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Preliminarily Design of Portable and Sustainable Solar Refrigerator

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ABSTRACT
This paper presents a preliminary design of a sustainable, portable solar refrigerator, which uses a solar adsorption system. The aim is to achieve a sustainable design that includes not only the materials but also considertions for the useful life of the equipment and its final disposition.
This equipment has been considered as an economical solution for rural communities where there is no electricity, and whose food goods need to be preserved.
The suggested design considers a CPC as primary source of energy. For the coolant fluid twosubstances were analyzed: water, methanol.
Vegetal carbon is recommended, for this project, as adsorbent material that is usually used in several researches around world as substitute of activated coal.
The results are compared with other designs and it was observed that the prototype presented is sustainable and meet sustainable criteria, because is cheaper, portable and uses natural charcoal.
Keywords: Solar cooling, adsorption cycle, CPC.

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I. INTRODUCTION

According to the International Institute of Energy, approximately 15% of all electricity produced in the world is used for cooling processes [1]. Currently the most widely used are vapor-compression refrigeration systems, which work with synthetic materials, such as CFCs, HCFCs (chlorofluorocarbons and hydro-chlorofluorocarbons) or HFCs. When these substances are released into the atmosphereaffect the ozone layer and contribute to the greenhouse effect. [2], estimated that emissions from synthetic refrigerants, during operation or after life represent 33.3% of the greenhouse effect [3].Various protocols, such as the Montreal Protocol (1987) and the Kyoto Protocol (1997), were established in order to eliminate or at least significantly reduce emissions of these gases. [4] [5].

Countries around the world have made some efforts to make some changes or eliminate the use of HCFCs. According to SEMARNAT (Secretariat of environment and natural resources in Mexico) the "National Plan for Elimination of hydro-chlorofluorocarbons (HCFC) ", aims to eliminate 30% of consumption of HCFCs by 2018. Despite these efforts in some countries, after 29 years of being created the Montreal Protocol, the situation continues to claim the development of alternative technologies that operate with friendly substances to the environment, mainly due to increased emissions of HFCs, although the emission of CFCs and HCFCs have been declined since 1980s. [6][7].

Based on the above, it may be noted that it is important to developed cooling systems that consume no electricity and do not use refrigerants CFCs that affect the ozone layer and produce greenhouse effect. Solar refrigeration is an alternative, there are many research works in this field. Most of them are focused in solar absorption cycle. This thermodynamic process may be broken down into three basic stages: evaporation, absorption, and regeneration. The main components of an absorption cooling system are the absorber, pump, expansion valve, regenerator, and generator. These systems can be made more efficient by adding a stage to increase heat transfer efficiency. The common refrigerant-absorbent used are ammonia/water, and LiBr/water. Some authors like Romero [8]. have analyzed the COP and the performance of this kind of systems. A single effect chiller with this principle has a COP between 0.6 to 0.7, while a double effect chiller has a COP between 0.8 to 1.2.[7]. Applications in Mexico of this absorption refrigeration systems are developed by [9].

Meanwhile, adsorption coolingprocess consists of pressurization heating, desorption at constant condenser pressure, depressurization cooling, and adsorption at constant evaporator pressure, a major description of this cycle will be described in the following section.

In fact solar adsorption refrigeration technology has received a lot of attention due to their noiseless and environmentally friendly refrigerants. However, certain drawbacks have become obstacles to its real application, such as the discontinuous operation of the cycle and the large volume and weight of the traditional solar adsorption systems [10]

There are several works that analyze different ways to increment the performance and COP of the adsoption cycle. Most of them conclude that the main way to improve the COP is to enhance the thermal conductivity of the adsorber. Some works like [11] add fins to the adsorber in order to increment the heat transfer in this element. Other works analyze different solar collector/adsorbet bed design[12].

Therefore, the purpose of this paper is to shown a preliminary design of a compact refrigerator adsorption system that uses solar energy for cooling and food preservation, particularly seafood, operating with a CPC (Composed-Parabolic Concentrator) collector and adsorption system, using natural refrigerants. This design is compact in order to avoid the problem of large volume that most of the adsorption refrigeration have. Also includes the CPC concentrator system in order to improve the heat transfer in the adsorbent. [11].

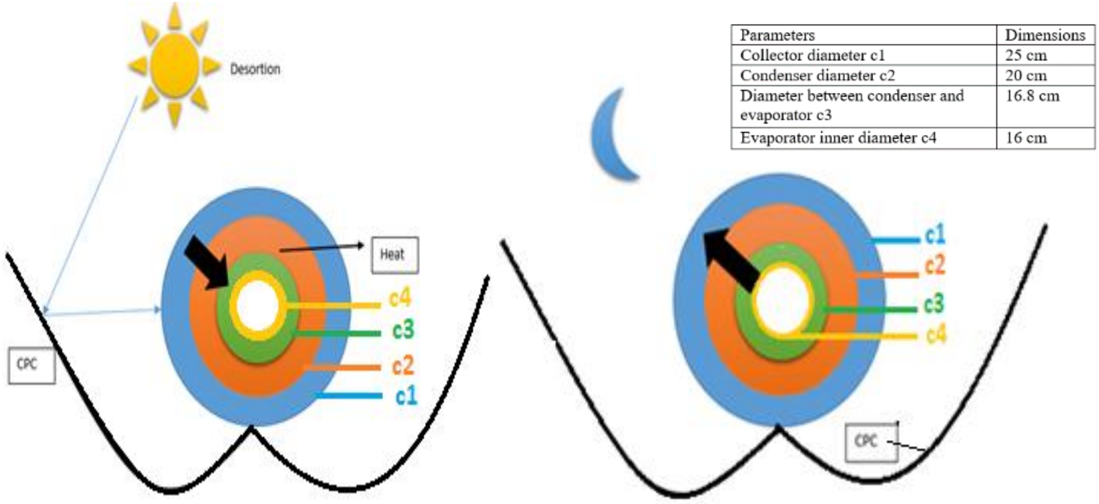
This work proposes the use of adsorbent as natural coal made from biomass. And the analysis between twopairs of adsorbent-adsorbate: coal - water, coal – biogas. As it was already mentioned that the solar refrigerator would be used for seafood, thus is proposed that the design be portable to be used in rural communities with no electricity for the conservation of their food.

Is important to point out that this paper presents a preliminary design and a theoretical analysis. The prototype is under construction and the experimental results will be presented in future works.

Nomenclature

PARAMETER	SYMBOL	UNIT
Collector diameter	*c1*	cm
Condenser diameter	*c2*	cm
Diameter of cylinder between condenser and evaporator	*c3*	cm
Evaporator inner diameter	*c4*	cm
Energy	*Q*	kJ
Heat of desorption	*H*	$kJ\ kg^{-1}$
Latent heat	*L*	$kJ\ kg^{-1}$
Latent heat of fusion of ice at 273 K	*L**	$kJ\ kg^{-1}$
Mass	*m*	kg
Specific heat	*Cp*	$kJ\ kg^{-1}\ K^{-1}$
Temperature	*T*	K
Total solar energy input to the system during the day	Q_I	kJ
Concentration of refrigerant	*X*	kg adsorbate kg^{-1} adsorbent

SUBSCRIPTIONS	
Adsorbent carbon	ac
Condenser	c
Evaporator	e
Refrigerant	r
Saturation	s
Points in Clapeyron diagram	A, B, C, D
Total	T



Parameters	Dimensions
Collector diameter c1	25 cm
Condenser diameter c2	20 cm
Diameter between condenser and evaporator c3	16.8 cm
Evaporator inner diameter c4	16 cm

(a) Daytime (heat/desorption) **(b)** Nighttime (evaporation/adsorption)

Fig. 1: Operation principle of solid adsorption refrigeration system using solar heat. A- sorption bed (solar collector); B condenser, C- evaporator and D- cold area.

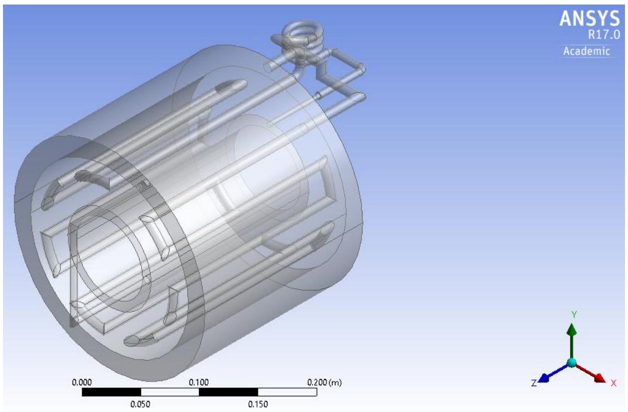


Fig. 2: Solar Refrigerator demonstration system

II. PROTOTYPE DESIGN

The prototype described in this paper consists of four concentric cylinder, called c1, c2, c3, c4; c1 is considering that larger diameter and below cylinder c4 is smaller diameter. (Fig.1).

The space between cylinders c1 and c2, conforms the collector of the adsorption system, wherein the pair adsorbate-adsorbent is placed (is the absorber of the solar concentrator). The second space formed by the c2 and c3 is where a serpentine is located and water to form the condenser; the space formed by c3 and c4 are the evaporator.

The condenser and evaporator are connected by a small serpentine, which acts as expansion valve.

It is important to mention that cylinder c1 should be a material with high thermal conductivity, so that the solar radiation concentrated by the CPC is absorbed; c2 must be an insulating material to completely separate the area of the collector and the condenser; c3 is the cylinder that separates the condenser and the evaporator and also should be an insulating material; finally cylinder c4 must have a high conductivity to extract energy from the area to be cooled, in which food will be located; finally it is rejoined the evaporator with a manifold by a pipe. Figure 2 shows an isometric diagram of the configuration proposed.

III. ADSORPTION CAPACITY OF DIFFERENT MATERIALS

As a part of the project, it was analyzed the adsorption capacity of different materials because this is the first and fundamental part for thermal calculation and the subsequent design of the solar refrigerator. Authors like [13], made a comparison of adsorption capacity between orange peel and orange peel modified with chitosan for removal methyl of orange, of that investigation it was found that orange peel is best adsorbent that orange peel modified [6]

On the other hand, in 2007, E. Gonzalez [14], analyzed the percentage of adsorption for two particle sizes of 0.425 mm and 0.5 mm, managed to obtain maximum removal percentage of 66.8% and 62.5%, concluded that smaller particles are more adsorption capacity [15].

In Mexico and Malaysia, there are extensive analysis of materials with different adsorption capacities, such analysis has concluded that in order to make a sustainable adsorption system it is necessary to analyze local organic materials from the place they are used [16]. According to the analysis capacity of adsorption and desorption for proposals mixtures, tests were performed by analyzing the adsorption capacity of methylene blue, these tests were proposed by Xialong Zhang and Vargas with a stirring time of 24 hours and 48 hours respectively, which adsorption capacities were determined with efficiencies up to 60%[17][18]. The parameters used for testing the adsorption capacity are shown in table 1 were considered [19].

Table 1: Testing parameters [19].

Parameter	**Specification**
Reactive	Methylene blue
Volume of solute	10 mL
Concentrations	(2- 50 mg/L)
Temperature to generate coal	350°C
Types of organic material to generate coal	-Tangerine peel -Orange peel -Tomato peel -Shell “huaje”
Mass of adsorbent	4 mg

The results of capacity of adsorption are shown in fig. 3 and it can be observed that the coal which has higher adsorption capacity is the huaje, followed by tomato and finally orange. But it is important to note that these three samples have higher adsorption capacity than activated commercial coal for fishbowl. This preliminary result is very important because if the coal is not activatedit would not be used substances like phenolphthalein or oxalic acid and therefore waste pollutants are reduced by the project.

IV. THEORETICAL ANALYSIS OF A SOLAR ADSORPTION REFRIGERATION SYSTEM

4.1. Principles of operation

The principles of operation of the adsorption refrigeration system are described by the ideal cycle in the Clapeyron diagram (ln P versus–1/T). See Fig. 4. It is formed by the following stages:

a) Isosteric heating. At sunrise, sunlight falls in the parabolic solar collector, which contains the activated carbon saturated with methanol at the focal line. The mixture is heated until its pressure reaches a level that enables refrigerant to be desorbed (state B).

b) Desorption and condensation. Between B and D addition of heat from the solar energy results in desorption of vapor refrigerant, which condenses in the condenser by the air surrounding it. In an ideal cycle, the condensation pressure remains constant. At state D, when the maximum temperature of adsorbent is reached, solar irradiance starts to decrease.

c) Isosteric cooling. At state D, the temperature and pressure decrease. Meanwhile, the liquid refrigerant is being collected in the evaporator.

d) Adsorption and evaporation. The adsorbent continues decreasing its temperature and pump the refrigerant. This evaporates and extracts heat from the evaporator generating a cold atmosphere. At sunrise the next day, the temperature of the collector is minimal and reaches the value at state A., the cycle is said to be intermittent because the cold production happens during the night.

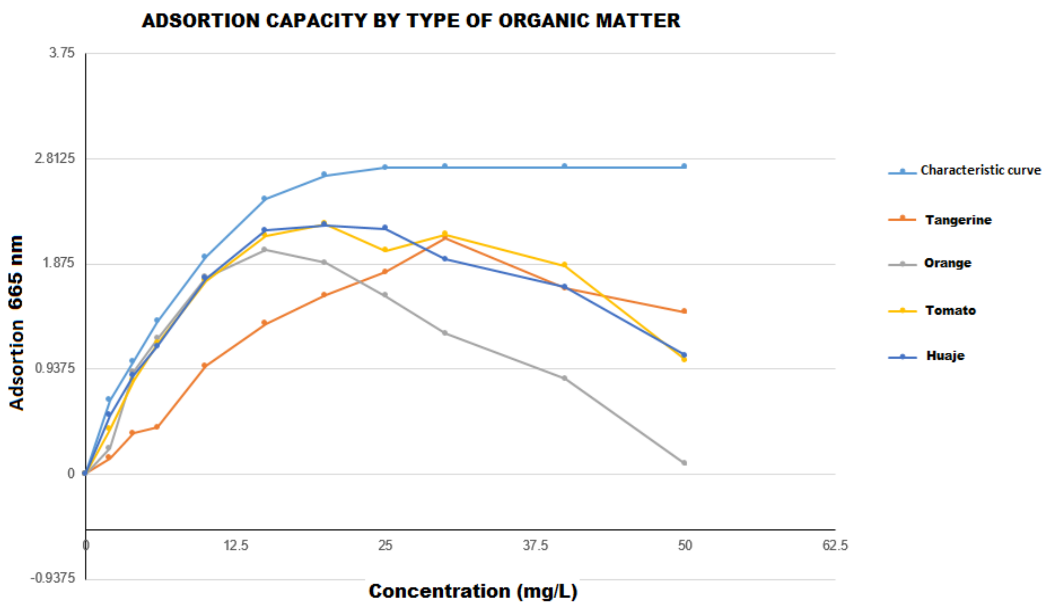


Fig. 3: Comparison of adsorptivity between organic materials.

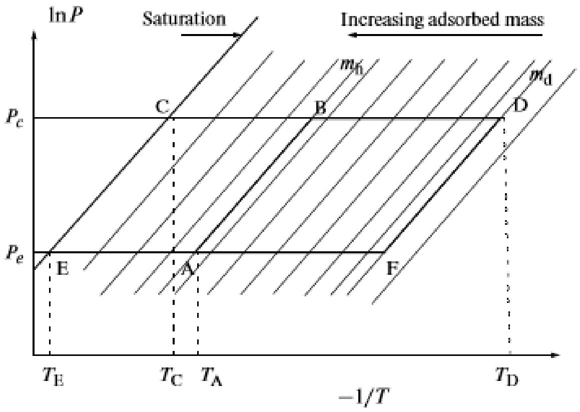


Fig. 4: Clapeyron diagram of ideal adsorption cycle. [20]

The system is composed of a sorption bed (c1-c2 in fig. 1), which locates at the focal line of the CPC, a condenser (the serpentine located between c2 and c3 is in fig. 1), and an evaporator that acts like a refrigerator. The adsorbent and the adsorbate are in a closed and vacuumed system. The collector is supplied with activated carbon, which is adsorbed with natural refrigerant (methanol or water). During the daytime Fig. 1a, the adsorbent (carbon) and the natural refrigerant is heated in the CPC. The natural refrigerant evaporates from the adsorbent and then is cooled by the condenser and stored in the evaporator. In the nighttime Fig. 1b, the ambient air cools the collector and the temperature of the adsorbent reaches a minimum. In this period, natural refrigerant begins to evaporate by adsorbing heat from the water to be frozen and is adsorbed by the adsorbent. As the evaporation of the natural refrigerant continues, the water temperature decreases until it reaches 273 K, where ice starts to be formed. An ideal cycle assumes the use of valves to connect the collector, condenser, and the evaporator. In real unit, this can be avoided and we may depend on the pressure difference to move the refrigerant.

From the literature analyzed it can be found that good heat transfer performance of the adsorber can increase the total heat transfer coefficient and increase the heating rate of the adsorbent. Also it was observed that it is equally important to have a good mass transfer performance which will reduce the diffusion time of refrigerant in adsorbent and sorten the adsorption/desorption time.

Taking this information as a reference in this paper it is proposed a compact design of a solar refrigeration system, this design applies a CPC as an adsorbent in order to enhance the adsorbent temperature and heat transfer.

4.2. Thermodynamics and transfer design procedure

The cycle begins at point A (see fig. 4) where the adsorbent bed is at temperature T_A and pressure $P_e = P_s(T_e)$. During the daylight, AB represents the heating of the pair. The system follows the isotherm $X_A = X(T_A, P_e)$. [20]

Pressure increases until it reaches the value $P_c = P_s(T_c)$ at point B. Thus, the energy used to raise thetemperature of both the adsorbent (ac) and adsorbate (r) from point A to B is given by:

$Q_{AB} = m_{ac}C_{p_{ac}}(T_B - T_A) + m_{ac}X_{r-A}C_{p_r}(T_B - T_A)$ (1)

Additional heating of the adsorbent from B to D causes some adsorbate to desorbed and its vapor to be condensed at pressure P_c. When the adsorbent reaches its maximum temperature T_D, desorption stops, and the adsorbate accumulates into the evaporator. The energy used for the additional heating of the adsorbent to point D and desorption of the adsorbate is given by:

$Q_{BD} =$
$m_{ac}C_{pac}(T_D - T_B) + m_{ac}\left(\frac{X_{r-A}+X_{r-D}}{2}\right)C_{pr}(T_D -$
$TB + macXg$ (2)

The total energy gained by the system during the daytime will be:

$Q_T = (Q_{AB} - Q_{BD})$ (3)

During the night-time, the temperature decreases from D to F, therefore, decreasing the pressure from P_c to P_e. Then the adsorption and evaporation occur while the adsorbent is cooled from F to A. During this period, heat is withdrawn to decrease the temperature of the adsorbent and to withdraw adsorption heat. The total heat released during the cooling period will be the heat of vaporization of adsorbate, this is given by:

$Q_{e1} = m_{ac}(X_{r-A} - X_{r-D})L_r$ (4)

From heat transfer equation, the energy necessary for cooling the liquid adsorbate from the temperature at which it is condensed to the temperature at which it evaporates is given by:

$Q_{e2} = m_{ac}c_{p_r}(X_{r-A} - X_{r-D})(T_c - T_e)$ (5)

And thus the net energy actually used to produce cold area will be:

$Q_e = Q_{e1} - Q_{e2}$ (6)

The performance of the adsorption refrigeration can be expressed in terms:

The collector efficiency

$\eta_1 = \frac{Q_T}{Q_I}$ (7)

The evaporator efficiency

$\eta_2 = \frac{Q_{ICE}}{Q_e}$ (8)

The cycle COP is given by:

$$COP_{cycle} = \frac{Q_{el}}{Q_T} \quad (9)$$

While the net COP is given by:

$$COP_{net} = \frac{Q_{ICE}}{Q_I} \quad (10)$$

Where Q_I is the Total solar energy input to the system during the day.

Equations 1-10 were used to achieve the thermal analysis of the system proposed, results are shown in the following section.

V. RESULTS AND DISCUSSION

5.1. Considerations for the thermal and CFD analysis

As observed in figures 1 and 2, in this preliminary design it was proposed an assembly of four concentric cylinders. The main restriction of the design was the dimensions of the commercial materials aluminum tube and nylamid available in the mexican market.

The function of the cylinder of c1shown in fig. 1, is to be the absorber of the solar concentrator while the function of the cylinder c4 is to be the wall of contact between evaporator and cold area therefore the material of the these two cylinders must be aluminumschedule 40, with athermic conductivity is of 168 W/m-K.

Table 2: Design parameters

Parameters	Dimensions
Collector diameter c1	0.25 m
Condenser diameter c2	0.20 m
Diameter c3	0.168 m
Evaporator inner diameter c4	0.16 m
Serpentine tube diameter	9.58 mm
Condenser tubes	22
Condenser length	0.20 m
CPC opening capture	0.70 m^2
CPC Length	0.5 m
CPC aluminum reflectance	0.8
Solar radiation	700W/m^2

The function of the cylinder of c_2 in the same figure, is to be the wall of separation between the thermic compressor and the condenser and the function of the cylinderc_3 is to be the wall of separation between the condenser and the evaporator, the material of these two cylinders must be non-conductive so it was selectednylamid with a thermic conductivity of 0,29 W/ m-K.

The volume in the cold areais 0,5 liter. This volume is filled with waterwith an initial ambient temperature of 15 ° C and the temperature goal of -5 °C.

Inside the thermic compressor there is a mass flow of 0,00117 kg/s so it will take time to evaporate about of one hour and ten minutes.

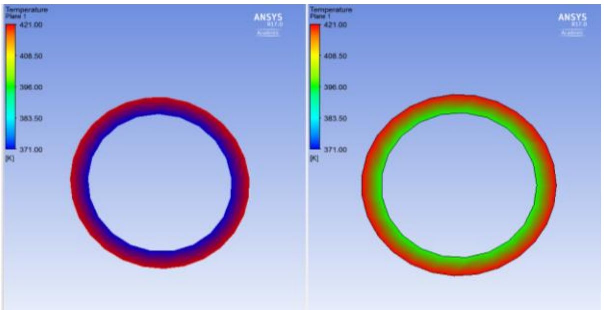
5.2 Results of the CFD analysis

The CFD simulation is about of the heat transfer in collector, it is considered that the outlet temperature is constant with a value of 421K and a model of radiation-convection is applied. The CFd analysis was made considering two refrigerants: water and methanol in order to observe the difference between the properties for both cases. Finally the thermal analysis was made using methanol because it was observed that the results with water are not good. The properties of the working fluids are shown in table 3.

Table 3: Fluids adsorbates properties

Fluid	Density ($kg\,m^{-3}$)	Spec. heat ($J\,kg^{-1}\,K^{-1}$)	Thermal cond. ($W\,m^{-1}\,K^{-1}$)	Viscosity ($kg\,m^{-1}\,s^{-1}$)
Methanol	*785*	2532	0.2022	.0005495
H_2O	*998.2*	4182	0.6	.001003

The comparison of the temperature profile for each working fluid are shown in Fig. 5. The range of temperatures is 381 K to 421 K. The dimensions are the same for the three analyses.

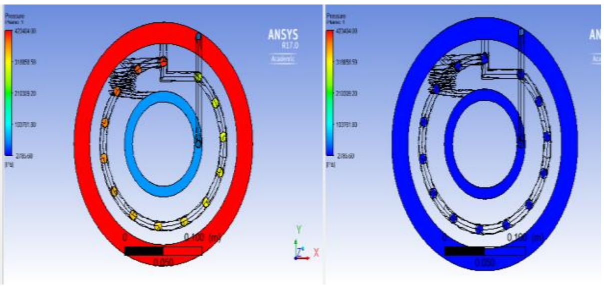


(a) Collector (Fluid methanol) (b) Collector (Fluid H_2O)

Fig. 5: Ansys radiation and natural convection with adsorbate: a) Methanol, b) H_2O.

In the preliminary design, the pressure in the prototype is very important according to the Clapeyron diagram. Fig. 6 shows the pressure profile in the collector and the evaporator for each case.

Is it may be observed when the working fluid is water, the pressure decreases dramatically in the collector. Nevertheless if methanol is used the pressure remains constant in the collector and decreases along the evaporator.



(a) Prototype (Fluid methanol) (b) Prototype r (Fluid H_2O)

Fig. 6: Variation of pressure.

5.3 Results of thermal analysis

With the thermal analysis shown in section 4.2, the amounts of adsorbent- adsorbate pair were obtained. The table 4 shows the amounts obtained for the preliminary design.

Table 4. Adsorbent and adsorbate mass and characteristics.

Material	Mass	Adsorption capacity
Adsorbate Huaje Carbon	0.5 kg	0.58kg-adsorbate/kg-adsorbent
Adsorbent Methanol	0.70kg	

The thermal results and the temperatures obtained in evaporator and compressor are shown in table 5. Also it was obtained the COP and it was observed that this value is between ranges 0.1-0.4 which is the value suggested for some authors [18].

Table 5. Results of the thermal analysis

Parámetro	Value obt.
CPC absorber inside temperature (°C)	118
Compresor temperature (°C)	90
Outlet evaporator temperature (Pa)	15
Cold zone temperature(°C)	-5
Q_L (Heat transfer in cold zone [J])	207 330
Q_T[MJ]	1,287
COP	0,1496

These results were compared with the prototype designed by Wang[21] The comparison between them is shown in table 5. It was observed that the design presented in this paper is able to obtain the desired temperature using a small and portable prototype and with less quantity of adsorbate and adsorbent. Also it was observed that the prototype presented in this paper is cheaper than the one presented in [21] because there is no necessity of the micro vacuum pump and the whole system is smaller than the one presented by Wang [21].

Unfortunately it is observed that the value of the COP obtained with the portable design is lower than the value obtained with the Wang prototype which has a COP of 0.16. This is due to the amount of adsorbent and adsorbate used.

Also the cost of the mexican prototipe is extremely lower thant the one presented in [21], this is very important because the design proposed in this paper is considered to be applied for smal comunities of fichingman.

VI. CONCLUSIONS

In this work it is observed that the proposed design of the portable solar adsorption refrigerator is feasible. In this design it is proposed that all the elements are together as concentric cylinders, according to the determined dimensions it was observed that this proposal is achievable.

Table 5. Comparison between Wang [21] prototype and mexican portable design.

	Wang prototype	Mexican portable prototype.	Observations
COP	↑	↓	Wang prototype has a higher value of COP
T_{min}	↑	↓	Wang prorotype reaches a temperatura of: -3°C And the Mexican prototipe reaches a 5°C.
Adsorbent quantity	↑	↓	Wang prototype: 29 kg. Mexican prototype: 2 Kg
Adsorbate quantity	↑	↓	Wang prototype: 7,5 kg. Mexican prototype: 1,58 Kg
Size	↑	↓	Wang prototype: 2,5 m^2apróx. Mexican prototype: 0,5 m^2 .
Cost	↑	↓	Wang prototype: Cost is more than 3000 USD due to all the components and vacuum pumps that are required. Mexican prototype: Less than 1000 USD.
Portability	↓	↑	Wang prototype: This system is not portable because all the elements are separeted and it needs to be in a fixed place. Mexican prototype is compact and all the elements are in the absorber of the CPC.

Also in this paper absorptivity values of charcoal obtained from different waste organic matter were analyzed. It was observed that the waste of the local product "huaje" has the major adsorption capacity, even more than the values obtained with activated charcoal.

As a result of the thermal analysis it was determined the adsorbent and adsorbate quantity required for the design proposed. The values obtained were 50g of adsorbate and 70g of adsorbent, for 1 liter of water. These values are considered suitable for a portable design. Also it was obtained the COP of the system and this value is similar to the suggested by different authors.

A CFD analysis was made in order to obtain the temperature profiles for the evaporator and condenser. It was observed that the best results are obtained with methanol. This results reinforces the proposal of using methanol as working fluid.

It was compared the design proposed with previous designs and it was observed that the prototype presented in this paper has good characteristics and cost.

In future works it is proposed to compare the theoretic and experimental results with the CFD simulations and also to prove the portable solar refrigerator in rural communities. Also it is proposed to scale the design in order to have double cooling capacity.

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