Delgado and al., 1982) on the AC-35 activated carbon / methanol pair, this field has seen significant development [2] (Buchter and al., 2003), [7] (Djebiret and al.,

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2019), yet no prototype had previously been built or tested in Madagascar. The present work addresses this gap by presenting a complete thermodynamic study based on the Dubinin-Astakhov model, the sizing of each component, the experimental realization of a prototype using locally available materials, and the results of two experimental tests conducted on May 5 and 6, 2023.

2. LITERATURE REVIEW

Solar adsorption refrigeration systems have been the subject of numerous studies since the pioneering work [1] (Delgado and al., 1982), who demonstrated as early as 1982 the feasibility of the AC-35 activated carbon / methanol pair for solar-powered ice production. [11] (Passos and al., 1986) laid the theoretical foundations of the intermittent cycle for this pair, showing that COP_{th} can reach 0,40 to 0,55 depending on operating temperatures. On the experimental side, [5] (Mhiri and El Golli, 1996) achieved a specific production of 3,05 kg of ice per m² of collector per day with a COPs of 0,14 to 0,19, while [3] (Hildbrand and al., 2004) reached a COP_s of 0,10 to 0,22 in Switzerland using the silica gel / water pair. In Africa, [2] (Buchter and al., 2003) confirmed the applicability of this technology in Burkina Faso, [4] (Lemmini and Errougani, 2005) obtained a COP_s of 0,04 to 0,08 in Morocco, and [6], [7] (Djebiret and al., 2015 and 2019) experimentally validated a COP_{th} of 0,43 to 0,47 in Algeria. Taken together, these studies confirm that the AC-35/methanol pair is particularly well suited to solar ice production, and that the Dubinin-Astakhov model remains the reference modeling tool for this pair [8] (Pons and Grenier, 1986), with performance strongly governed by local operating temperatures. None of these studies, however, was conducted in Madagascar.

3. METHODOLOGIES

3.1 Study site and climatic data of Antsiranana

Antsiranana (12° 25′ S, 49° 17′ E) is located at the northern tip of Madagascar, in a dry tropical climate zone tempered by south-easterly trade winds. The city enjoys high annual sunshine, with global irradiation ranging from 4,5 to 7,2 kWh/m²/day depending on the month.

3.1.a. Operating temperatures

The cycle's operating temperatures are established from climatic statistics recorded at the Antsiranana meteorological station over twelve years (2011–2022). The design follows a worst-case sizing principle, ensuring that the system will operate reliably under all climatic conditions encountered at the site.

Table 1 : Retained operating temperatures

Parameter	Symbol	Value [°C]	Justification
Evaporation temperature	T_e	- 6	Target temperature of the cold chamber for ice production.
Adsorption temperature	T_a	26,45	Maximum nighttime value over 12 years, worst-case for adsorption.
Condensation temperature	T_c	31,9	Maximum daytime value over 12 years, worst thermodynamic case.
Regeneration temperature	T_g	110	Methanol usage limit (decomposition above 120°C).

The maximum nighttime temperature $T_a = 26,45\,°C$ is chosen because adsorption at higher temperatures is less efficient according to the D-A model, thereby representing the most unfavorable condition. The temperature $T_c = 31,9\,°C$ corresponds to the maximum daytime ambient temperature, which imposes the highest condensation pressure and consequently reduces the cycled mass Δm.

3.1.b. Solar irradiation

The minimum daily irradiation in Antsiranana occurs in June (dry season). For worst-case sizing.

The daily irradiation is expressed as :

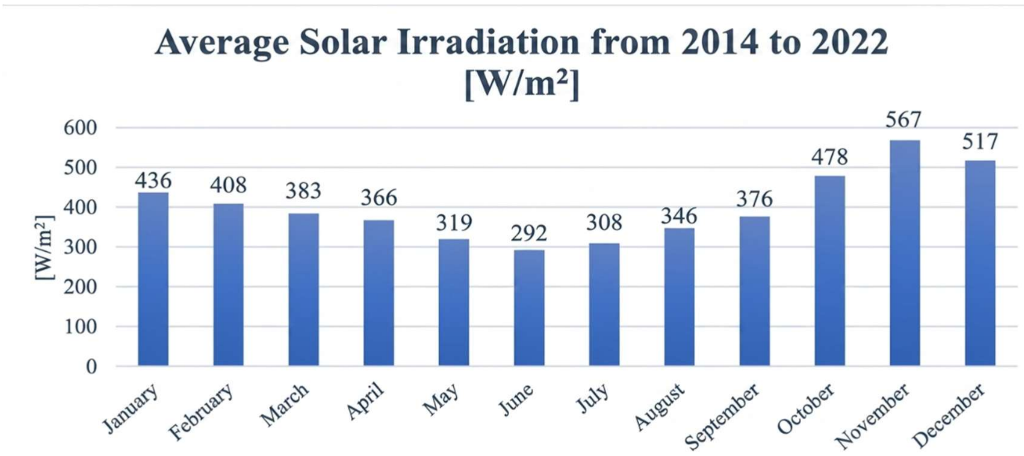

Figure 1 : Monthly average solar irradiation over 9 years

$$H = G_{avg}.t_{eff} \quad (1)$$

Where :

H : daily irradiation [J/m^2/day] ;

G_{avg} : average daily solar irradiation [W/m^2] ;

t_{eff} : effective sunshine duration [s].

Hence

$$H = 292 \times (8 \times 3600)$$

$$H = 8{,}41\ MJ/m^2/day$$

This value is conservative : the months of October to December show irradiation exceeding 400 W/m², approximately 40% higher than the design case.

3.2. Thermodynamic model and adsorption equilibrium

3.2.a. Operating principle

The solar adsorption ice machine operates according to an intermittent day-night cycle. During the day, solar radiation heats the adsorber containing AC-35 activated carbon impregnated with methanol. The rise in temperature causes the methanol to desorb, condensing in the air condenser. At night, the adsorber cools down, its pressure drops, and it adsorbs methanol vapor from the evaporator. The evaporation of methanol draws latent heat from the water inside the cold chamber, producing ice.

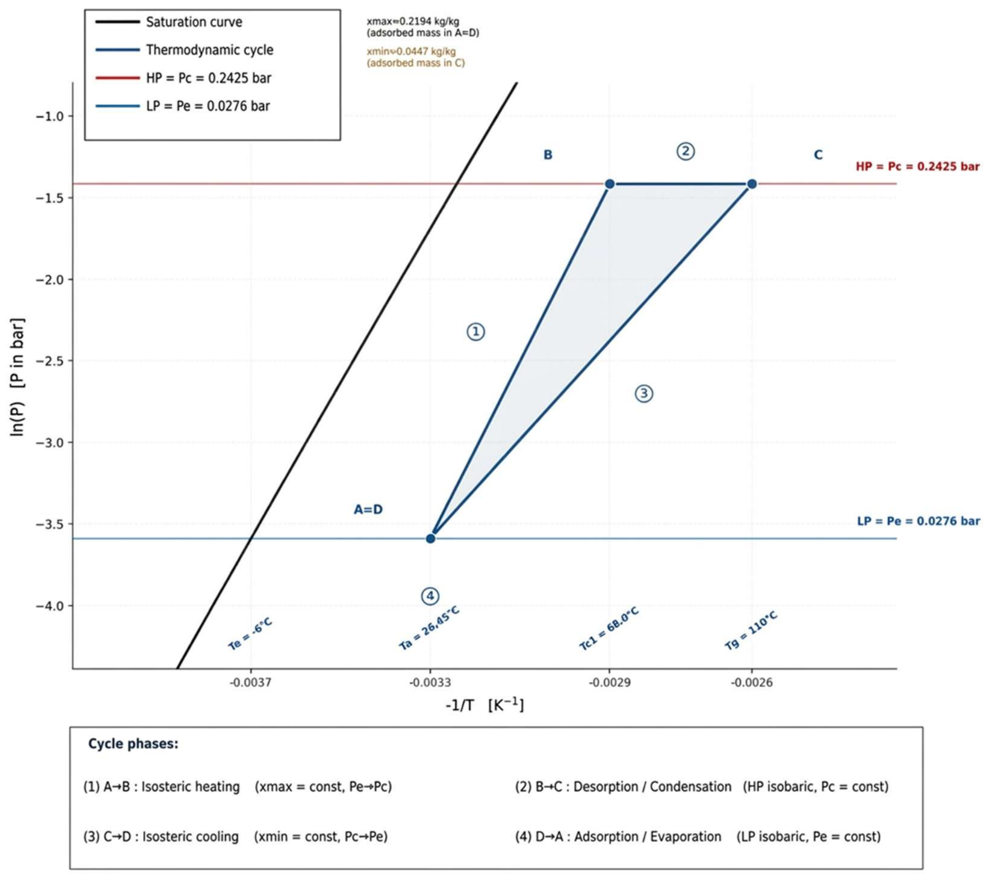

Figure 2 : Ideal Clapeyron thermodynamic cycle of the AC-35/methanol solar ice-making machine in Antsiranana

The cycle consists of four phases represented in the Clapeyron diagram (Figure 2) :

3.2.b. Dubinin-Astakhov model

The adsorption equilibrium of the AC-35 activated carbon / methanol pair is described by the Dubinin-Astakhov (D-A) model [8] (Pons and Grenier, 1986), expressed as :

$$m(T,P) = W_0.\rho_l(T).exp\left[-D\left(T_K\, ln\frac{P_S(T)}{P}\right)^n\right] \qquad (2)$$

where m is the mass of methanol adsorbed per unit mass of activated carbon [kg meth/kg AC], W_0 the micropore volume [m³/kg], $\rho_l(T)$ the density of liquid methanol [kg/m³], T_K the absolute temperature [K], $P_s(T)$ the saturation vapor pressure of methanol [bar], and P the equilibrium pressure [bar].

The model parameters for the AC-35/methanol pair were determined experimentally by [8] (Pons and Grenier, 1986).

Table 2 : D-A model parameters for AC-35/methanol

Parameter	Symbol	Value	Unit	Source
Microporous volume	W_0	0,425 × 10⁻³	m^3/kg	[8] Pons & Grenier, 1986
D-A constant	D	5,02 × 10⁻⁷	$(K.ln)^{-n}$	[6] Djebiret and al., 2015
Heterogeneity exponent	n	2,15	-	[8] Pons & Grenier, 1986

The density of liquid methanol is given by [9] (M. Diny, 1996):

$$\rho_l(T) = 1283{,}31 - 3{,}3389.T_K + 8{,}652.10^{-3}.T_K{}^2 - 1{,}017.10^{-5}.T_K{}^3 \quad (3)$$

The saturation vapor pressure of methanol is calculated using the Antoine equation :

$$log_{10}(P_s) = 5{,}20409 - 1580{,}674/(T_c + 239{,}726) \quad (4)$$

3.2.c. Adsorbed masses and cycled mass

The operating pressures are calculated from equation (4) :

$$P_e = P_s(T_e) = P_s(-6°C) = 0{,}0276\ bar \quad (5)$$

$$P_c = P_s(T_c) = P_s(31{,}9°C) = 0{,}2425\ bar \quad (6)$$

The adsorbed masses at the two isosteres of the cycle are calculated analytically using equation (2) :

$$x_{max} = m(T_a, P_e) = m(26{,}45\ ;\ 0{,}0276) = 0{,}2194\ kg/kg \quad (8)$$

$$x_{min} = m(T_g, P_c) = m(110\ ;\ 0{,}2425) = 0{,}0447\ kg/kg \quad (9)$$

$$\Delta m = x_{max} - x_{min} \quad (10)$$

$$\Delta m = 0{,}1747\ kg/kg$$

3.2.d. Threshold temperatures of the cycle

The threshold temperatures T_{c1} (start of desorption) and T_{c2} (start of adsorption) are determined by analytically solving the isostere equalities :

$$T_{c1}: m(T_a\ ; P_e) = m(T_{c1}\ ; P_c) \ \rightarrow\ T_{c1} = 68{,}0\ °C \quad (11)$$

$$T_{c2}: m(T_g\ ; P_c) = m(T_{c2}\ ; P_e) \ \rightarrow\ T_{c2} = 61{,}4\ °C \quad (12)$$

3.3 Thermal balance and sizing

3.3.a. Cooling capacity required Q_f

The daily cooling capacity required to produce ice $m_{ice} =\ 3\ kg$ from water at 25 °C is the sum of three contributions :

$$Q_f = Q_0 + Q_1 + Q_2 \quad (13)$$

$$Q_0 = m_{water}.Cp_{water}.\Delta T \quad (14)$$

$$= 3{,}3 \times 4180 \times 25$$

$$Q_0 = 344850\,J$$

$$Q_1 = m_{ice}.L_f \qquad (15)$$

$$= 3{,}0 \times 333500$$
$$Q_1 = 1000500\,J$$

$$Q_2 = m_{ice}.Cp_{ice}.|T_e| \qquad (16)$$

$$= 3{,}0 \times 2090 \times 6$$

$$Q_2 = 37620\,J$$

$$Q_f = 344850 + 1000500 + 37620$$

$$Q_f = 1383\,kJ$$

3.3.b. Mass of methanol and activated carbon

The mass of methanol evaporated per cycle is given by the thermal equilibrium at the evaporator :

$$m_{meth} = Q_f/[L_v(T_e) - Cp_l.(T_c - T_e)] \qquad (17)$$

With $L_v(T_e = -6\,°C) = 1193633\,J/kg$ (calculated using the correlation of [1] (Delgado and al., 1982)) and $Cp_l = 2380\,J/kg \cdot K$;

$$m_{meth} = 1382970/[1193633 - 2389.(37{,}9)]$$

$$m_{meth} = 1{,}253\,kg$$

The mass of activated carbon is derived from the cycled mass :

$$m_a = m_{meth}/\Delta m \ (18)$$

$$= 1{,}253 / 0{,}1747$$

$$m_a = 7{,}17\,kg$$

3.3.c. Heat supplied to the adsorber Q_c

The daily heat Q_c to be supplied to the adsorber comprises four terms [6] (Djebiret and al., 2015) :

$$Q_c = Q_{1c} + Q_{2c} + Q_{3c} + Q_{des} \qquad (19)$$

$$Q_{1c} = m_a.Cp_{CA}.(T_g - T_a) \qquad (20)$$

$$= 7{,}17 \times 920 \times 83{,}55$$

$$Q_{1c} = 551129\,J$$

$$Q_{2c} = m_{metal}.Cp_{metal}.(T_g - T_a) \qquad (21)$$

$$= 4{,}45 \times 900 \times 83{,}55$$

$$Q_{2c} = 334618\,J$$

$$Q_{3c} = m_{meth.moy}.Cp_l.(T_g - T_a) \qquad (22)$$

$$= 0{,}946 \times 2380 \times 83{,}55$$

$$Q_{3c} = 188411\,J$$

$$Q_{des} = \Delta m.m_a.\Delta H \quad (23)$$

$$= 0{,}1747 \times 7{,}17 \times L_V(31{,}9)$$

$$Q_{des} = 1736398\, J$$

$$Q_c = 551129 + 334618 + 188411 + 1736398$$

$$Q_c = 2\,810\,556\, J$$

$$Q_c = 2\,810\, kJ$$

3.3.d. Performance coefficients

The thermodynamic coefficient of performance is defined as the ratio of the cooling capacity produced to the heat supplied to the generator [6] (Djebiret and al., 2015) :

$$COP_{th} = Q_f/Q_c \quad (24)$$

$$= 1382970/2810556$$

$$COP_{th} = 0{,}492$$

The solar coefficient of performance, a standard benchmark in the literature [3] (Hildbrand and al., 2004), [4] Lemmini and Errougani, 2005), is defined as :

$$COP_s = Q_f/(H.S) \quad (25)$$

$$= 1382970/(8410000 \times 0{,}70)$$

$$COP_s = 0{,}235$$

3.3.e Component sizing

This table summarizes the calculated dimensions for each component of the prototype.

Table 3 : Prototype sizing results

Component	Expression	Numerical calculation	Retained result
Collector-adsorber	$S = Q_c/(\eta.H)$; $\eta = 0{,}40$	$= 2810556/(0{,}40 \times 8410000)$	0,70 m² (1000×700 mm)
Methanol mass	$m_{meth} = Q_f/[L_v(T_e) - Cp_l.(T_c - T_e)]$	=1 382 970/1 103 431	1,253 kg
Activated carbon mass	$m_a = m_{meth}/\Delta m$	=1,253/0,1747	7,17 kg AC-35
Evaporator	$S_{ev} = P_{ev}/(K.\|T_e\|)$	=96/(150×6)	1 067 cm²
Condenser	$L = S_{cond}/(\pi.d_{ext})$	=0,041/(π×0,008)	1,63 m (8 mm tube)
No. of adsorber prisms	$N = \lceil V_{CA}/V_{hex} \rceil$	=⌈17,93/8,31⌉	3 hexagonal prisms

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3.4. Prototype realization

3.4.a. General Design

The prototype built in Antsiranana comprises three main elements: the collector-adsorber, the condenser, and the refrigerated chamber equipped with its evaporator. The entire thermodynamic circuit is maintained under vacuum, with an operating pressure ranging between 0,027 bar (low pressure, evaporator side) and 0,243 bar (high pressure, condenser side), a condition essential for methanol evaporation at the low temperatures required by the refrigeration cycle.

3.4.b. Hexagonal collector-adsorber : a constructive innovation

The prototype's main originality lies in the hexagonal geometry of the adsorber, made from aluminum-zinc sheet metal (thickness

Figure 3 : Solar ice-making machine built in Antsiranana

$e = 0{,}35\ mm\ e$, $\lambda = 160\ W/m.K$). This choice is motivated by three reasons: local availability of the material in Antsiranana, ease of shaping by folding without specialized equipment, and adequate thermal conductivity.

The thermal resistance of the sheet metal is verified using the Biot number :

$$Bi = h.e/\lambda \qquad (26)$$

h: natural convection coefficient between air and the sheet metal [$W/m^2.K$]

$$Bi = 10 \times 0{,}00035/160$$

$$Bi = 2{,}2.10^{-5} << 1$$

$Bi \ll 1$ confirms that the wall's thermal resistance is entirely negligible: heat transfer to the activated carbon bed is as efficient as with a solid copper tube. Three hexagonal prisms of side $a = 8\ cm$ and height $h = 50\ cm$ are used, each containing approximately 2,4 kg of AC-35 activated carbon.

The aluminum-zinc sheet has a specific heat capacity $Cp = 900\ J/kg.K$, higher than that of copper (385 *J/kg·K*). This difference results in an additional sensible heat Q_{2c} of 191 kJ per cycle, corresponding to an estimated penalty $\Delta COP_{th} \approx -0{,}036$ relative to an all-copper adsorber of the same mass. This trade-off is accepted in favour of local manufacturability.

3.4.c. Condenser and evaporator

The condenser consists of a copper tube coil with an outer diameter of 8 mm and a length of 1,63 m, immersed in a water reservoir operating by natural convection. Methanol condensation occurs through heat exchange with the reservoir water, ensuring efficient dissipation of the latent heat released during vapor liquefaction. The evaporator is a copper tank with a heat exchange surface of 1 067 cm², placed inside the refrigerated chamber, which is thermally insulated by a 5 cm layer of expanded polystyrene, ensuring minimal heat loss to the ambient environment.

4. EXPERIMENTAL RESULTS

4.1. Test procedure

Two tests were carried out on May 5 and 6, 2023, in Antsiranana. Ten type K thermocouples, connected to a data logger, recorded the temperatures of the adsorber, condenser, evaporator, and ambient environment, with readings taken every 15 minutes over a 24 hour period. The system operated through a complete day-night cycle without manual intervention.

4.2. First test

The first test was carried out on Friday, May 5, 2023, in Antsiranana.

Table 4 : Measurements taken during the 1st Test on May 5, 2023

Time (h)	T adsorber [°C]	T condenser [°C]	T evaporator [°C]	T ambient [°C]
08:00	25	25	23	24
09:30	38	27	21	26
11:00	55	29	19	28
12:30	70	32	17	30
14:00	82	34	13	30
15:00	84,6 (max)	34,0 (max)	10	29
16:00	83	33	7	29
18:00	61	29	2	27
20:00	37	26	−0,5	24
22:00	25	24	−2,0	22
00:00	23	23	−3,2	22
02:00	21	22	−3,5	21
03:00	21	22	−3,6 (min)	21
04:00	20	21	−3,0	21

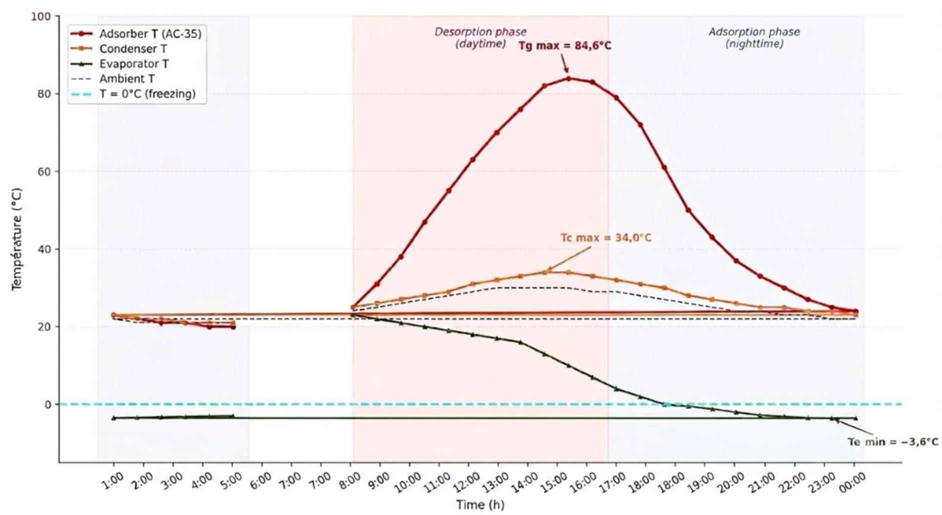

Figure 4 : Temperature evolution during the 1st test

4.2.a. Interpretation

From 8:00 am onward, solar radiation gradually heats the adsorber up to a maximum of $T_{g_{max}} = 84{,}6\,°C$ reached around 3:00 pm, triggering methanol desorption, which condenses in the water tank at $T_{c_{max}} = 34{,}0\,°C$**.** At the same time, the condensed methanol flows toward the evaporator and begins cooling it progressively during the day, with the evaporator temperature dropping from 23 °C to approximately 10 °C before 4:00 pm. From sunset onward, the adsorber cools naturally and readsorbs methanol vapour from the evaporator, intensifying cold production until a minimum of $T_{e_{min}} = -3{,}6\,°C$ is reached around 3:00 AM, confirming effective ice production inside the cold store.

4.2.b. Estimation of ice produced

The amount of ice produced during test 1 is estimated by applying the D-A model to the experimental temperatures :

$$\Delta m_{exp1} = m(T_a = 21{,}5°C\ ;\ P_{e_{ex}}\quad) - m(T_g = 84{,}6°C\ ;\ P_{c_{exp1}}) \qquad (27)$$

$$\Delta m_{ex} \quad = 0{,}1175\ kg/kg$$

$$m_{ice_{exp1}} = (Q_{f_{exp1}} - Q_{0_{water}})/(L_f + Cp_{ice} \times \left|T_{e_{exp1}}\right| \qquad (28)$$

$$m_{ice_{exp1}} \approx 2{,}47\ kg$$

The machine produced approximately 2,47 kg of ice during Test 1, corresponding to 3,53 kg/m² of collector per day. This result represents 82% of the nominal target (3 kg/day) and exceeds the specific production reported by the Mhiri & El Golli (1996) reference, which achieved 3,05 kg/m²/day with a regeneration temperature of 90 – 110 °C. Here, $T_{g_{max}} = 84{,}6\,°C$ is the favorable nighttime climatic conditions of Antsiranana alone ($T_a = 21{,}5\,°C$) compensate for the incomplete regeneration.

4.3. Second test

The second test was carried out on Saturday, May 6, 2023, in Antsiranana, the day after Test 1, under slightly better sunshine conditions.

Table 5 : Measurements taken during the 2nd test on May 6, 2023

Time (h)	T adsorber [°C]	T condenser [°C]	T evaporator [°C]	T ambient [°C]
08:00	26	25	23	24
09:30	42	29	21	27
11:00	63	33	19	30
12:30	80	36	15	31
14:00	91	37	10	31
14:45	93,4 (max)	37,0 (max)	6	30
16:00	92	35	3	30
18:00	69	31	0	27
20:00	42	27	−1,5	25
22:00	27	25	−3,0	23
00:00	24	23	−3,8	22
02:00	22	22	−4,2	22
03:30	21	22	−4,4 (min)	22
04:25	20	21	−3,7	21

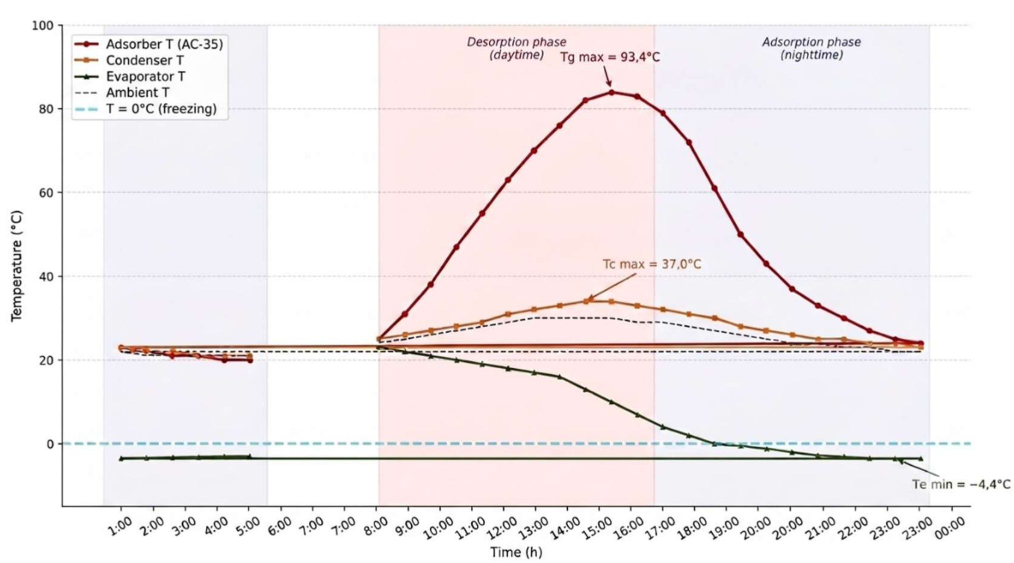

Figure 5 : Temperature evolution during the 2nd test

4.3.a. Interpretation

Benefiting from slightly higher solar irradiation than test 1, the adsorber reaches its peak $T_{g_{max}} = 93,4\ °C$ around 2:45 pm, an increase of +8,8 °C, enabling more complete desorption and condensation at $T_{c_{max}} = 37,0\ °C$. The evaporator begins cooling during the day, drops below 0 °C by 6:00 pm, and reaches $T_{e_{min}} = -4,4\ °C$ minimum around 3:30 am, 0,8 °C lower than in test 1, confirming higher ice production (~2,84 kg) thanks to more complete regeneration of the activated carbon.

4.3.b. Estimation of ice produced

The amount of ice produced during test 2 is estimated as follows:

$$\Delta m_{exp2} = m(T_a = 22°C\ ;\ P_{e_{exp2}}) - m(T_g = 93,4°C\ ;\ P_{c_{exp2}}) \quad (29)$$

$$\Delta m_{exp2} = 0,1380\ kg/kg$$

$$m_{ice_{exp2}} = (Q_{f_{exp2}} - Q_{0_{water}})/(L_f + Cp_{ice} \times \left|T_{e_{exp2}}\right| \quad (30)$$

$$m_{ice_{exp1}} \approx 2,84\ kg$$

The machine produced approximately 2,84 kg of ice during the 2nd test, corresponding to 4,06 kg/m² of sensor per day. This result represents 95% of the nominal target (3 kg/day) and clearly exceeds the Mhiri & El Golli reference (3,05 kg/m²/day). The progression observed between the two tests ($T_{g_{max}}: 84,6 \rightarrow 93,4\ °C;\ glace: 2,47\ \rightarrow\ 2,8\ kg$) confirms that dry-season $T_g > 100\ °C$ conditions would allow the nominal target of 3 kg/day to be reached and even exceeded.

4.4. Comparison of performance coefficients with the literature

Table 6 : Performance coefficients of this work vs the literature

Reference	$T_e[°C]$	$T_a[°C]$	$T_c[°C]$	$T_g[°C]$	COP_{th}	COP_s	$S\ [m^2]$
[1] Delgado and al. (1982)	-10	20	20	100	0,50	0,15	4,0
[11] Passos and al. (1986)	-10	20	30	100-120	0,40-0,55	-	-
[5] Mhiri & El Golli (1996)	-5	20	30	90-120	0,38-0,47	0,14-0,19	4,0
[3] Hildbrand and al. (2004)	0	-	-	-	-	0,10-0,22	2,0
[4] Lemmini & Errougani (2005)	-	-	-	-	-	0,04-0,08	1,5
[6] Djebiret and al. (2015)	1	25	35	80-120	0,43	-	-
[7] Djebiret and al. (2019)	1	25	35-37	80-110	0,47	0,07-0,09	0,19

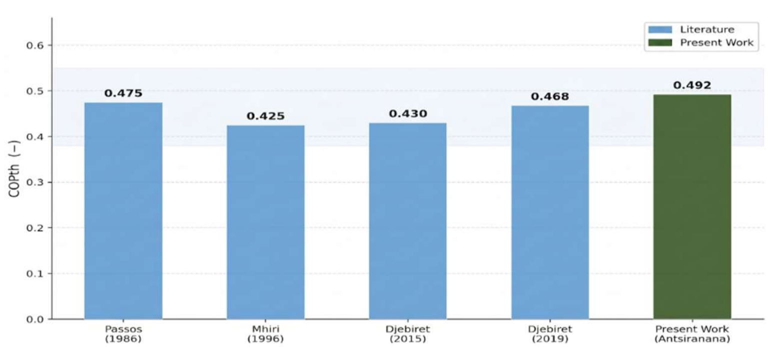

Figure 6 : Thermal coefficient of performance COP_{th} of this work vs literature

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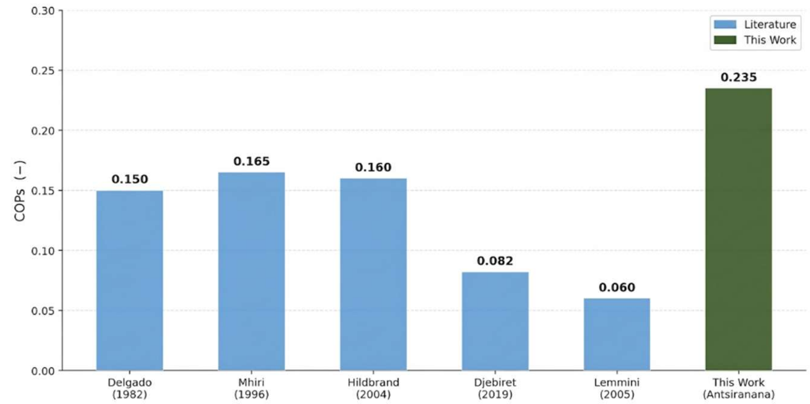

Figure 7 : Solar coefficient of performance COP_s of this work vs literature

This work in Antsiranana (2023)	-6	26,45	31,9	110	0,492	0,235	0,70

The $COP_{th} = 0{,}492$ falls within the reference range of 0,38 to 0,55 [11] (Passos and al., 1986). The $COP_s = 0{,}235$ lies in the upper range reported in the literature, explained by the favorable sunshine conditions in Antsiranana ($H_{min} = 8{,}41\ MJ/m^2/day$ in June) and the moderate nighttime temperature ($T_{a_{max}} = 26{,}45\ °C$) resulting from the trade winds.

4.5. Specific ice production

Table 7 : Specific ice production of this work compared with the literature

Reference	Specific production [*kg/m²/day*]	T_g [°C]	Type
Delgado et al. (1982)	6,25	100	Simulation
Mhiri & El Golli (1996)	3,05	90 – 110	Simulation
Djebiret et al. (2019)	(Te=+1°C)	80 – 110	Laboratory
This work (1st test)	3,53	84,6	Experimental
This work (2nd test)	4,06	93,4	Experimental

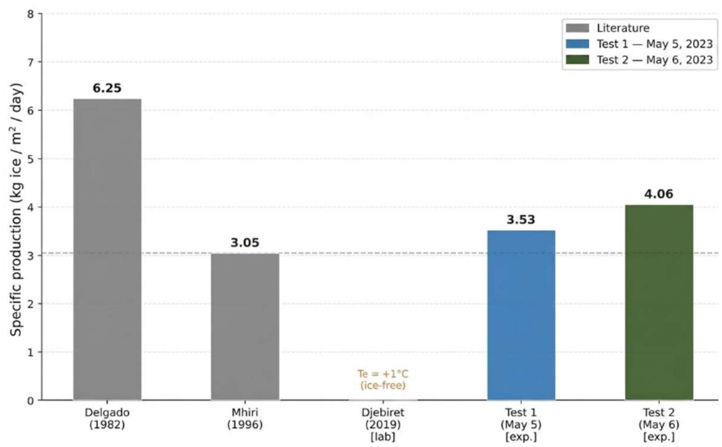

Figure 8 : Specific ice production tests 1 and 2 vs literature

5. DISCUSSION

The results of both tests confirm the technical feasibility of the prototype. The experimentally cycled masses ($\Delta m_{exp1} = 0{,}1175\ kg/kg,\ \Delta m_{exp2} = 0{,}1380\ kg/kg$) are consistent with the D-A model, and the deviation from the nominal value (0.1747 kg/kg) is entirely explained by the measured regeneration temperatures (84,6 °C and 93,4 °C), both lower than the design value of 110 °C. Despite this gap, both tests exceed the reference specific production reported by [5] (Mhiri and El Golli, 1996) (3,05 kg/m²/day), reaching 3,53 and 4,06 kg/m²/day respectively, thanks to the moderate nighttime adsorption temperature in Antsiranana ($T_a \approx 21 - 22\ °C$), which maximizes the adsorbed mass and compensates for the incomplete regeneration. COPth falls within the range reported in the literature (0,38 – 0,55), and $COP_s = 0{,}235$ lies in its upper range, with the thermal penalty associated with the aluminum-zinc material remaining moderate. The gap between the measured and nominal T_g reflects thermal losses at the collector, which could be reduced by adding a glazing cover an improvement that, combined with dry-season irradiation ($H > 400\ W/m^2$), would allow the system to reach higher regeneration temperatures $T_g > 100\ °C$ and achieve the nominal production target of 3 kg of ice per day.

6. CONCLUSION

This work represents the first experimental demonstration of a locally built solar adsorption ice machine in Madagascar. The functional prototype developed in Antsiranana, based on the AC-35 activated carbon / methanol pair and a hexagonal aluminum-zinc sheet adsorber, validates both the thermodynamic approach through the D-A model and the constructive feasibility using locally available materials. The May 2023 tests produced 2,47 to 2,84 kg of ice per day over a 0,70 m² sensor, exceeding the specific production reported by the Mhiri & El Golli (1996) reference despite non-optimal irradiation conditions confirming that Antsiranana's nighttime climatic conditions represent a natural advantage for this type of system. These results pave the way for scaling up toward community-based food preservation applications in off-grid areas of Madagascar, with immediate next steps including sensor optimization through glazing and performance validation during the dry season.

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