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Design of Portable and Sustainable Solar Refrigerator

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Abstract

This paper is presented as a preliminary design of a 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 considerations 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, which its three analyzed substances are: water, methanol and biogas, obtained from the bovine manure and organic domestic trash (wastage).

Vegetal carbon is recommended, for this project, as adsorbent material that is usually used in several researches around world as substitute of activated coal.

Keywords: *Solar cooling, adsorption cycle, CPC.*

1. Introduction

Cooling is one of the basic principles of food safety around the world because food slows degradation (Das Surah, 2010).However, according to the International Institute of Energy, approximately 15% of all electricity produced in the world it is used for cooling processes (Kim DS, 2008). Currently the most widely used are vapor-compression refrigeration systems, which work with synthetic materials, such as CFCs, HCFCs or HFCs. When released into the atmosphere, such refrigerants affect the ozone layer and contribute to the greenhouse effect. JA Edmunds et. al (1987), estimated that emissions from synthetic refrigerants, during operation or after life represent 33.3% of the greenhouse effect (Fernandes, 2012). As an immediate response care environment, 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. (Gupta, 2013 and Gutierrez, 2013).

Countries around the world have made some efforts to make the change or elimination of the use of HCFCs. According to SEMARNAT (Secretariat of environment and natural resources) in Mexico in 2010 was totally eliminated in the country consumption of chlorofluorocarbons (CFCs), substances used in refrigeration, air conditioning, aerosols and polyurethane foams and raised under the framework of the "National Plan for Elimination of hydro-chlorofluorocarbons (HCFC) ", which aims to eliminate 30% of consumption of HCFCs by 2018. Despite 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. (Metivier, 2003 and Hassan, 2012).

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Computational fluid dynamics (CFD) modelling would be a viable choice, which can reduce experiments (Y Ge et al, 2010). Many studies have shown that CFD modelling is a promising and valuable tool to improve refrigeration efficiency in terms of energy savings and the required temperature maintenance. (Foster et al, 2005)

Based on the above, it may be noted that it is important to developed cooling systems that consume no electricity, because electricity usually comes from fossil sources; also, it is necessary that this system do not use refrigerants CFCs that affect the ozone layer and produce greenhouse effect. Therefore, the purpose of this research project is to design a refrigerator that uses solar energy for cooling and food preservation, particularly seafood, operating with a CPC collector and adsorption system, using natural refrigerants; proposing the analysis between three pairs of adsorbent-adsorbate: coal - water, coal -methanol and coal-biogas, and selecting the best option for the design of the prototype. As already it mentioned that the solar refrigerator would be used for seafood, thus is proposed that the design be portable for to be used in rural communities with no electricity for the conservation of their food.

Nomenclature

Quantity	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	*QI*	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

2. Solar adsorption refrigeration system

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. 1.

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).

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.

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

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.

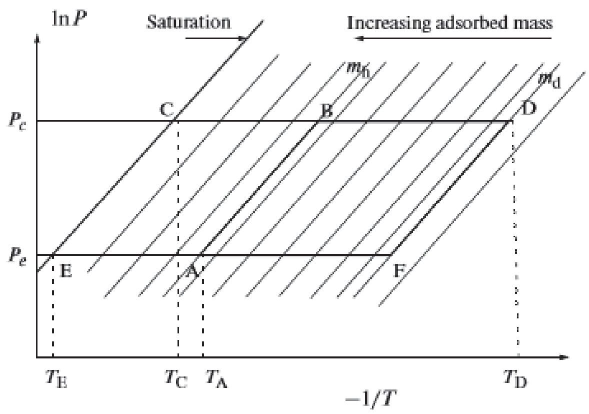
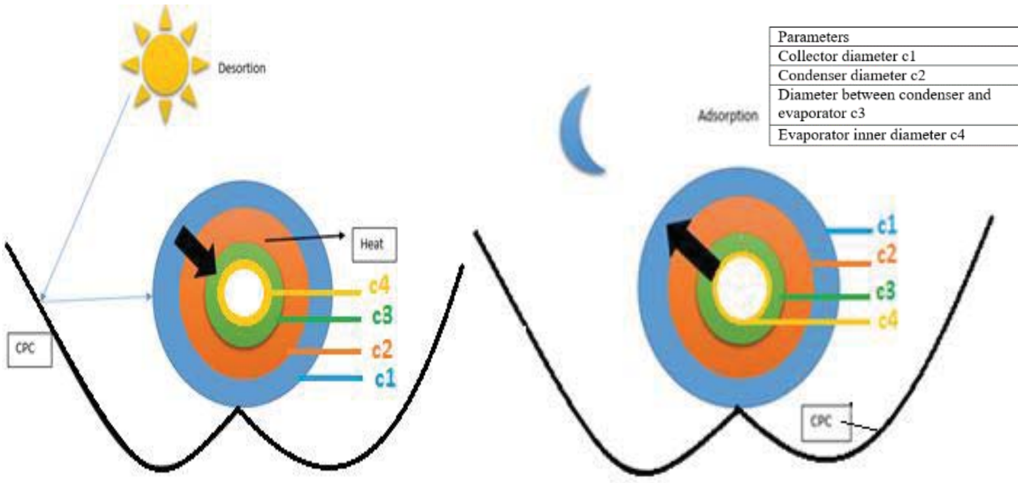


Fig. 1: Clapeyron diagram of ideal adsorption cycle. (Tashtoush et al., 2010)

The operation and principle of the solar adsorption refrigeration system is shown in Fig. 2. The system is composed of a sorption bed, which locates at the focal line of a solar collector, a condenser, 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 carbon, which is adsorbed with natural refrigerant (methanol, water or biogas). During the daytime Fig. 2a, the adsorbent (carbon) and the natural refrigerant is heated in the collector. The natural refrigerant evaporates from the adsorbent and then is cooled by the condenser and stored in the evaporator. In the nighttime Fig. 2b, 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.



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

3. Description of the design

The prototype consists of four concentric cylinder, called c1, c2, c3, c4; c1 is considering that larger diameter and below cylinder c4 is smaller diameter. (Fig.2). The first space formed by c1 and c2, forms the area called collector, wherein the pair adsorbate-adsorbent is placed. The second space formed by the c2 and c3 is the space 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 performs the function of expansion valve.

It is important to mention that 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 should also be an insulating material separates the condenser and the evaporator; however c4 must have a high conductivity to extract energy from the area to be cooled, in which food will be located; finally rejoins the evaporator with the manifold by a pipe; in Figure 3 shows the configuration proposed.

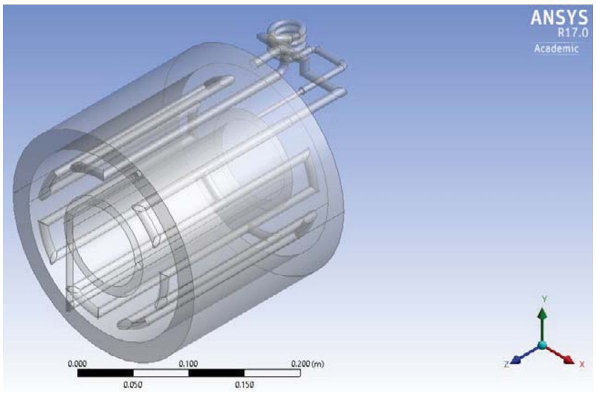


Fig. 3: Solar Refrigerator demonstration system

4. Adsorption capacity of different materials

As part of the project, we have 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. Jaraba (2012), 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 material orange peel modified (Metivier, 2003).

On the other hand, in 2008, E. Gonzalez, 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 (Incar, 2014).

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.[9], [10]. 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%. (Anisur, 2013 and Fernandes, 2014)

For testing, the following parameters shown in table 1 were considered. (Xialong, 2015).

Table 1: Testing parameters

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 they show in fig. 4 and it can be seen that the types of coal which has higher adsorption capacity in descending order they are: huaje, tomato and orange, but it is important to note that these three samples have higher adsorption capacity than activated coal for fishbowl, this preliminary result is very important because if we do not activate the coals we would not use substances as phenolphthalein or oxalic acid and therefore waste pollutants are reduced by the project.

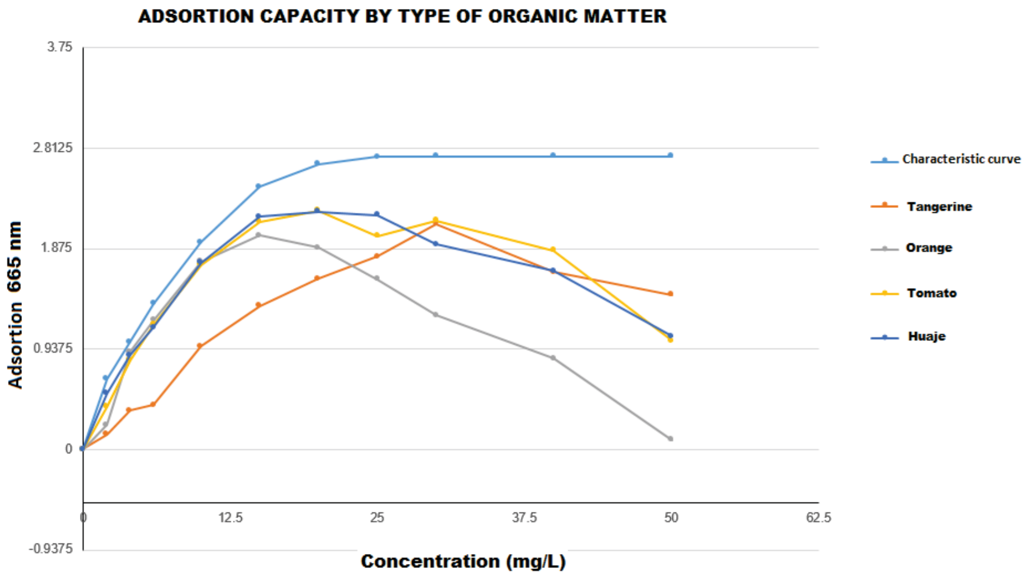


Fig. 4: Comparison of adsorptivity between organic materials

Regarding the materials used as adsorbates, it is important to point out that the biogas to be analyzed shall be deemed like methane for analysis in Ansys (CFD) and the other two adsorbates to analyze are H_2O and methanol, for the properties adsorbates are considered the values of the database of CFD.

5. Thermodynamics and transfer design procedure

The cycle begins at point A (see fig. 1) where the adsorbent bed is at law temperature T_A and at law pressure $P_e = P_s(T_e)$. During the daylight, AB represents the heating of the pair. The system follows the isotherm $X_A = X(T_A, P_e)$. (Tashtoush et al., (2010)

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

$$Q_{AB} = m_{ac} C_{pac} (T_B - T_A) + m_{ac} X_{r-A} C_{pr} (T_B - T_A). \quad \text{(eq.1)}$$

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:

$$Q_{BD} = m_{ac} C_{pac} (T_D - T_B) + m_{ac} \left(\frac{X_{r-A} + X_{r-D}}{2} \right) C_{pr} (T_D - T_B) + m_{ac} (X_g) H. \quad \text{(eq. 2)}$$

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

$$Q_T = (Q_{AB} + Q_{BD}). \quad \text{(eq.3)}$$

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:

$$Q_{e1} = m_{ac}(X_{r\text{–A}} - X_{r\text{–D}})L_r. \quad \text{(eq. 4)}$$

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:

$$Q_{e2} = m_{ac} C_{pr}(X_{r-\text{A}} - X_{r-\text{D}})(T_c - T_e). \quad \text{(eq. 5)}$$

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

$$Q_e = Q_{e1} - Q_{e2}. \quad \text{(eq. 6)}$$

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

The collector efficiency $\eta_1 = Q_T / Q_I$. (eq. 7)

The evaporator efficiency $\eta_2 = Q_{ice} / Q_e$. (eq. 8)

The cycle COP = Q_{el} / Q_T. (eq. 9)

The net COP = Q_{ice} / Q_I. (eq. 10)

6. CFD simulation

The software SolidWorks is used to build up the geometry model of the constructed component. Smooth transition is introduced at the junctions. Structured tetrahedrons elements are applied for meshing. The commercial code FLUENT is employed as the equation solver to solve the governing equations. The SIMPLE algorithm is selected to compute the velocity, pressure and temperature, and the calculations are performed in single precision.

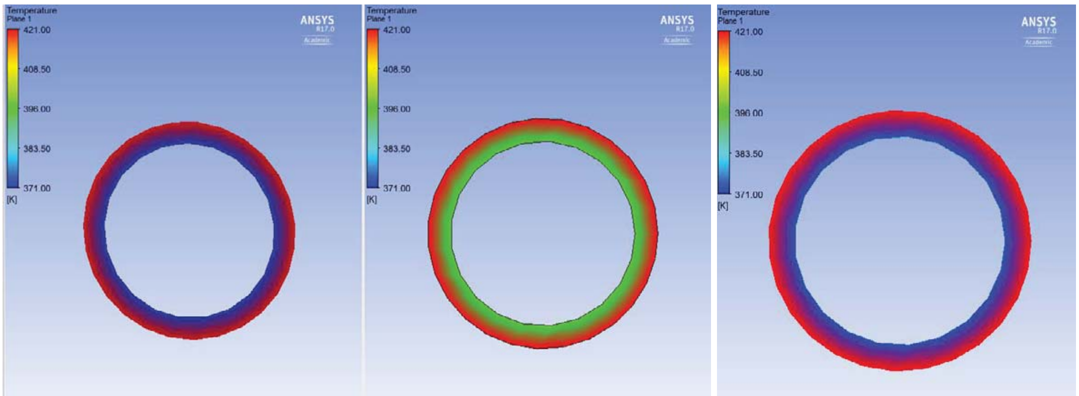
In the CFD simulation about radiation and natural convection, the model used is surface to surface (S2S) for the analysis assumes that all surface are gray and diffuse, the type is pressure- based, and consider that the radiation is constant around of diameter c1. And the method of the assembly meshing is tetrahedrons, using 836 nodes for fig. 5 and 19850 nodes for the fig. 6.

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 properties of the working fluid are shown in table 2

Table 2: Fluids adsorbates properties

Fluid	Density (kg m^{-3})	Specific heat (J kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})	Viscosity (kg m^{-1} s^{-1})
Methanol	*785*	2532	.2022	.0005495
H_2O	*998.2*	4182	.6	.001003
Biogas	*0.6679*	2222	.0332	1.087e-05

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.

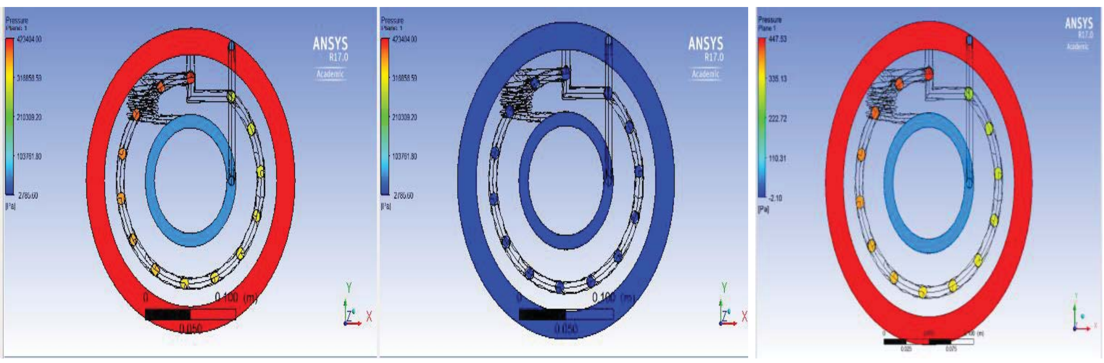


(a) Collector (Fluid methanol) **(b) Collector (Fluid H_2O)** **(c) Collector (Fluid Biogas)**

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

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 or Biogas is used the pressure remains constant in the collector and decreases along the evaporator.



(a) Prototype (Fluid methanol) **(b) Prototype r (Fluid H_2O)** **(c) Prototype (Fluid Biogas)**

Fig. 6: Variation of pressure.

7. Results and discussion

7.1. Results of thermal analysis

In this preliminary design it was proposed assembly of four concentric cylinders, the main restriction of the design are the commercial dimensions found in the national market of alluminium tube and nylamid. The length of the cylinders are 50 cm and the dimensions in order descendent with commercial units are 6",5",3" and 1 1/2".

The function of the cylinder of 6" is be the absorber of the solar concentrator and the function of the cylinder 1 1/2" is be the wall of contact between evaporator and cold area therefore the material of the these two cylinders are alluminium cedule 40, because of termic conductivity is around of 168 W/(m K) and on these two wall is neccesary a high termic conductivity.

The function of the cylinder of 5" is be the wall of separation between the termic compressor and condenser and the function of the cylinder of de 3" is be the wall of separation between the condenser and the evaporator, the caracteristic principal of these tubes are that the material is non conductor and the material select is nylamid with a termic conductivity of 0,29 W/ mK.

The volume in the cold area is to achieve freeze approximately 0,5 liter of water. It was considered an initial ambient temperature of 15 ° C and the temperature goal of -5 °C. The initial conditions of latent and sensible heat are obtained from the total heat extracted from the cold area the which is 203,15 kJ. The mass of the refrigerant is of 0,25 kg considering that the adsorption capacity is of 0,58 kg adsorbate/kg adsorbent and the mass of adsorbent is of 0,30 kg.

The average solar radiation considered is 700 W/m2 and the captation area is 0,70 m2, through free convection was calculated superficial temperature of the absorber of 120 °C and heat transfer of 294 W.

The general equation of heat conduction is used to determine the internal temperature which is 118 °C.

Boiling inside the termic compressor has a mass flow of 0,00117 kg/s so it will take time to evaporate around of one hour, ten minutes.

The length of the tube for the condenser is at least 20 cm for evaporate all volume of refrigerant.The cooling fluid is water to condense to the refrigerant. The coefficient of convection of water is 48,99 W/m2 K

The condensation time considered was 15 minutes and the diameter between the B and C is 9.58 mm. The CPC material was considered to be aluminum with a reflectance of 0.8.

Whit the thermal analysis shown in section 5, the amounts of adsorbent- adsorbate pair were obtained. The table 2 shows the amounts obtained for the preliminary design. Also it was obtained the COP and it was observed that this value id between ranges 0.1-0.4 which is suggested for some authors (Fernandes, 2014).

Table 2: Design parameters

Parameters	Dimensions
Collector diameter c1	25 cm
Condenser diameter c2	20 cm
Diameter between condenser and evaporator	16.8 cm
Evaporator inner diameter c4	16 cm
Condenser tubes	22
Adsorbate mass	50g
Adsorbent mass	70g
CPC opening capture	0.60 m^2
COP	0.22

7.2 Discussion of CFD results

At the beginning of calculation, all the parameters took the values defined at point A. The boundary conditions used are shown in table 3.

Table 3: Boundary conditions

Parameter	Value
Condenser pressure inlet	423 kPa
Evaporator pressure inlet	103 kPa

In the Fig. 5 show the difference of the temperature are based in the specific heat of each fluid and the variation of temperature determined the change of phase of the fluids. These results are very important for the final design because is necessary the change of temperature for each element of the refrigeration cycle also the pressure change in each element propose for the prototype.

8. Conclusion

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.

Also in this paper adsorptivity 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 biogas and methanol. This results reinforces the proposal of using biogas as working fluid.

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.

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