

Design And Construction Of A Solar Energy Refrigeration System Using Vacuum Concentric Tubes With Adsorption.

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Abstract: - The R&D project that is envisioned here, will consist in the physical construction of a Solar Refrigeration System. The theory, on which our design will be based, will be that of using an adsorption thermodynamic system based on the use of an Activated Charcoal and Methanol as working fluid. The Solar collector will consist of a Vacuum Concentric Tubes (VCT)(Tubes that are actually in our position in the Dom. Rep.) The refrigeration cycle will consist of a de-adsorption of the methanol during the heating period of the solar radiation of the day. The vapor will condense and accumulate as a liquid during this period. During the night the process will invert and methanol will be absorbed by the Activated Charcoal and evaporate, lowering its pressure and temperature, producing ice in a refrigerated isolated box. This box can be used as a refrigerated in remote places. It is our intention to establish an R&D process in order to fabricate a working commercial model that can produce refrigeration plus hot water simultaneously.

Keywords: Solar Energy, Refrigeration and A/C, Vacuum Solar Tube Collector.

1. - Introduction: The Dominican Republic is at the present stage immersed in a critical situation due to the inability to satisfy the energy needs of its people. It struggles day to day in order to make the needed equilibrium between supply and demand of its electric power in the utility grid. Costs of producing electric power from fossil fuels are too big a burden to the nation. Therefore it is our intention with this R&D project to try within ourselves to make the difference, although we are aware and recognize our intrinsic limitations of an underdeveloped country. Substitution of fossil fuels by solar energy is our goal in this segment of energy requirements, which represent more than 60 % of the consumption. (Air Conditioning, refrigeration and water heating.)

RESEARCH AND DEVELOPMENT PROCEDURE.

The process that will be executed in this project is divided in three main sections. First, will be involved in the establishment of the thermodynamic theory used for the proper formulations and modeling, plus bibliographic search. Second, design of our prototype and selection and procurement of materials. Third, Construction and experimentation of model, with all possible scenarios taken into consideration. In all sections of this project, students of last year of Mechanical Engineering will be involved as part of they thesis requirements. The University possesses mechanical engineering laboratories that can do all the necessary works indoors. We have all machine shops and tolls needed in our Campus Oriental in Santo Domingo. At the present time, we have all the needed Solar Vacuum Tubes in our possession. These tubes were bought in China, and specifications are given further in this paper. The central part of this R&D project is the use of the Solar Vacuum Tubes. Supplier was: Xu Guangwen, COAST CORP LTD, Tel: 86 4512735906 Fax:864512735876864512308891 Email:guangwen@public.hr.hl.cn

Section 1:

THERMODYNAMIC CYCLE OF REFRIGERATION PROPOSED.

1. ADSORPTION CYCLES FOR SOLAR COOLING

Adsorption cycles for solar cooling are described and past work reviewed, but is our intention to built a refrigeration system that will work with solar energy. Because of the fact that Vacuum Solar Tubes are available at economic values, it is our belief that due to their high efficiencies we can make a difference from previous research work done in this subject. Zeolites have been used as adsorbents in many systems, but this work concentrates on activated charcoal adsorption.

A general study of the cycle thermodynamics shows that provided the latent heat of the refrigerant exceeds about 10(K) kJ/kg and the concentration change exceeds about 10% then the coefficient of performance (COP) can only be slightly improved by further increase. Looking at activated charcoal in particular, the Dubinin- Astakhov (D--A) equation is used to predict cycle COPS based on limited data available for chosen refrigerants and carbons. Of the refrigerants that are sub atmospheric at -10°C . methanol, acetonitrile, methylamine, and NO_2 are suitable, with methanol giving the best COP. Of the refrigerants above atmospheric pressure at -10°C , ammonia, formaldehyde, and SO_2 are suitable. Overall, methanol gives the best COP, with 0.5 being achievable in a single-stage cycle.

Solar cooling could be a useful technology in areas of the world where there is a demand for cooling, high insolation levels, and no firm electricity supply to power conventional systems. The most promising applications are vaccine storage and food storage (particularly fish). Solar thermal systems for refrigeration have been studied for some years, and many refrigerators built and tested. Earlier work concentrated on intermittent absorption cycles such as the ammonia—water machines built Exell [1. 2] and Van Paasen[3]. More recently, solid adsorption cycles have been examined. These have the advantage of requiring no rectifiers, valves, or liquid seals such as are needed in the ammonia water cycle.

The adsorption cycle is best understood with reference to the p - T - x (pressure-temperature-concentration) diagram of Fig. 1 and the schematic diagram of Fig. 2. The processes involved are as follows:

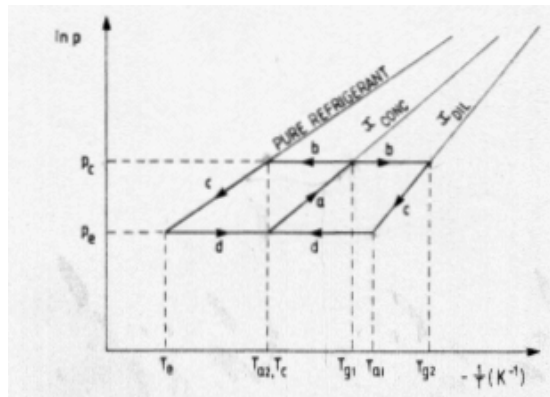


Figure 1.- p - T - x diagram of a simple adsorption cycle.

1. Starting in the morning with the valve open and at ambient temperature of about 30 C (T_{a2} the rich concentration adsorbent in the generator/absorber is heated by solar energy until the pressure reaches

- a level that enables refrigerant to desorb and be condensed in an air or water cooled condenser.
2. Refrigerant is driven off at constant pressure, the adsorbent becoming more and more dilute until the maximum cycle temperature of about 100°C (T_{g2}) is reached. The condensed liquid is collected in a receiver.
 3. The valve is shut, and the adsorbent cools and reduces its pressure. At some stage of the evening or night its pressure will be the saturated vapor pressure of refrigerant at -10°C , (T_e) which is sufficiently low for ice production.
 4. The valve is now opened, and the liquid refrigerant starts to boil in the evaporator. Initially the refrigerant within the evaporator and receiver simply cools itself, but having dropped below 0°C it can start to freeze water. Adsorption is completed by the following morning, completing the cycle. During this process heat is released in the absorber and so the generator/absorber must be cooled by ambient temperature air or water.

This ideal cycle can be used to calculate COPs with reasonable accuracy, but in practice an isolating valve is not necessary and processes *c* and *d* merge into a smooth curve and there are no sharp corners on the experimental *p-T-v* diagram. The diagram used is essentially the same for all adsorption cycles.

Although silica gel has been used in at least one closed-cycle refrigerating system, the vast majority of experience is with zeolites or activated carbons. Critoph and Vogel [8] compared zeolites and active charcoal with refrigerants R11, R12, R22, and R14 and in all cases found charcoal a preferable adsorbent for solar cooling. Meunier *et al.* [7...10] have compared synthetic zeolite—water, synthetic zeolite—methanol and

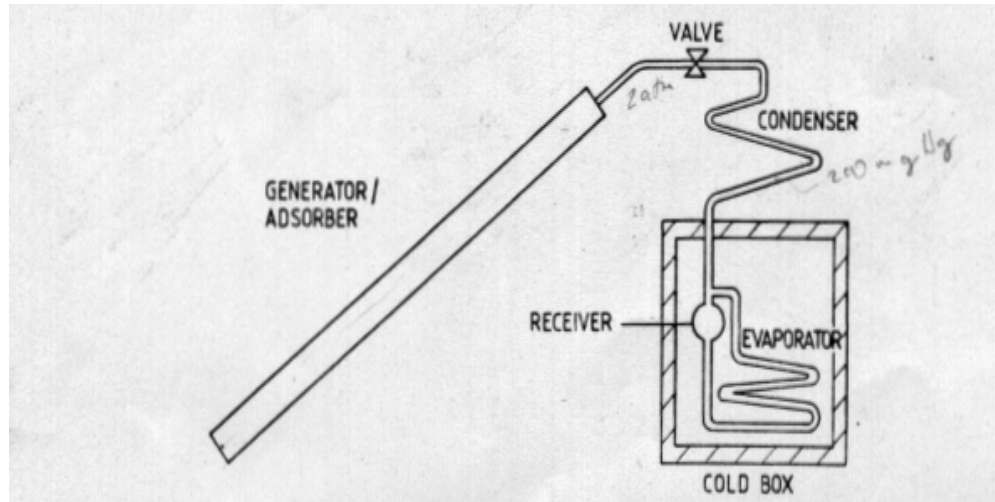


Figure 2.- Schematic diagram of the simple adsorption cycle.

charcoal—methanol combinations. They find that activated charcoal-methanol gives a better COP generally but that when the nighttime ambient temperature to evaporating temperature difference is particularly high then a zeolite—water combination is better. However, this will also require a higher generating temperature from the solar collector during the day. Meunier, comparing AC35-methanol with zeolite 13X-water, suggests that the zeolite combination will only be superior when the temperature lift (adsorption- evaporating temperature) exceeds 45°C . The COP is based on heat input to the adsorbent rather than to the solar collector and so the reduced solar collector efficiency at higher temperatures may actually make charcoal—methanol combinations superior at even higher temperature lifts.

There are other reasons for preferring charcoals:

1. Activated charcoals are cheaper than zeolites.
2. Activated charcoals can be made with properties to suit particular applications by varying the activation time and temperature etc.
3. Activated charcoals (particular coconut shell charcoal can be manufactured in the Dominican Republic.)

2. THERMODYNAMICS OF ADSORPTION CYCLES

Consider the p - T - x diagram of Fig. 1. The various temperatures are: T_{a1} = temperature at start of adsorption, T_{a2} = temperature at end of adsorption, T_e = evaporating temperature, T_c = condensing temperature, T_{g1} = temperature at start of generation, T_{g2} = temperature at end of generation. T_e depends on the application; air conditioning, ice making, deep freeze, etc. T_c is a heat rejection temperature and should be as near to ambient as heat transfer and economics will allow. T_{a2} should be as low as possible so that the strong concentration is as high as possible—this maximizes the concentration change in desorption, thus minimizing the quantity of charcoal that must be wastefully heated and cooled with the adsorbed refrigerant. T_{a2} is also limited by ambient temperature and heat transfer considerations. Although T_{a2} is not necessarily equal to T_c (different heat exchangers may be used and the ambient temperature may change between adsorption and desorption) it is useful to consider the simple case where they are equal.

Both the pure refrigerant and the isosteres approximately obey Trouton's rule, and assuming that the isosteres on the $\ln p$ vs. $1/T$ diagram are indeed linear, it can be shown that $T_{g1}T_{a1} = T_{g2}T_{a2}$.

In the case of solar cooling, T_{a2} might vary between 25°C and 45°C depending on ambient conditions, and T_e could vary between -20°C for cold storage to +5°C for air conditioning. A few possible combinations are listed with calculated value of T_{g1} in table 1.

Table 1.- Typical Cycle Temperatures

Application	Ambiente Temperature	T_e °C	T_{a2} °C	T_{g1} °C
Freezing	Moderate	-20	25	79
	Hot	-20	45	126
Ice Making	Moderate	-10	25	65
	Hot	-10	45	112
Air Conditioning	Moderate	5	25	46
	Hot	5	45	91

The values of T_{g2} are normally within 2 to 5°C of the results for detailed calculations on specific pairs. Given that T_{g1} is the temperature at the start of generation and that in practice T_{g2} will be at least 10°C higher (probably more) the importance of keeping T_{a2} low can be seen. Heat rejection from the condenser and adsorber should be as close to ambient as possible to avoid excessively high solar collection temperatures. The assumption that $T_{a2} = T_c$, is reasonable in many circumstances but may not be true for a diurnal cycle in a climate with large diurnal temperature variations. The maximum cycle temperature T_{g2} is not fixed by the above relationships but is a design variable that must be optimized. The higher T_{g2} , the more refrigerant is driven off and so the greater the cooling effect per Unit mass of adsorbent. However, progressively less refrigerant is desorbed as the temperature rises, and the extra heat input is mainly used in sensible heating of adsorbent and refrigerant, rather than in desorption.

Considering the ideal case of an adsorbent with negligible thermal mass and a refrigerant of negligible specific heat compared to enthalpy of vaporization, then the COP = Enthalpy of vaporization (at T_e) / Mean heat of adsorption. Taking a base of $T_e = -10^\circ\text{C}$, $T_c = 30^\circ\text{C}$, and $T_g = 90^\circ\text{C}$, then the ideal COP is **0.83**. This may be compared with the Carnot COP of a similar cycle $T_e = -10^\circ\text{C}$, $T_A = 30^\circ\text{C}$, $T_{g2} = 90^\circ\text{C}$ which is **1.09**. The difference is, of course, due to the constant heat source and sink temperatures assumed in the Carnot cycle. This is a new and useful limitation on cycle efficiencies specific to adsorption or adsorption cycles.

When taking account of the sensible heating and cooling of adsorbent and refrigerant, the COP is further reduced. For any particular application. T_e , T_c , and T_{a2} are fixed, and T_{g1} and DH/L can be calculated. It can be seen that the refrigerant needs a high, and if possible a low c_{pR} . Unfortunately, high latent heats tend to be associated with high specific heats and so a high specific heat must be tolerated. The adsorbent

should have as low a specific heat as possible, but its main requirement is that it gives a high concentration change between T_{g1} and T_{g2}

The reasoning presented as a theory and postulate, will provide a practical cycle COP with limitation lower than that of pure calculations, but more specific information must be provided to calculate the COP'S. The objective of our research project will be to construct with the Vacuum Tubes in our possession a working model and find the parameters that will fit these equations.

Section 2: TUBULAR SOLAR ENERGY COLLECTORS

1. Solar Energy With Vacuum Tubes. Our Method Of Choice.

Two general methods exist *for* significantly improving the performance of solar collectors above the minimum flat-plate collector level. The first method increases solar flux incident on the receiver; the second method involves the reduction of parasitic heat loss from the receiver surface, such as the Tubular Vacuum Solar Collectors. Tubular collectors, with their inherently high compressive strength and resistance to implosion, afford the only practical means for completely eliminating convection losses by surrounding the receiver with a vacuum on the order of 10^{-4} mmHg. The analysis of evacuated tubular collectors is the principal topic of this section.

2. Evacuated-Tube Collectors.

Evacuated-tube devices have been proposed as efficient solar energy collectors since the early 20th Century. In 1909, Emmett^o proposed several evacuated-tube concepts for solar energy collection, two of which are being sold commercially today. Speyer^o also proposed a tubular evacuated flat-plate design for high-temperature operation. With the recent advances in vacuum technology, evacuated-tube collectors can be reliably mass-produced. Their high-temperature effectiveness is essential for the efficient operation of solar air-conditioning systems and process heat systems.

The level of evacuation required for suppression of convection and conduction can be calculated from basic heat-transfer theory. As the tubular collector is evacuated, **reduction** of heat loss first occurs because of the reduction of the Rayleigh number. The effect is proportional to the square root of density. When, the Rayleigh number is further reduced below the lower threshold for convection, the heat—transfer mechanism is by conduction only. For most gases the thermal conductivity is independent of pressure if **the mean free** path is less than the heat— transfer path length.

3. Optical Analysis of the CTC. (Concentric Tube Collector)

Since close packing of CTC tubes in an array can result in shading losses at any angle other than normal incidence, it is cost-effective to space the tubes apart and to use a back reflector in order to capture any radiation passing between the tubes. Evacuated—tube designs and concentrating designs should be closely packed to optimize solar energy collection. Beekley and Mather (ref) base analyzed the CTC in detail and their analysis is recommended for further studies. CTC arrays can collect both direct and diffuse radiation. Each radiation component must be analyzed in turn.

4. Thermal Analysis of the CTC

The heat loss from a CTC occurs primarily through the mechanism of radiation from the absorber surface. The rate of heat loss per unit absorber area q_L , then can be expressed as $q_L = U_c(T_r - T_a)$. Total thermal resistance $1/U_c$, is the sum of three resistances: R_1 — radiative exchange from absorber tube to cover tube R_2 — conduction through glass tube R_3 — convection and radiation to environment.

The CTC energy delivery rate q_u on an aperture area basis can be written as where A_b is the projected area of a tube (its diameter) and A_r is the receiver or absorber area. The receiver-to-collector aperture area ratio is $pDr./d$.

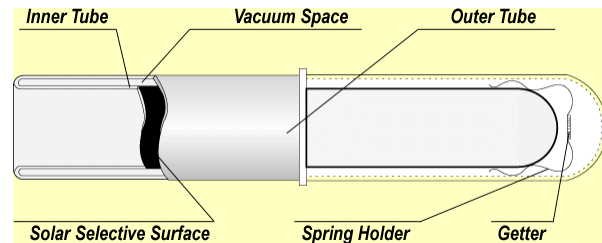
$$q_u = \frac{D_r}{d} [\tau_e \alpha_r I_{eff} - \pi U_c (T_r - T_a)]$$

5. Physical and Thermal Characteristics of the Evacuated-Tube Solar Collector

The tubes that are actually in our possession have the following characteristics:

- Tube is a new generation of sun-heat collect device with low cost but high efficiency of solar thermal conversion.

- Tube is made of all-glass body and has the configuration of two concentric Borosilicate glass tubes, Inner glass tube (Absorber glass tube) and Outer glass tube (Cover glass tube).
- There is a selective absorbing surface on the outside of inner glass tube (Absorber glass tube), this selective absorbing surface is based as a layer of aluminum-nitrogen, this aluminum-nitrogen layer was manufactured using a special coated surface by using the process of magnetron sputtering.
- The jacket between cover (outer) and inner glass tubes is evacuated and permanently sealed off.
- These Tubes are widely utilized due to their high efficiency, low heat losses, long lifetime and low costs. Outside Diameter OD47 mm.



Specifications of Glass Vacuum Tubes:

Tube material: Borosilicate glass, Configuration: Two concentric tubes Length: 1.5 meters, Cover tube diameter: 47mm Absorber tube diameter: 37mm Net weight of tube: 1.4kgs of 1.5 meter. Tube wall thickness: 1.6mm Transmittance of cover tube: 91% Solar absorptance (AM1.5): 93%Emittance (80 c): 6% Pressure of vacuum space: < 0.005Pa Stagnation temperature (typical): 200 c degree Heat loss coefficient of tube: < 0.8W/m².c Impact resistance: withstand 25mm diameter hailstone without breaking glass strength (pressure tested): 1 Mpa Lifetime: 15 - 20Years

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