Solar adsorption refrigeration unit (SARU)

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Abstract This paper describes a solar adsorption refrigerator for small fishing boats. The rationale for this proposal stems from the need that low-income fishers have to improve their bargaining power in the market, optimally, through the implementation of environmentally-friendly technology.

Keywords adsorption; solar concentrators; working fluids; open adsorption cycle; closed adsorption cycle

1. Introduction

Using renewable technologies like the one projected is a clear way of reducing CO_2 emissions, especially in Mexico, where almost 75% of the primary energy supply to produce electricity comes from the burning of fossil fuels. Renewable energy is a key tool for sustainable development since it can help low income groups to increase their earnings without risking the capacity of future generations to be able to do the same. In Mexico, fishing is an activity limited by the lack of resources and technology designated to this activity by the federal government. Most fishermen see their benefits reduced due to their lack of reliable preservation methods for the catch they bring to the market. We expect that by installing a solar adsorption refrigerator on their boats, the capacity and potential of carrying fresh fish will increase favorably as well as the quality and sales of their business.

Mexico is a country with a great extension of littorals. Although the Mexican fishing industry is not developed to its maximum potential, it represents an important economic sector, which provides for a vast number of families. According to the National Institute of Statistics (INEGI), there is a total capture volume of different species of 1.5 million tonnes, which turn into approximately 1.3 million tonnes in shore product (losing 0.23 million tonnes, approximately, which stands for the 15% of the initial capture), and only 0.83 million tonnes of these are actually processed, which means that only 54% of the capture is actually processed. The fishing fleet consists of 77,000 crafts of which only 4.3% are considered large (storage capacity of more than 10 tonnes), while the rest are considered small crafts.

One of the main problems associated with this industry is the conservation of the product up to its final consumption. According to INEGI, 30% of the frozen product and 42% of the canned product is lost to decomposition; this is in addition to the losses on the fresh product handling. In addition, most fishermen are grouped in co-operatives which have reduced budgets to invest in efficient conservation systems for their products.

Solar energy has great potential as an alternative energy source to the burning of fossil fuels. Every 15 seconds the earth's surface receives enough solar radiation to satisfy the [i]actual annual electricity human demand [1]. In the case of Mexico, solar incidence is considered high, with a mean global radiation of over 2000 kWh/m^2 annually.

Renewable energy will be used as an alternative to run the proposed fish conservation cooling system with relatively low management and operation costs and minimum environmental impact.

2. Solar collector

The collecting unit proposed for this system is a specifically designed flat plate solar collector that will be mounted as a roof for the fishing boat, thus enhancing working conditions due to the shadow it will cast on the fishing crew. This type of device is ideal for the meteorological conditions found in most parts of the Mexican Littoral.

A flat-plate collector is a large, shallow box (typically mounted on a roof) that heats water using the sun's energy. This type of solar collector consists of an absorber plate enclosed in a well-insulated case with a glass cover and a heat exchange fluid (typically air or water). The absorber is painted black for a maximum absorption across the solar spectrum. The sides and bottom of the collector are usually insulated to minimize heat loss. Sunlight passes through the glazing and strikes the absorber plate where solar-thermal conversion takes place. The heat is transferred to the fluid. They are usually made of metal (typically copper or aluminum) because metal is a good heat conductor. Copper is more expensive, but is a better conductor and less prone to corrosion than aluminum. In locations with average available solar energy, flat plate collectors are sized approximately one-half to one square foot per gallon of one-day's hot water use. The main use of this technology is in residential buildings where the demand for hot water has a large impact on energy bills.

Solar flat-plate collectors operate in bright sunshine and in cloudy conditions taking advantage of both direct and diffuse radiation. The working fluid could be circulated within tubes welded to the absorber plate and then used directly or as a medium for further energy conversion inside a heat exchanger. Figure 1 shows a typical flat-plate solar collector using water as the working fluid. The overall efficiency can be enhanced by optimum orientation of the collector based on simple solar geometry calculations to allow maximum radiation to impact on the absorber plate. The angle of elevation can be adjusted for optimum performance throughout the year. Conventional, simple flat-plate solar collectors have been developed for use in sunny and warm climates. Their benefits are greatly reduced during cold, cloudy and windy conditions. Furthermore, climatic influences, such as condensation and moisture, will cause early deterioration of internal materials resulting in reduced performance and system failure.

3. Adsorption

Solar energy can also be used to run adsorption cycles. Adsorption is a physical process that should be distinguished from absorption, which is a chemical process.

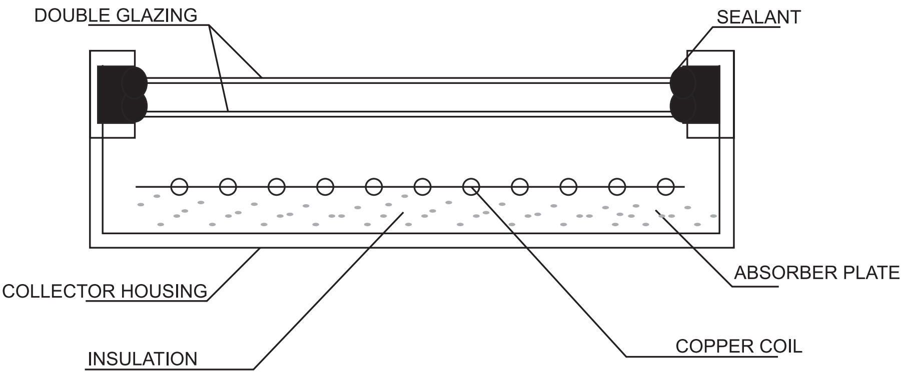

Figure 1. *Typical cross section of a flat plate solar collector.*

Just as there is an attraction between a solid and a liquid at a surface, there is also an attraction between a gas and a solid at a surface [2]. This cohesive force can be used to attract a vapour to the surface of a solid until saturation for cooling purposes in an adsorption cycle. The adsorption cycle consists of an adsorbent bed, a condenser and an evaporator. A combination of adsorbent and adsorbate is confined in a closed system. The working fluid boils in the evaporator and the vapour is adsorbed onto a solid adsorbent bed, often activated carbon. When the refrigerant in the evaporator is exhausted it must be recovered from the adsorbent. This is achieved by heating the adsorbent, driving off refrigerant vapour, which is then cooled and condensed. A solar-powered, adsorption system would regenerate the adsorbent when the solar intensity is greatest. This would usually coincide with the time when cooling is most required. The intermittent operation of the adsorption system could be overcome using multiple adsorbent beds with one bed operating while the other is regenerated. Adsorption takes place in the adsorbent bed, while evaporation of the adsorbate occurs in the evaporator. The evaporator then absorbs heat from the ambient; hence refrigeration is achieved. Selection of adsorbents is a significant factor enhancing the performance of the adsorption cycle [3]. The COP of a basic one-adsorber cycle depends mainly on the operating temperatures, the equipment design, the selected pair and the cooling rate. Figure 2 shows a basic adsorber cycle. There have been a number of ideas developed using adsorption and solar power; most of these ideas have focused on the use of adsorption for refrigeration purposes rather than for air conditioning.

A solar-powered, adsorption cycle could use ammonia as the refrigerant and strontium chloride as the solid adsorbent [4]. In this system, the solar collector is used also as a reactor. The overall efficiency of this solar adsorption refrigerator was calculated to be 4%.

Hybrid solar/gas adsorbers have been developed recently. One using ammonia and active carbon fibre is similar to the Hahne heat pump system; another hybrid solar/gas adsorption icemaker was developed using a water heater. In this

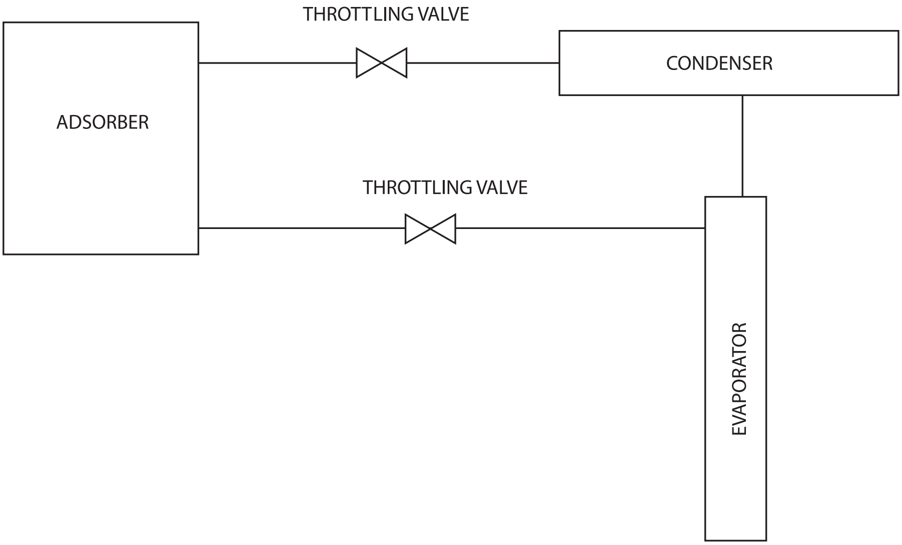

Figure 2. *Schematic of a Basic Adsorption Cycle.*

way, both water heating and ice making can be achieved with the same system. The simulated efficiencies for this system are up to 23% for refrigeration and 38% for heating.

The use of waste heat at low temperatures is an important environmental issue.

Adsorption cycles have a distinct advantage over other systems because of their ability to produce cooling using low grade waste heat, and also since they are benign in their effect on the environment. However, currently available adsorption chillers are not suitable to be adapted to the systems like fuel cells. A new adsorption refrigeration cycle has been developed combined with a mechanical booster pump which is placed between the adsorbent beds and the condenser to reduce the pressure inside the adsorption bed for regeneration, or evaporator to be adsorbed at pressurized conditions. This work deals with the performance testing of a cooling system based on a new adsorption cycle with a cooling capacity of 50 kW, and an estimated cooling COP larger than 10.

Adsorption, also known as physio-sorption, is the process by which molecules of a fluid are fixed on the walls of a solid material [5].

The process of adsorption involves the separation of a substance from one phase accompanied by its accumulation or concentration at the surface of another. The adsorbing phase is the adsorbent, and the material concentrated or adsorbed at the surface of that phase is the adsorbate.

Physical adsorption is caused mainly by Van Der Waals and electrostatic forces between adsorbate molecules and the atoms which compose the adsorbent surface. Thus adsorbents are characterized first by surface properties such as surface area and polarity.

A large specific surface area is preferable for providing large adsorption capacity, but the creation of a large internal surface area in a limited volume inevitably gives rise to large numbers of small sized pores between adsorption surfaces.

Surface polarity corresponds to affinity with polar substances such as water or alcohols. Polar adsorbents are thus called ‘hydrophilic’ and aluminosilicates such as zeolites, porous alumina, silica gel or silica-alumina are examples of adsorbents of this type. On the other hand, non-polar adsorbents are generally ‘hydrophobic’. Carbonaceous adsorbents, polymer adsorbents and silicalite are typical non-polar adsorbents. These adsorbents have more affinity with oil or hydrocarbons than water.

4. Description of the system

4.1. Open solar adsorption fridge cycle

Figure 3 shows a layout of the open-cycle adsorption cooling box proposed. The designed prototype will take ocean water by using a water pump (labelled 1) that will deliver it to a desalination filter (2) so no rust will be accumulated. Afterwards, water will be stored in the first water tank (3) where it will be sent to the Manifold (4) that will make it circulate around the solar collector in order to increase its temperature. The water tank will close its valve when the manifold is full. The

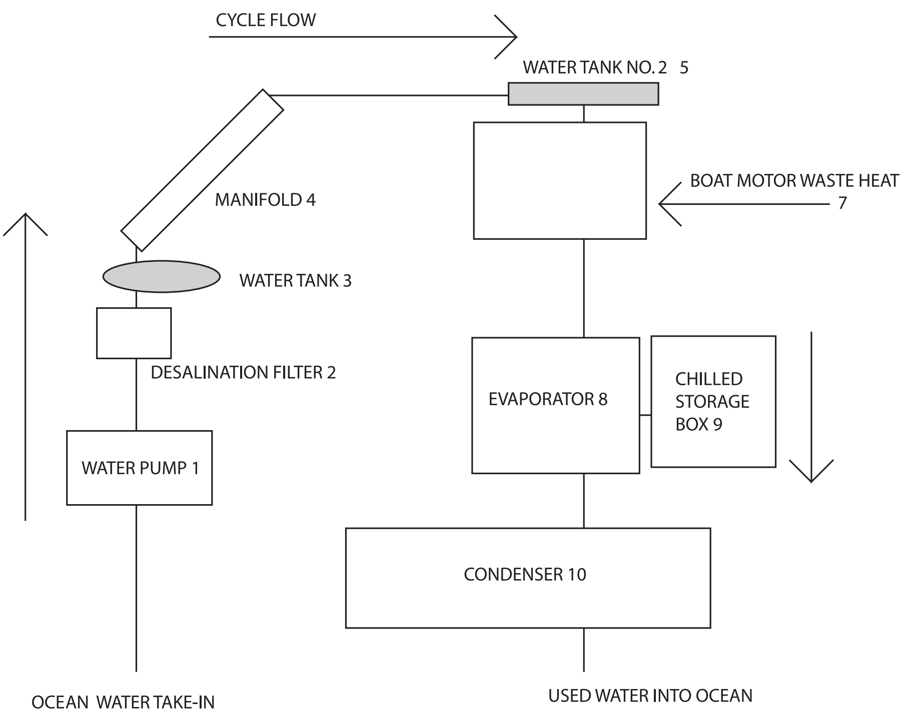

Figure 3. *Description of the Open Cycle Solar Adsorption Fridge.*

Manifold (4) will take hot water into the second water tank (5) in order to send only hot water into the adsorber. Then, the adsorber (6) will increase its potential by receiving the waste heat (7) produced by the motor of the boat. In this step, the working pair, Silica gel-Water, will react. During the evaporating process, the evaporator (8) will produce a cooling effect in order to chill the storage box (9). Finally, the condenser (10) will take place where the water vapour will become liquid again and will be disposed off to the ocean in order to maintain the consumption of fresh water during the cooling process.

4.2. Closed solar adsorption fridge cycle

In the alternative design prototype we plan to follow a closed adsorption cycle as shown in Figure 4. At the beginning of the process, the methanol in the Manifold (1) will circulate around the solar collector in order to increase its temperature. The Manifold (1) will take hot methanol into the adsorber containing activated carbon. Then, the adsorber (2) will increase its potential by receiving the waste heat (3) produced by the motor of the boat. In this step, the working pair, Methanol-Activated Carbon will react. During the evaporating process, the evaporator (4) will produce a cooling effect in order to chill the storage box (5). Finally, condensation (6) will take place where the methanol vapour will become liquid again and will be sent to the manifold again in order to carry on with the cycle.

Many benefits may be achieved by introducing this new technology to fishing communities. All of these benefits can be observed both from the environmental and

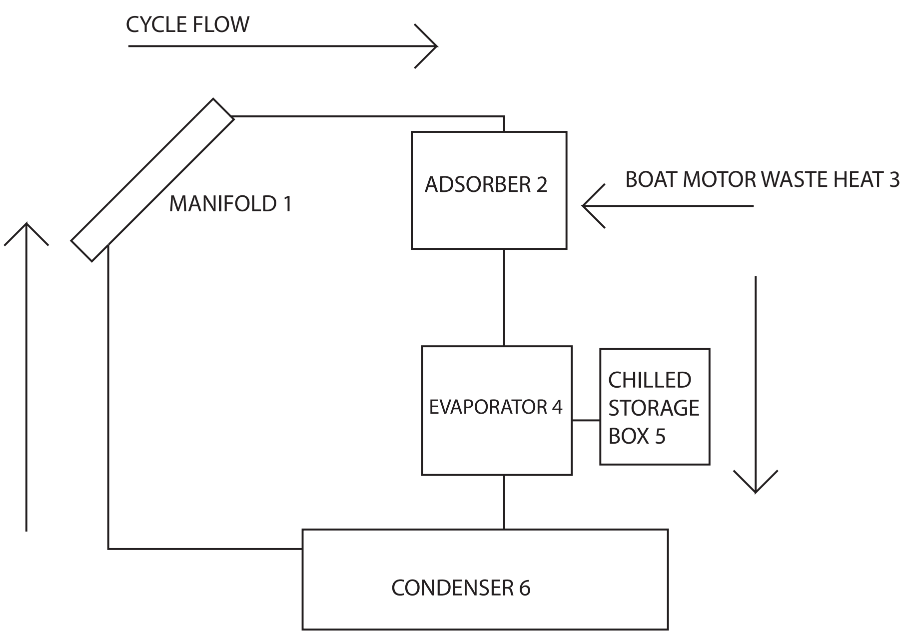

Figure 4. *Description of the Closed Solar Adsorption Fridge Cycle.*

the economic viewpoint. Thus, in order to elaborate not only a scrutiny but also an evaluation of the solar fridge described in this paper, the authors studied three main aspects of the proposal:

1. Technological innovation: where a brief explanation will be offered about the author's criterion to choose the open solar adsorption fridge cycle over the closed solar adsorption fridge cycle.
2. Economic suitability: this will be assessed in a Cost-Benefit analysis.
3. Sustainable design: the explanation of the benefits of sustainable technology.

5. Theory

5.1. Solar Collector Efficiency

To calculate the efficiency on the collector it is important to know the incident angle θ.

To calculate the incident angle, some solar geometry must be taken into consideration regarding the site of operation for the parabolic trough. Solar geometry studies the relation between a surface and solar radiation. The incident angle θ is the angle between the sun's rays and a normal to the surface as shown in Figure 5.

The latitude is L. The hour angle H is the angle through which the earth must turn to bring the meridian of the point directly in line with the sun's rays. The declination angle θ is the angular distance of the sun's rays north or south of the equator and can be calculated using:

$$\delta = 23.47 \sin[360(284 + N)/365] \quad (1)$$

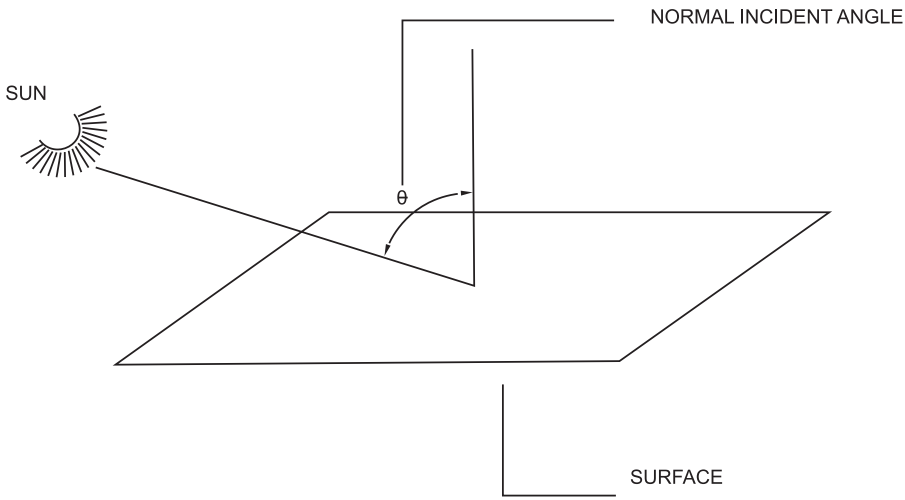

Figure 5. *Incident Angle.*

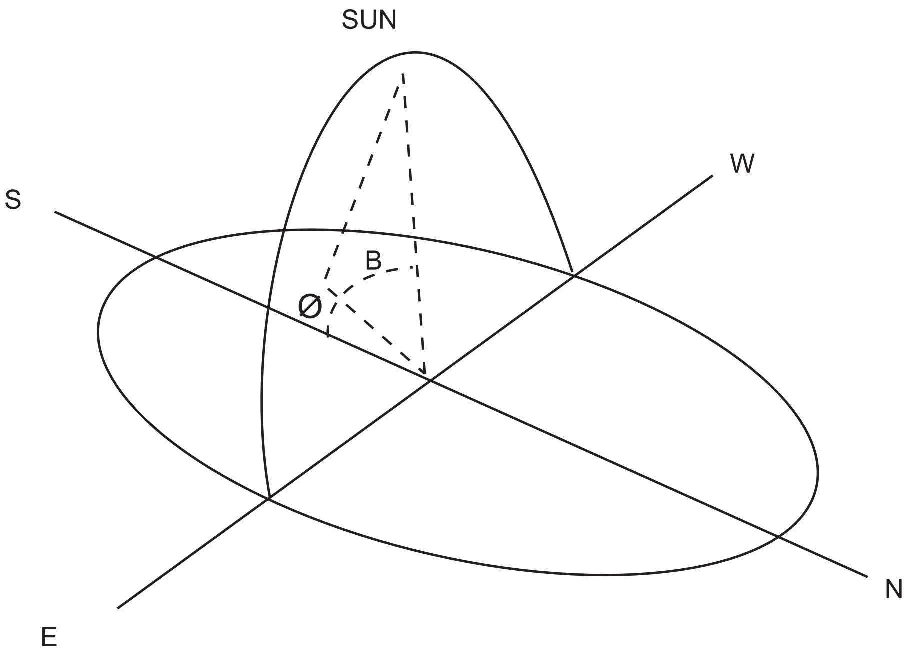

Figure 6. *Altitude and Azimuth angles.*

Figure 6 shows a diagram of the altitude angle β; which is the angle measured from a horizontal plane on earth up to the sun, and is calculated as follows:

$$\sin\beta = \cos L \cos H \cos\delta + \sin L \sin\delta \quad (2)$$

The solar azimuth ϕ is the angle between the sun's rays and the south:

$$\sin\phi = \cos\delta \sin H/\cos\beta \quad \text{for} \quad \phi < 90° \quad (3)$$

To be able to compute the incident angle δ of an arbitrarily orientated surface, the surface azimuth ψ and the solar-surface azimuth γ must be known. The surface azimuth ψ depends on the orientation of the surface in relation to the south, and the solar-surface angle γ is computed as follows:

$$\gamma = \phi +/- \psi \quad (4)$$

The plus sign is chosen if ϕ and ψ are on opposite side of south and the negative sign applies when both angles are on the same side of south.

The tilt angle Σ is the angle of the surface tipped up from the horizontal from the south as shown in Figure 7. The tilt angle depends on the inclination of the surface from the ground.

Knowing the previous data, the incident angle can be calculated with equation 5:

$$\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma \quad (5)$$

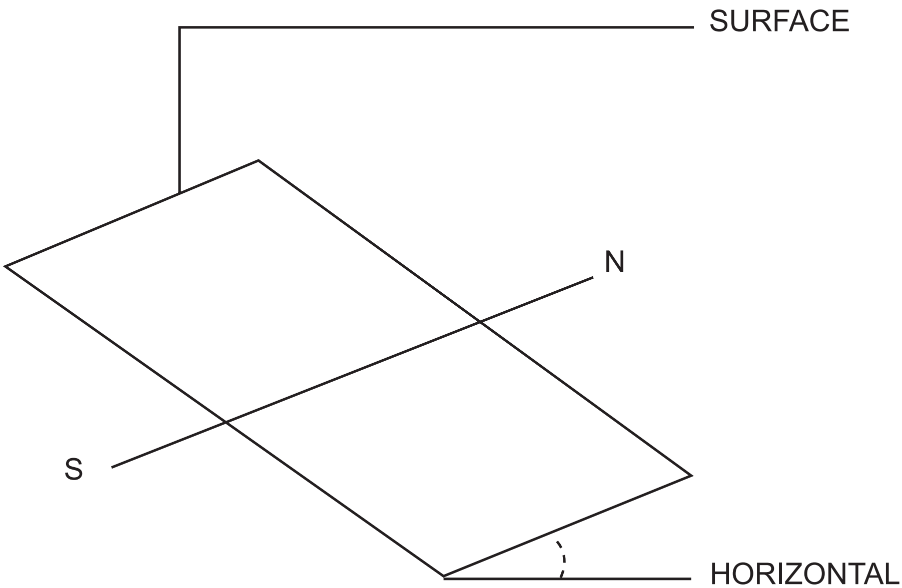

Figure 7. *Tilt angle.*

5.2. Principle of adsorption cycles for refrigeration

The heat-regenerative cycles are often called ‘cycles with temperature fronts’, or ‘cycles with thermal wave’. The basis of the heat-regenerative cycles is to implement the following five devices in series on the circuit of the heat-transfer fluid (in the following ‘HX’ means ‘heat-transfer’):

1) a first adsorber;
2) a heat exchanger that heats the HX-fluid up to the maximal temperature of the cycle (Heating System);
3) a second adsorber;
4) a heat exchanger that cools the HX-fluid up to the minimal temperature of the cycle (Cooling System);
5) a reversible pump for circulating the HX-fluid.

Two adsorbers are installed in the machine as shown in Figure 8. They are exactly similar and are operated out of phase. It results that the condenser and evaporator of the unit are almost continuously on duty.

On the HX-fluid circuit are implemented two adsorbers, the heating and cooling systems for the HX-fluid and a reversible pump.

The main feature of the adsorption cycle with heat-regeneration is to design the adsorbers in such a way that the HX-fluid undergoes large temperature differences when flowing through the adsorbers.

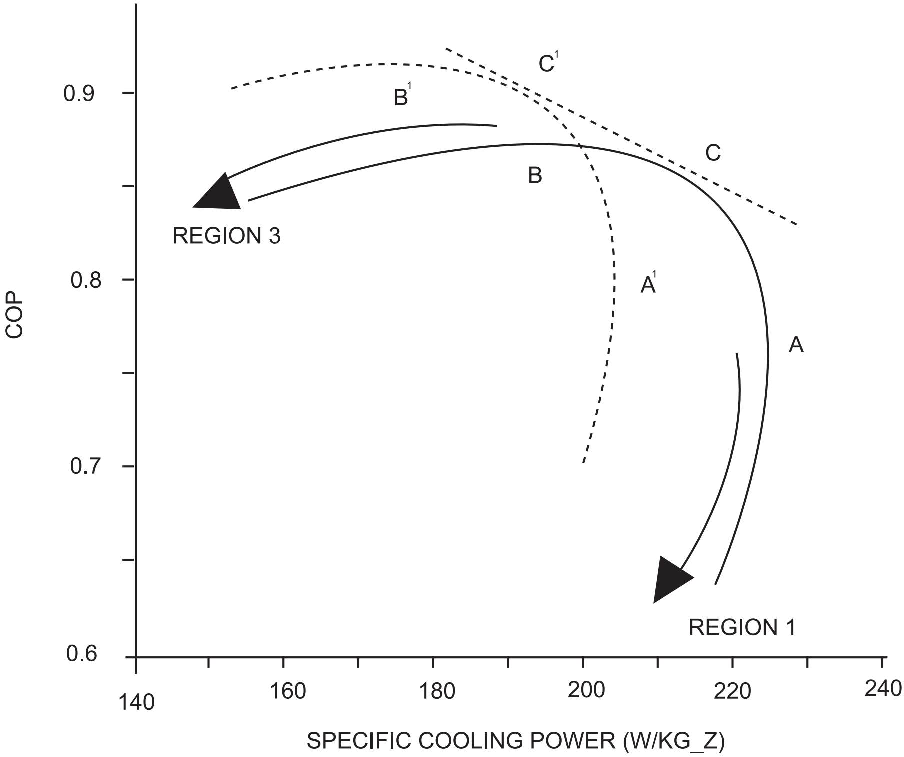

Figure 8. *Schematic representation of the main components of an adsorption unit operated with heat-regeneration.*

5.3. First Law analysis

It is well-known that solid sorption cycles are intermittent. To determine how long should the cycle period be, a model of the process is helpful.

A model of the process yields as result, first the COP of the refrigeration cycle, second the cooling capacity per unit mass of adsorbent, the Specific Cooling Power SCP. On the former, three 'regions' are indicated:

- The 'Region 1' corresponds to 'long cycles'.
- The 'Region 3' corresponds to 'short cycles'.

These two points A and B are remarkable. The first one yields the maximal cooling power, the second one the maximal COP on this curve.

- In the third region, between points A and B, COP and SCP vary in opposite directions. An optimal cycle period should be found somewhere between A and B.

Indeed, let us now consider the second 'performance curve'. This second curve has been calculated with the same method but with another value of the HX-fluid flow rate, slightly smaller than the former one. This second curve also exhibits three

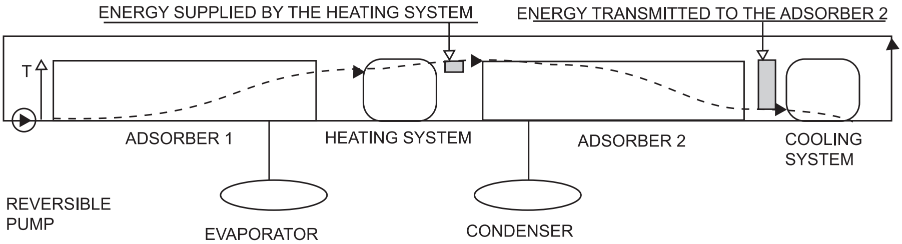

Figure 9. *Performance curves calculated for two values of the HX-fluid flow rate.*

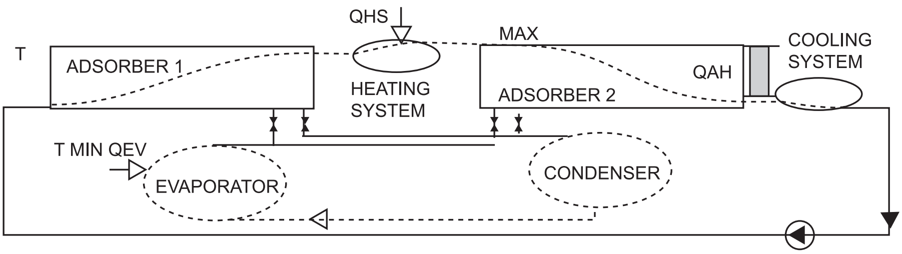

Figure 10. *Presentation of the three main heat quantities that describe the process:* Q_{EV} *is the cold production au the evaporator;* Q_{AH} *is the heat quantity supplied to the adsorbers by the HX-fluid in the heating periods and* Q_{HS} *is the energy supplied by the heat source.*

regions. Moreover, it can be seen that some points of this second curve lie above point B. For one point of this second curve, a point close to C', the cooling power can be the same as for point B but with a larger COP: that point obviously has better performance than point B.

By this means, it appears that the optimal operation points are the ones located on the curve that 'envelops' all the 'performance curves', the black dashed curve in Figure 9 and the points C and C'. These points correspond to objectively optimal cycle periods because they yield the largest COP possible for a given cooling power (and not for a given HX-fluid flow rate).

From the shape of the performance curves in Figure 9, it can be considered that the whole process is ruled by two opposite trends, one pushing for long cycles, the other one for short cycles. The optimal cycle period results from a trade-off between these trends.

The adsorption cycle with heat-regeneration can be efficiently analyzed when considering that it consists of an *adsorption cycle for refrigeration* combined with a *heat storage process*.

5.4. Heat storage process

The process of 'heat-regeneration' is well-known in the field of heat storage processes. Classical heat-regenerators (Figure 10) have been widely investigated for decades, and it is clearly established that the thermodynamic efficiency of the heat storage process continuously decreases with the cycle period. We consider the 'Heat Recovery Factor'.

When considering now the heat quantities shown in Figure 10, the 'Heat-Recovery-Factor', F_{HR} is the ratio of the energy supplied to the adsorber in heating period, Q_{AH}, which is not supplied by the heat source (and therefore is internally recovered):

$$F_{HR} = \frac{Q_{AH} - Q_{HS}}{Q_{AH}} \quad (6)$$

This factor represents the efficiency of the heat-regenerative process operated for storing heat in the adsorber.

5.5. Adsorption cycle for refrigeration

It can be seen from Figures 8 and 10 that the heat-regenerative process obviously saves energy when compared to the simple effect cycle as long as the heat power supplied by the heat source is less than the heat power transmitted to the adsorber in heating period (No 2 in those figures). This is the case as long as the temperature increase undergone by the HX-fluid in the Heating System is smaller than its temperature decrease in this.

It results from this description that, at the moments of flow reversals i.e. at the end of each half-cycle, temperature is absolutely non-uniform in the adsorbers.

The COP of an intermittent (simple effect) cycle operated between these two temperature profiles can be defined as:

$$COP_i = \frac{Q_{EV}}{Q_{AH}} \quad (7)$$

It can now easily be seen that the cycle COP, can be related to the Heat Recovery Factor and to *COPi* as follows:

$$COP = \frac{COP_i}{1 - F_{HR}} \quad (8)$$

This description shows that the two processes (heat-regenerative heat-storage + adsorption cycle with non-uniform temperature) interfere and this equation shows how their respective efficiencies contribute to the efficiency of the refrigeration (heat-pumping) adsorption cycle with heat-regeneration.

6. Economics

Catch loss of fish due to sun exposure is estimated around 40% of the total catch for the Middle Baja California Region with small fishing boats (i.e. 22 ft long). The use of our projected device would reduce catch loss to around 10%. Therefore, gross annual benefit yields would be 30% of total catch. Initial investment costs require a disbursement of USD $3693 and an annual maintenance cost of USD $50. Cost-benefit analysis compares 'with and without device' scenarios. We used a 5% discount rate which represents a 30-year average real interest rate of the Mexican Government Bonds (*Certificados de la Tesorería de la Federación*).

	Scenario 1: 5%, USD$ 3693.65	Scenario 2: 10%, USD$ 3693.65	Scenario 3: 5%, USD% 7336.71	Scenario 4: 10%, USD$ 7336.71
Benefit-Cost Ratio (NBwR / NBwoR)	1.25	1.23	1.16	1.15

Figure 11. *Results of the cost-benefit analysis.*

The cost-benefit scenarios assume that: a) Fish-catch is feasible between 45 and 180 days a year depending on fish species and seasonal circumstances; b) the device would not work during the 19 rainy days of the year (Mexican Meteorological Service www.smn.cna.gob.mx); c) Time horizon is 15 years.

The detriment represents 40% of the fishing extraction of the small fishing boats. When the refrigerator is used, this loss is calculated at 10%. The refrigerator's feasibility is evaluated by the comparison of the generated benefits when it is implemented against those when it is not.

The utilized discount rate was that of 5%. For simulation purposes, the number of annual fishing days was calculated between 45 and 180, depending on the species of fish. It is important to emphasize that the solar refrigerator does not function during rainy days. For the study zone (Baja California) the annual average of rainy days is 19. This data is important because the 19 days are considered as non-fishing days for the refrigerator scenario. The period of analysis is 15 years.

With the purpose of observing if the profit value of the project is strong enough to carry out, and in order to have a profitable project, it was necessary that the ratio of net benefits be greater than 1.0. The analysis of sensibility included 4 scenarios that combined two rates of discount, one of 5% and the other of 10%, and two total costs for the refrigerator, the original one of USD $3693 and the other of USD $7336.

The results, as shown in Figure 11, demonstrate that greater benefits are obtained in the scenario with the refrigerator regarding the counter-factual setting, which is proved by observing the ratios presented below. The ratio between the net profit of the scenario with the refrigerator and the counter-factual one is close to 1.25. This means that in the scenario with the refrigerator, 25% more benefits are obtained than in the counter-factual one. Therefore as is represented in the chart, the solar refrigerator is an economically viable project. Appendix 1 shows the calculus sheets for the economic analysis.

7. Conclusions and further work

The system proposed in this paper is a feasible option for the purpose of providing small fishing boats in small fishing communities in Mexico with a cooling box to improve their selling capacity. Adsorption cycles have been properly analyzed in the past for refrigeration purposes of a similar capacity to the one intended with this project.

The next step of this project should be the building of a laboratory prototype (using the design layout described in section 4.1) of the open cycle system simulating movement and sea-water and decide upon a large-scale field prototype. The authors believe enough theory supports the laboratory stage proposed as the next phase of this project. The performance of the proposed SARU depends on an efficient solar collector and the temperature and pressure differential obtained from the heating- regenerating process (which could be enhanced with higher temperature solar collectors).

The results obtained from the economic analysis, show that the implementation of a solar refrigerator is feasible to manufacture and a greater benefit level is reached without manufacturing it, even though its elaboration costs are incurred.

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Appendix: Calculus sheet for economic analysis.

Scenario 1: Data for the Solar Adsorption Refrigeration Unit. Rate of discount 5% and initial investment of USD $3,693.65

Year	Discount Rate	Direct Benefits with Refrigerator	Direct Benefits without Refrigerator	Discounted W Benefits	Discounted WO Benefits	Costs with Refrigerator	Costs without Refrigerator	Discounted W Costs	Discounted WO Costs	Net Benefits with Refrigerator	Net Benefits without Refrigerator	NB W/R – NB WO/R	Benefit Cost Ratio
1	1.0500	5,747.93	4,291.63	5,474.22	4,087.27	3,693.65	0.00	3,517.76	0.00	1,956.46	4,087.27	−2,130.81	
2	1.1025	5,747.93	4,291.63	5,213.54	3,892.63	50.60	0.00	45.89	0.00	5,167.65	3,892.63	1,275.01	
3	1.1576	5,747.93	4,291.63	4,965.28	3,707.27	50.60	0.00	43.71	0.00	4,921.57	3,707.27	1,214.30	
4	1.2155	5,747.93	4,291.63	4,728.84	3,530.73	50.60	0.00	41.63	0.00	4,687.21	3,530.73	1,156.48	
5	1.2763	5,747.93	4,291.63	4,503.65	3,362.60	50.60	0.00	39.64	0.00	4,464.01	3,362.60	1,101.41	
6	1.3401	5,747.93	4,291.63	4,289.19	3,202.48	50.60	0.00	37.76	0.00	4,251.44	3,202.48	1,048.96	
7	1.4071	5,747.93	4,291.63	4,084.95	3,049.98	50.60	0.00	35.96	0.00	4,048.99	3,049.98	999.01	
8	1.4775	5,747.93	4,291.63	3,890.43	2,904.74	50.60	0.00	34.25	0.00	3,856.18	2,904.74	951.44	
9	1.5513	5,747.93	4,291.63	3,705.17	2,766.42	50.60	0.00	32.62	0.00	3,672.55	2,766.42	906.13	
10	1.6289	5,747.93	4,291.63	3,528.73	2,634.69	50.60	0.00	31.06	0.00	3,497.67	2,634.69	862.98	
11	1.7103	5,747.93	4,291.63	3,360.70	2,509.23	50.60	0.00	29.58	0.00	3,331.11	2,509.23	821.89	
12	1.7959	5,747.93	4,291.63	3,200.66	2,389.74	50.60	0.00	28.17	0.00	3,172.49	2,389.74	782.75	
13	1.8856	5,747.93	4,291.63	3,048.25	2,275.94	50.60	0.00	26.83	0.00	3,021.42	2,275.94	745.47	
14	1.9799	5,747.93	4,291.63	2,903.10	2,167.56	50.60	0.00	25.56	0.00	2,877.54	2,167.56	709.98	
15	2.0789	5,747.93	4,291.63	2,764.85	2,064.35	50.60	0.00	24.34	0.00	2,740.51	2,064.35	676.17	
Total				**59,661.55**	**44,545.63**					**55,666.78**	**44,545.63**	**11,121.15**	**1.2497**

Scenario 2: Data for the Solar Adsorption Refrigeration Unit. Rate of discount 10% and initial investment of USD $3,693.65

Year	Discount Rate	Direct Benefits with Refrigerator	Direct Benefits without Refrigerator	Discounted W Benefits	Discounted WO Benefits	Costs with Refrigerator	Costs without Refrigerator	Discounted W Costs	Discounted WO Costs	Net Benefits with Refrigerator	Net Benefits without Refrigerator	NB W/R – NB WO/R	Benefit Cost Ratio
1	1.1000	5,747.93	4,291.63	5,225.39	3,901.48	3,693.65	0.00	3,357.87	0.00	1,531.74	3,901.48	−2,369.74	
2	1.2100	5,747.93	4,291.63	4,750.36	3,546.80	50.60	0.00	41.82	0.00	4,699.76	3,546.80	1,152.96	
3	1.2705	5,747.93	4,291.63	4,524.15	3,377.91	50.60	0.00	39.83	0.00	4,473.55	3,377.91	1,095.65	

4	1.3340	5,747.93	4,291.63	4,308.71	3,217.05	50.60	0.00	37.93	0.00	4,258.11	3,217.05	1,041.06	
5	1.4007	5,747.93	4,291.63	4,103.54	3,063.86	50.60	0.00	36.12	0.00	4,052.94	3,063.86	989.08	
6	1.4708	5,747.93	4,291.63	3,908.13	2,917.96	50.60	0.00	34.40	0.00	3,857.53	2,917.96	939.57	
7	1.5443	5,747.93	4,291.63	3,722.03	2,779.01	50.60	0.00	32.76	0.00	3,671.43	2,779.01	892.42	
8	1.6215	5,747.93	4,291.63	3,544.79	2,646.68	50.60	0.00	31.20	0.00	3,494.19	2,646.68	847.51	
9	1.7026	5,747.93	4,291.63	3,375.99	2,520.64	50.60	0.00	29.72	0.00	3,325.39	2,520.64	804.75	
10	1.7877	5,747.93	4,291.63	3,215.23	2,400.61	50.60	0.00	28.30	0.00	3,164.63	2,400.61	764.02	
11	1.8771	5,747.93	4,291.63	3,062.12	2,286.30	50.60	0.00	26.96	0.00	3,011.52	2,286.30	725.22	
12	1.9710	5,747.93	4,291.63	2,916.31	2,177.43	50.60	0.00	25.67	0.00	2,865.71	2,177.43	688.28	
13	2.0695	5,747.93	4,291.63	2,777.43	2,073.74	50.60	0.00	24.45	0.00	2,726.84	2,073.74	653.10	
14	2.1730	5,747.93	4,291.63	2,645.18	1,974.99	50.60	0.00	23.28	0.00	2,594.58	1,974.99	619.59	
15	2.2816	5,747.93	4,291.63	2,519.21	1,880.94	50.60	0.00	22.18	0.00	2,468.62	1,880.94	587.67	
Total				**54,598.56**	**40,765.41**					**50,196.53**	**40,765.41**	**9,431.13**	**1.2314**

Scenario 3: Data for the Solar Adsorption Refrigeration Unit. Rate of discount 5% and initial investment of USD $7,336.71

Year	Discount Rate	Direct Benefits with Refrigerator	Direct Benefits without Refrigerator	Discounted W Benefits	Discounted WO Benefits	Costs with Refrigerator	Costs without Refrigerator	Discounted W Costs	Discounted WO Costs	Net Benefits with Refrigerator	Net Benefits without Refrigerator	NB W/R – NB WO/R	Benefit Cost Ratio
1	1.0500	5,747.93	4,291.63	5,474.22	4,087.27	7,336.71	0.00	6,987.34	0.00	−1,862.49	4,087.27	−2,130.81	
2	1.1025	5,747.93	4,291.63	5,213.54	3,892.63	50.60	0.00	45.89	0.00	5,162.94	3,892.63	1,275.01	
3	1.1576	5,747.93	4,291.63	4,965.28	3,707.27	50.60	0.00	43.71	0.00	4,914.68	3,707.27	1,214.30	
4	1.2155	5,747.93	4,291.63	4,728.84	3,530.73	50.60	0.00	41.63	0.00	4,678.24	3,530.73	1,156.48	
5	1.2763	5,747.93	4,291.63	4,503.65	3,362.60	50.60	0.00	39.64	0.00	4,453.06	3,362.60	1,101.41	
6	1.3401	5,747.93	4,291.63	4,289.19	3,202.48	50.60	0.00	37.76	0.00	4,238.60	3,202.48	1,048.96	
7	1.4071	5,747.93	4,291.63	4,084.95	3,049.98	50.60	0.00	35.96	0.00	4,034.35	3,049.98	999.01	
8	1.4775	5,747.93	4,291.63	3,890.43	2,904.74	50.60	0.00	34.25	0.00	3,839.83	2,904.74	951.44	
9	1.5513	5,747.93	4,291.63	3,705.17	2,766.42	50.60	0.00	32.62	0.00	3,654.57	2,766.42	906.13	
10	1.6289	5,747.93	4,291.63	3,528.73	2,634.69	50.60	0.00	31.06	0.00	3,478.13	2,634.69	862.98	
11	1.7103	5,747.93	4,291.63	3,360.70	2,509.23	50.60	0.00	29.58	0.00	3,310.10	2,509.23	821.89	
12	1.7959	5,747.93	4,291.63	3,200.66	2,389.74	50.60	0.00	28.17	0.00	3,150.06	2,389.74	782.75	
13	1.8856	5,747.93	4,291.63	3,048.25	2,275.94	50.60	0.00	26.83	0.00	2,997.65	2,275.94	745.47	
14	1.9799	5,747.93	4,291.63	2,903.10	2,167.56	50.60	0.00	25.56	0.00	2,852.50	2,167.56	709.98	

Scenario 3 continued:Data for the Solar Adsorption Refrigeration Unit. Rate of discount 5% and initial investment of USD $7,336.71

Year	Discount Rate	Direct Benefit with Refrigerator	Direct Benefit without Refrigerator	Benefits W/R discounted	Benefits WO/R discounted	Costs with Refrigerator	Costs without Refrigerator	Costs W/R discounted	Costs WO/R discounted	Net Benefit with Refrigerator	Net Benefit without Refrigerator	NB W/R – NB WO/R	Quotient (NBWR/ NBWOR)
15	2.0789	5,747.93	4,291.63	2,764.85	2,064.35	50.60	0.00	24.34	0.00	2,714.25	2,064.35	676.17	
Total				**59,661.55**	**44,545.63**					**51,616.47**	**44,545.63**	**11,121.15**	**1.1587**

Scenario 4: Data for the Solar Adsorption Refrigeration Unit. Rate of discount 10% and initial investment of USD $7,336.71

Year	Discount Rate	Direct Benefits with Refrigerator	Direct Benefits without Refrigerator	Discounted W Benefits	Discounted WO Benefits	Costs with Refrigerator	Costs without Refrigerator	Discounted W Costs	Discounted WO Costs	Net Benefits with Refrigerator	Net Benefits without Refrigerator	NB W/R – NB WO/R	Benefit Cost Ratio
1	1.1000	5,747.93	4,291.63	5,225.39	3,901.48	7,336.71	0.00	6,669.73	0.00	−2,111.32	3,901.48	−6,012.80	
2	1.1550	5,747.93	4,291.63	4,976.56	3,715.70	50.60	0.00	43.81	0.00	4,925.96	3,715.70	1,210.27	
3	1.2128	5,747.93	4,291.63	4,739.58	3,538.76	50.60	0.00	41.72	0.00	4,688.99	3,538.76	1,150.23	
4	1.2734	5,747.93	4,291.63	4,513.89	3,370.25	50.60	0.00	39.73	0.00	4,463.29	3,370.25	1,093.05	
5	1.3371	5,747.93	4,291.63	4,298.94	3,209.76	50.60	0.00	37.84	0.00	4,248.34	3,209.76	1,038.59	
6	1.4039	5,747.93	4,291.63	4,094.23	3,056.91	50.60	0.00	36.04	0.00	4,043.63	3,056.91	986.72	
7	1.4741	5,747.93	4,291.63	3,899.27	2,911.34	50.60	0.00	34.32	0.00	3,848.67	2,911.34	937.32	
8	1.5478	5,747.93	4,291.63	3,713.59	2,772.71	50.60	0.00	32.69	0.00	3,662.99	2,772.71	890.28	
9	1.6252	5,747.93	4,291.63	3,536.75	2,640.68	50.60	0.00	31.13	0.00	3,486.15	2,640.68	845.48	
10	1.7065	5,747.93	4,291.63	3,368.33	2,514.93	50.60	0.00	29.65	0.00	3,317.74	2,514.93	802.81	
11	1.7918	5,747.93	4,291.63	3,207.94	2,395.17	50.60	0.00	28.24	0.00	3,157.34	2,395.17	762.17	
12	1.8814	5,747.93	4,291.63	3,055.18	2,281.11	50.60	0.00	26.89	0.00	3,004.58	2,281.11	723.47	
13	1.9754	5,747.93	4,291.63	2,909.69	2,172.49	50.60	0.00	25.61	0.00	2,859.10	2,172.49	686.61	
14	2.0742	5,747.93	4,291.63	2,771.14	2,069.04	50.60	0.00	24.39	0.00	2,720.54	2,069.04	651.50	
15	2.1779	5,747.93	4,291.63	2,639.18	1,970.51	50.60	0.00	23.23	0.00	2,588.58	1,970.51	618.07	
Total				**56,949.66**	**42,520.83**					**48,904.58**	**42,520.83**	**6,383.75**	**1.1501**

W = with, WO = without, R = refrigerator, NB = Net Benefit