Proposal for an Adsorption Solar-Driven Air-Conditioning Unit for Public Offices

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ABSTRACT

A simple prototype air conditioning unit driven entirely by solar energy is proposed aiming at replacing the conventional vapor compression air-conditioning systems which are reasonable for the global warming. The proposed model is supposed to be used in conditioning the governmental offices during the working hours in the weekdays when both the sunshine and the need for air-conditioning reach their maximum levels at the same instance. Solar adsorption refrigeration devices have no moving parts consequently they are noiseless, non-corrosive, cheap to maintain, long lasting in addition to being environmentally friendly with zero ozone depletion as well as zero global warming potentials. For these reasons, the research activities are of increasing interest in this aspect in order to provide optimum solutions for the crucial points that impede making these systems capable to meet the criteria for commercialization.

Keywords: Adsorption, solar energy, air-conditioning, refrigeration

INTRODUCTION

The world is facing energy crisis due to the expected shortage of fossil fuel in the short run. The depletion of conventional energy sources manifesting itself in the sharp increase of oil prices. From the environmental point of view, the irresponsible use of conventional fossil fuels leads to ecological problems due to increase in pollution with increasing the emission of carbon dioxide. More specifically, the expanding demands on air-conditioning units, which use of CFCs and HCFC as refrigerants, contribute significantly to depleting the ozone layer. Such arising problems redirected the attention of scientists to develop and invent alternative systems for wiser energy management and for implementing renewable energy resources as the driving power. The situation in Lebanon necessitates a faster movement towards the implementation of renewable energies and the reduction of fossil fuel consumption. Relying on tourism as the main source of income makes it difficult to restrict the air-conditioning usage. Since Lebanon has no oil or natural gas resources, it is therefore essential to seek another ways to offer comfortable life with reasonable and non-conventional systems which do not rely on fossil fuel.

Solar assisted air-conditioning with low grade heat input is one of the promising solutions to the aforementioned problems. In Middle East countries, the levels of sunshine and the need for air-conditioners reach maximum levels in the day time and therefore utilizing the solar energy will be promising to reduce the heavy dependence on conventional fossil fuel. Adsorption machines are one of those interesting alternatives that would replace traditional ways for refrigeration. Adsorption solar refrigerators and air conditioning systems can be put into work with good COP using waste heat energy released from boilers and heating equipment.

MOTIVATION

The main motivation in the present project is to use solar energy, which has high potential in the Middle East region, to drive air-conditioning units running inside the public office, universities and governmental building. The idea behind selecting such places is that they work mostly during the day time and hardly such places need air-conditioning after sunset or before sunrise. Therefore, the air-conditioner unit will work only during the daytime and no need to store energy to be used to drive the unit at night. The project aims at replacing the conventional air-conditioners those working with the banned HFCs and heavily electricity consumers. The limited resources of energy in Lebanon and the sharp increase of oil prices necessitate the quick incentive to find alternatives for the conventional energy resources from one side and to reduce the energy consumption by different sectors from the other side. The present project considers the air-conditioning sector as one of the heavily energy consuming sectors in Lebanon with steep increase of energy demand from year to year. It will achieve various objectives simultaneously, for instance; reducing CO2 emissions, reducing global warming, and reducing the energy consumption. The present paper focuses on the first phase of the project which includes; comprehensive literature review for the adsorption systems and their applications; and the layout of the proposed prototype. Details of the thermodynamics analysis and measuring the performance of the system are ongoing and will be a subject of further publication. The next section presents various applications and experimental trials to apply solar energy or waste heat recovery for refrigeration and air-conditioning purposes.

LITERATURE REVIEW

The adsorption systems are classified in the literature based on the application and the source of heat needed for desorption. Ice-making, refrigeration, air conditioning are among the applications tested by adsorption systems. Most of the applications use solar energy to drive the units and few researches rely on the energy waste recovery from boilers or vehicle exhausts. Details are given in the following sub-sections including the various pairs of adsorbent/absorber used in each experiment.

Solar Powered Adsorption Ice Maker

Ice makers place very large demand to preserve food, vaccine, and drugs. Research has been conducted to develop machines that could employ solar energy efficiently for this purpose [1]. In the late of 1970s, the development of sorption refrigeration systems powered by solar protruded after the pioneering work of Tchernev [2] who studied a basic solid sorption cycle with the working pair zeolite-water. Since then, a number of studies have been carried out, but the cost of these systems still makes them non-competitive for commercialization. Therefore, the focus of some research is concerned about cost reduction and increasing the efficiency of the machine.

Pons and Guilleminot [3] concluded that the solid sorption systems could be the basis for efficient solar powered refrigerators, and they developed a prototype with the pair Activated carbon-Methanol. The machine produced 6 kg of ice per m^2 of solar panel with C.O.P of 0.12, the rate of ice production remains one of the highest obtained by solar icemaker.

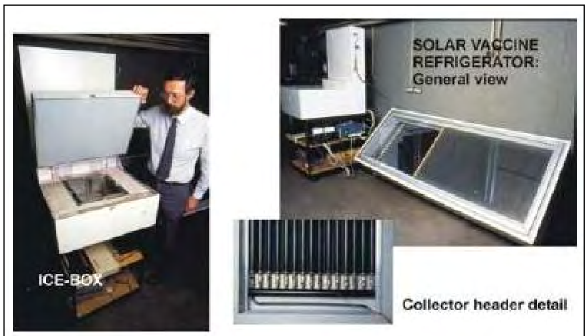

Figure 1. Solar cold box for vaccine preservation [4].

Critoph [4] mentioned solar vaccine refrigerator studied in his laboratory in the early 1990s, Figure 1, using the pair Activated carbon-Ammonia, where the author concluded that C.O.P and ice production of this machine were smaller than those produced by a machine with the pair Activated carbon-Methanol, but the former is less sensitive to small leakages which makes it more reliable to be applied in areas where maintenance is not readily available.

Li et al. [5] performed experiments with the solar icemaker that used Activated carbon-Methanol as working pair, had C.O.P ranging from 0.12 to 0.14 and produced between 5 and 6 kg of ice per m^2 of collector the author concluded that in order to improve the performance of this system, the heat transfer properties of the adsorber needed to be enhanced, this could be achieved by increasing the number of fins or using consolidated adsorbent.

Based on the previous prototype, Li et al. [6] developed a simpler solar powered icemaker without valves, the adsorber was placed inside an insulated case, which was covered by two transparent plastic fiber sheet. The experiments with this prototype were performed both under indoor and outdoor conditions. Under indoor conditions, with an insolation from 17 to 20 MJm^{-2} the ice production was between 6 and 7 kg per m^2 and the C.O.P between 0.13 and 0.15. Under outdoor conditions the system could produce 4 kg of ice per m^2 with C.O.P about 0.12. Based on these experiments two prototypes were developed that could produce 4 to 5 kg of ice per m^2 with C.O.P 0.12 to 0.14, the cost of such a machine was estimated to be no more than 250$ per m^2 of solar panel.

An adsorption icemaker, also with the pair Activated carbon-Methanol was tested in Burkina Faso by Buchter et al. [7] and the results were compared to those obtained by Boubakri et al. [8] and [9] in Morocco, with a similar system, which was commercially produced in the 1980s by the French company BLM. The main difference between those systems is the presence of ventilation dampers in the former. The machine tested in Burkina Faso presented a cooling performance about 35% higher than that of the machine tested in Morocco. The C.O.P of the former machine ranged from 0.09 to 0.13.

Hildbrand et al. [10] developed an adsorption icemaker in which water was used as refrigerant and the ice was produced within the evaporator. The adsorbent was silica gel and the total solar collector was 2 m^2, for insolation higher than 20 MJm^{-2} the C.O.P was between 0.12 and 0.23 when the mean outdoor temperature was between 12 and 25^oC, C.O.Ps higher than 0.15 were obtained with outdoor temperatures below 20^oC.

An innovative modular icemaker was tested by Khattab [11], it placed the adsorbent in a glass container, which was positioned between reflector panels, in order to improve the thermal properties of the adsorbent bed, four types of bed techniques were proposed. The configuration with granular carbon bonded with blackened steel had C.O.P. of 0.16 and a daily ice production of 9.4 kg per m^2 of adsorber when the insolation was about 20 MJm^{-2} and the average outdoor temperature was 29^oC. Under winter conditions with insolation of 17 MJm^{-2} and an average outdoor temperature of 20^oC, the C.O.P. obtained was 0.14 with a daily ice production of 6.9 kg per m^2. Oliveira [12] tested an adsorption icemaker with refrigerant mass recovery process that had daily ice production of 1.2 and 1.6 kg per kg adsorbent when the generating temperatures were 75^oC and 85^oC, respectively. The C.O.P in both cases was about 0.08.

Wang et al. [13] studied a different approach to increase the overall efficiency of the adsorption icemaker, who joined a solar water heater and an icemaker in the same machine. This machine used the pair Activated carbon-methanol and had 2 m^2 of evacuated tube collectors to warm 60 kg of water up to 90^0C. The daily ice production was about 10 kg when the insolation was about 22 MJm^{-2}. A similar system was studied by Wang et al. [14] who assumed that 4 kg of ice produced by the adsorption system could be used to keep a 100 L cold box at 5^oC or below for at least 55 hours if the heat input on the system was between 50 and 55 MJ. Under these conditions, the daily production of hot water would be 120 kg.

An experimental evaluation of an adsorptive solar-powered refrigerator, applied to ice production, using Activated carbon-methanol pair was made in a Brazilian region by Leite et al. [15], the machine used a bi-facially irradiated collector, its performance has been compared with similar machine using a single glazing cover tested in Tunisia. The present system's performance was shown to be significantly better, due to the use of devices to increase the solar energy collection efficiency, and to improve the heat dissipation of the adsorber during the refrigeration stage. This machine produced 6 kg of ice per m^2 of collector surface with a corresponding 0.085 daily solar C.O.P.

Pons et al. [16] built a solar-powered icemaker with Activated carbon-methanol pair in Orsay. They constructed a solar collector of 6 m^2 which contains, on the whole, 130 kg of Activated carbon. The condensers were air-cooled, and the evaporator had a net production of 30-35 kg of ice per sunny day. The ice was easily removed and in principle the machine could be automatically operated as shown in Figure 2. The net solar C.O.P was 0.11 which makes the machine one of the most efficient solar powered icemakers.

Solar Powered Adsorption Air Conditioners

Air-conditioning is an excellent application of solar energy, because the supply of sunshine and the need of refrigeration reach their maximum levels in the same season. Adsorption air conditioning has been of increasing interest particularly during summer since the demand of electricity is greatly increased due to the intense use of air conditioners. Thus the use of solar powered air conditioners seems to be an attractive solution.

At the end of 1980s, Grenier et al. [17] presented a solar adsorption air conditioning system that had 20 m^2 of solar panel and used the working pair zeolite and water, this system shown in Figure 3, was designed to refrigerate a 12 m^3 room for food preservation. When the insolation received by the solar collectors was about 22 MJm^{-2}, the cold room could store 1,000 kg of vegetables for a temperature difference of 20^oC between the ambient outside and the cold room, the C.O.P was 0.10.

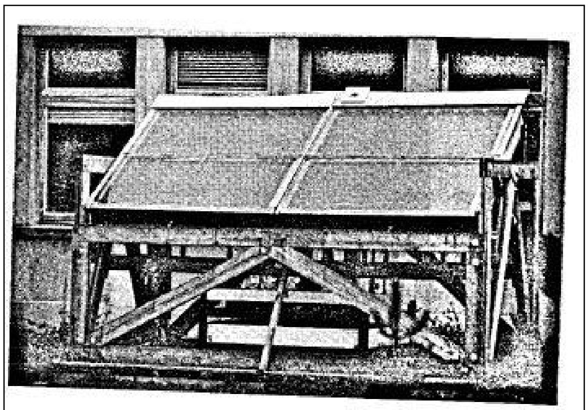

Figure 2. Photograph of the icemaker [16].

Figure 3. Cold storage room [17].

Saha et al. [18] experimentally investigated a double-stage four bed, non-regenerative adsorption chiller that could be powered by solar/waste heat sources at between 50°C and 70°C. The studied prototype produced cold water at 10°C and had a cooling power of 3.2 kW with a C.O.P of 0.36 when the heating source and sink temperatures of 55 and 30°C respectively. Flat plate collectors could easily produce hot water to regenerate the adsorbent of the chiller at these levels of temperature.

An adsorption air conditioning system was developed by Wang et al. [19] to be powered by heat sources with temperatures close to 100°C, evacuated tube collectors could be used to supply hot water at this level of temperature. The system consisted of two adsorbers, each with 26 kg of carbon inside and used methanol as refrigerant. The C.O.P of this system was significantly influenced by the cycle time. The operation of the system with cycle time of 30 minutes leads to C.O.P of 0.15 and a cooling power of 3.84 kW while operation with cycle time of 60 minutes leads to C.O.P of 0.21 and cooling power of 3.03 kW. To improve the performance of the system, the authors changed the adsorbers, keeping the same charge of carbon, and used a tube and plate heat exchanger being the carbon placed outside the tubes, between the plates. With the new design the C.O.P obtained was 0.4 and the cooling power was 3.80 kW. The experimental conditions in this case were: a heat source temperature of 100°C, an evaporation temperature of 10°C, a condensing temperature of 24°C and a cycle time of 50 minutes.

Liu et al. [20] developed an adsorption chiller with the pair silica gel-water, that had no refrigerant valves. This feature reduces the cost of the chiller, and makes it more reliable as there are fewer moving parts that could lead to air infiltration. The whole chiller contains 52.8 kg of silica gel divided between two adsorbent beds, which operate out of phase and thus produce constant cooling. Experiments with this prototype showed that a cooling power of 3.56 kW and C.O.P of 0.26 could be obtained when the mass and heat recovery processes are employed under the following operation conditions: an evaporation temperature of 7°C, a heat sink temperature of 28°C, and a heat source temperature of 85°C. To enhance the performance of the chiller, the research team developed a new prototype with some improvements. The new prototype had less non-continuous and movable pieces to reduce the number of possible places for inward leakage. The condenser was changed to avoid undesirable refrigerant evaporation that occurred inside this device during the operation of the first machine. The configuration of the adsorber was changed to improve the heat and mass transfer. The second prototype had a cooling and C.O.P about 34% and 28% higher than the first one. Experiments performed at a generation temperature of 80°C and an evaporation temperature of 13°C showed that C.O.P and the cooling power of this new system could reach 0.5 and 9 kW, respectively.

Xia et al. [21] developed a silica gel-water adsorption chiller driven by low temperature heat source. This chiller has two identical chambers and a second stage evaporator with methanol as working fluid. Each chamber contains one adsorber, one condenser and one evaporator. There is also a mass recovery tube between the two chambers. The solar powered water-heating unit includes almost 50m^2 of evacuated tube collectors, a water pump and a hot water storage tank. Experiments performed when hot water at 85°C was used to drive the chiller, resulted in a cooling power close to 4.96 kW, and with the corresponding cycle C.O.P around 0.32. When the hot water temperature was 65°C, the cooling power and cycle C.O.P were 2.97 kW and 0.23, respectively. Two chillers similar to the one described previously, but with a higher nominal capacity are used in the air conditioning system of a “green” building located in the Shanghai Research Institute of Building Science.

Nunez et al. [22] developed and tested a silica gel-water adsorption chiller with nominal cooling power of 3.5 kW. It had two adsorbers filled, each one, with 35 kg of adsorbent. The chiller operated at generation temperatures between 75 and 95°C, heat sink temperatures between 25 and 35°C, and evaporation temperature ranging from 10 to 20°C, the C.O.P varied from 0.4 to 0.6 according to the experimental condition.

Restuccia et al. [23] developed an adsorption chiller that employed silica gel impregnated with $CaCl_2$ as sorption material. This kind of adsorbent was used due to its high sorption ability (up to 0.7 kg of water per kg of dry sorbent) and due to the fact that most of the water content can be desorbed at generation temperatures between 90 and 100°C. When the condensation temperature was 35°C, the C.O.P of the chiller was close to 0.6 in the range of generation temperatures from 85 to 95°C, but it varied between 0.3 and 0.4 when the condensation temperature was 40°C. The evaporation temperature during these experiments was 10°C, the SCP was 20W kg^{-1} when the generation temperature was 95°C and the condensing temperature was 40°C. Another kind of solar powered air conditioner employs open adsorption system instead of closed ones. These system are called open because the refrigerant, which is water from the air is released to the atmosphere after the desorption process.

Ismail et al. [24] studied a system with silica gel designed to reduce the absolute humidity and enthalpy of the air used to cool grains. In such a system, the air passed through two silica gel beds and two heat exchangers to provide dry air during the night to grain storage room. The utilization of this system could keep the temperature of the grain at about 16^oC, while this temperature would be closer to 21^oC without the system. The C.O.P based only on the electricity supplied to the system was greatly influenced by the airflow rate, and it ranged from 3.9 to 30.3 for an airflow rate between 0.065 kg/s and 0.021 kg/s.

Toruwa et al. [25] also studied a system which is designed to provide conditioned air for grain storage. The system used solid compound desiccant comprised by a mixture of bentonite $CaCl_2$ vermiculite and cement with the mass ratio of 6:1:2:1. The compound desiccant was placed inside 0.9m^2 flat plate collector. The dehumidified air with 40% reduced relative humidity could be produced continually during nighttime at the rate of 2 m^3/min. During the daytime the desiccant material was regenerated inside the collector, by an insolation around 19MJm^{-2}. Desiccant systems can be also used to improve the performance of evaporative cooling systems. A ventilation system for evaporative cooling with desiccant wheel regenerated by solar energy is used to produce the cooling effect.

However this effect is increased by dehumidification of the air by the sorbent. Such a system was studied by Henning et al. [26] and could produce inlet room air at 19^oC when the ambient temperature was about 31^oC. The solar energy used for regeneration of the sorbent was close to 76% of the total input energy and the C.O.P of the system was 0.6.

The combination of desiccant wheel with the conventional compression chiller can also increase the efficiency of the system. This happens because the thermal driven sorption wheel does the removal of the latent load and the chiller just does the removal of the sensible load. In such a case the chiller can work at evaporation temperature close to 15^oC instead of the usual 5^oC which increases its efficiency.

Lu and Yan [27] studied another kind of open sorption system for air dehumidification and that could be regenerated by solar energy. The system identified as solar desiccant enhanced radiative cooling (SDERC), used silica gel as sorbent. The European project Clismol [28] presented examples of buildings that already use solar powered sorption air conditioners. The examples include applications of solid sorption chillers and solid desiccant systems. Some of the chillers were installed in a university hospital located in Freiburg, Germany, and in cosmetic company Sarantis S.A., in Greece, while some of the solid desiccant systems were installed in the Chamber of Commerce in Freiburg, and in the Renewable Energies Department, in Lisbon.

<u>Adsorption Icemakers Driven by Exhaust Gases:</u>

The efficiency of diesel engines is about 35%, and in the operation water-cooled engines about 35 and 30% of the input energy is wasted in the coolant and exhaust gases respectively [29]. Thus, recovering the waste heat can improve the energy management where such engines are employed. The use of this heat to regenerate the bed of the adsorption system is one of the alternatives to increase the overall efficiency of the diesel engine. The mechanical vapor compression system is currently the most available technology nowadays for refrigeration purposes on fishing boats, but it has certain drawbacks such as the increase of fuel consumption on the boats, because some extra energy is needed to drive the compressor. Fishing boats are generally powered by diesel engines, and the employment of adsorption refrigeration systems instead of mechanical compression ones, could reduce their fuel consumption.

Wang et al. [30] developed an adsorption system in which the sorption beds could be regenerated by using exhaust gases of diesel engine. This system was designed for ice production, and the working pair used was Activated carbon-methanol. The exhaust gases holding a temperature of about 500^oC heated water in a heat exchanger and this water was used to heat the adsorbent at the generation phase. The temperature of the hot water was adjusted to be lower than 120^oC, because methanol when in contact with activated carbon is unstable at temperature higher than this. The author used solidified adsorbent shown in Figure 4, instead of granular one because of the difference in the heat transfer coefficient of these two materials 99 and 25 $Wm^{-2}K^{-1}$ respectively.

The experiments with this prototype were performed with and without refrigerant mass recovery. The mass recovery proved to increase the ice production 11% with cycle time of 72 minutes and an evaporation temperature of -11^oC, the SCP was 16.8 Wkg^{-1} and the C.O.P was 0.12.

The consolidated carbon block was also used in a prototype developed by Wang and Wang [31]. The experiments with this machine employed heat and mass recovery processes to increase the SCP and the C.O.P. An oil burner simulated the heat from the

Figure 4. Consolidated carbon block [30].

exhaust gases of a diesel engine. The engine achieved the SCP of 27Wkg^{-1} with C.O.P of 0.18, which resulted in a flake ice production from 18 to 20kgh^{-1} at -7^{o}C.

Tamainot-Telto and Critoph [32] developed an adsorption system with consolidated carbon block, and utilized ammonia as refrigerant. This system presented SCP of 35 Wkg^{-1} and a C.O.P of o.10 when the evaporation temperature was -17^{o}C, the condensing temperature was 25^{o}C and the generation temperature was 105^{o}C. The authors mention that the use of higher generation temperatures and heat recovery process could lead to higher SCP and C.O.P.

Wang et al. [33] compared the performance of an adsorption system using different working pairs to identify the most suitable pair for adsorption ice making on fishing boats. The pairs compared were: 1) Activated carbon and methanol; 2) $CaCl_2$ and ammonia; 3) compound adsorbent (80% $Cacl_2$ and 20% of activated carbon) and ammonia. Best results are obtained from the composite adsorption ice maker that had the cooling power of 20.32 kW when the cycle time is 60 min, which is about 10 times that of the physical adsorption ice maker and 1.38 times that of the chemical adsorption ice maker.

Adsorption Air Conditioners Driven by Exhaust Gases

Air conditioning on vehicles could be another reasonable application for adsorption systems powered by exhaust gases. The vehicles more suitable for this kind of air conditioner are buses and locomotives, as adsorption systems usually still have large volume and mass.

Zhang [29] studied an adsorption air conditioning system that could have the sorption beds regenerated by the exhaust gases of a bus. The adsorber consists of two concentric pipes, and the exhaust gases or the cooing air flowed through the inner pipe, to release or to remove heat from the adsorbent, respectively. The adsorbent zeolite was placed between the inner and the outer pipe. Fins were attached to the inner pipe to increase the heat transfer between the fluids and the adsorbent, water was used as refrigerant. The C.O.P found was 0.38 and the specific cooling power (SCP) was 25.7Wkg^{-1}.

Lu et al. [34] developed an air conditioner with the pair zeolite-water that could be powered by the exhaust gases of a locomotive. This system was based on a laboratory prototype developed by Jiangzhou et al. [35]. It was designed to refrigerate the driver's cabin of a locomotive. The cooling power of such a system under typical running conditions ranged from 3 to 5 kW, with a C.O.P of 0.21. The temperature inside the cabin was between 4 and 6^{o}C lower than the ambient temperature. It was remarked that the velocity of the locomotive and the rotating speed of the engine have significant influence on the cooling and heating power of the air conditioner.

Tamainot-Telto and Critoph [36] studied a modular adsorption air conditioner, which was powered by hot air. The authors tested three different module configurations. The module that presented the best performance had 125μm fins around the evaporator/condenser. The results of the experiments with this module showed that under typical conditions (generation temperature 100^{o}C, condensing temperature of 30^{o}C and evaporation temperature of 15^{o}C) the cooling power was about 600Wkg^{-1}, and the C.O.P was 0.2 without any heat regenerative process, and estimated to be 0.5 with a two bed regenerative cycle.

Lambert and Jones [37] proposed detailed design and analysis of an automotive adsorption air conditioner using the pair Activated carbon-ammonia as shown in Figure 5. The C.O.P to maintain an already cooled cabin for a subcompact car is assumed to be 0.6 for uniform temperature heat recovery.

SELECTION OF THE WORKING PAIR

Methanol is a good working fluid because:

- It can evaporate at temperature below 0^{o} C (its melting point is -93.9^{o} C)
- Its normal boiling point (65^{o}C) is so much higher than room temperature that it is not necessary to build an absolutely leak proof machine. With methanol the machine is always at pressure lower than atmospheric. This is also an important safety factor because it means that, when leak occurs, air comes into the machine and can be detected by an abnormal increase in pressure and poor performance. Thus, there's adequate

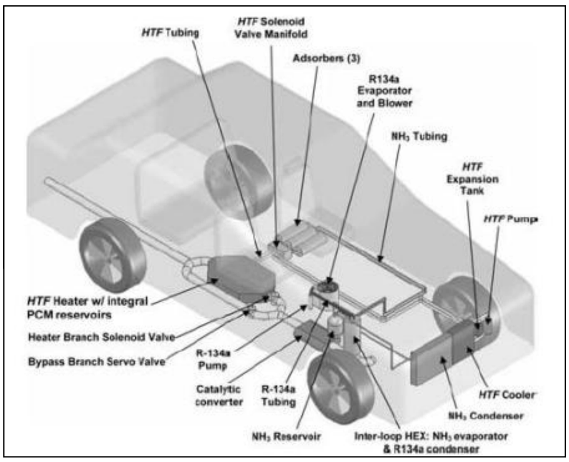

Figure 5. Layout of the exhaust-powered automotive adsorption heat pump [37].

warning before methanol can flow out of the pipes.

- Its enthalpy of vaporization is significant (L = 1100 kJ/kg).
- It doesn't create any corrosion problems.

Activated carbon has a significant volume of micro-pores of convenient size. Studies showed that activated carbon-Methanol seems to be a good pair for solar ice-maker with flat-plate collectors. Deing and Wang [39] made comparison between AC-M and Zeolite-water (Z-W) pairs and concluded that:

a) AC-M has adsorption characteristics such that in conditions typical of solar energy (Evaporation temperature T_e = -5^{o}C, condenser temperature T_c = ambient temperature T_a = 25^{o}C), the optimal cycle C.O.P. is obtained with desorption temperature T_d=110^{o}C. This is precisely the range of temperatures that can be reached with solar energy, this cycle C.O.P. is about 0.4. Whereas Zeolite-water at the same temperatures would give C.O.P = 0.3.

b) It also appeared that Methanol is less attracted by Carbon than water is by Zeolite: Methanol is easily absorbed. In order to increase cycle C.O.P. It is much more important, in the case of AC-M pair, to reduce (T_a-T_e) than to increase (T_d-T_c).

PROTOTYPE DESCRIPTION

As shown in Figure 6, the system consists of: (1) electric water heater, (2) two tanks to store hot and cold water respectively, (3) two adsorbers (A & B), (4) condenser, (5) evaporator, (6) circulating pump, and (7) needed accessories which include 3-way valves, pressure and temperature sensors and vacuum pump. The water in the hot water tank is heated by the electric water heater and used as heat source for heating the adsorbent beds. When hot water reaches the required temperature, hot water tank is connected to adsorber A to heat and desorbs the refrigerant (adsorbate) from the adsorbent (desorption phase). The vapor refrigerant is in turn cooled in the condenser and then passed to the evaporator, where again it gets evaporated at low pressure, therefore providing cooling to the space. During the same period, adsorber B adsorbs the vapor refrigerant leaving the evaporator. The operation of the system follows a periodic succession of cycles. Which means, when adsorber A is in the desorption phase (heating period), adsorber B will be in the adsorption phase (cooling period). Thus, the system can be grouped into three periods: 1) time duration to preheat the water in the hot water tank to the required temperature, 2) duration in which adsorber A/B is in the desorption phase, 3) duration in which adsorber A/B is in the adsorption phase.

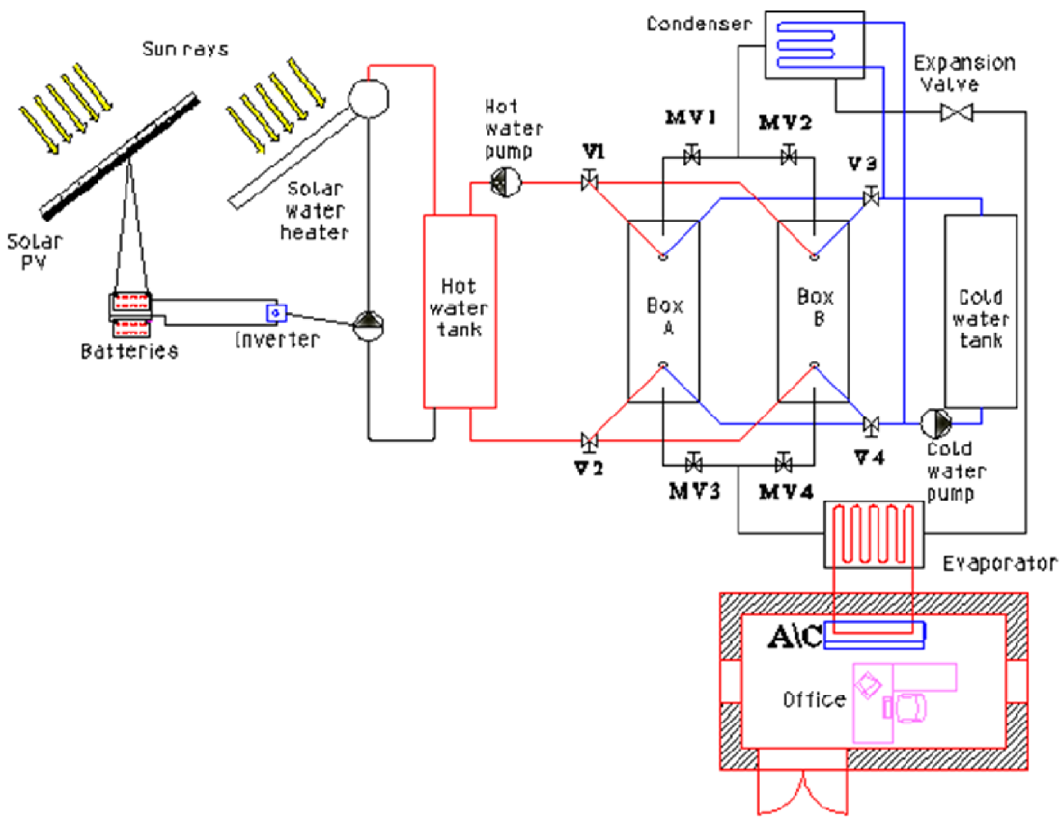

Figure 6. Layout of the proposed adsorption air-conditioning system

Samples of the activated carbon used in the experiments are shown in Figure 7. Previous studies showed that the performance of the system is affected by the tank volume. The system C.O.P decreases with the increase in tank volume. It is obvious that for low tank volumes, the water could attain the required adsorption temperature much earlier, which affects the system performance. Hence, it's recommended to minimize the volume to about 0.05 m^3. The condenser with dimensions of (32.5x25x8.7cm) is composed of 36 internally threaded copper tubes, having outside diameter 12.7mm and of inside diameter 9.5 mm, with external 70 aluminum fins. Pressure in the condenser is 101kPa at 65^{o}C. To increase the simplicity of the machine, the condenser is air-cooled by natural convection.

Evaporator has sufficient volume to contain all condensed methanol. For simplicity, it is intended to make the dimensions of the evaporator same as of the condenser (32.5x25x8.7 cm). The evaporator pressure is 7 kPa at temperature of 6^{o}C.

In order to measure the quantity of condensed methanol, and only for this reason, the methanol flowing down from the condenser has to be collected in a reservoir where the liquid level can be read off. The volume of the reservoir has to be 6L (16cm diameter, 30cm height) as the introduced methanol is 5.5 L. The capillary tube was designed with diameter 0.036" and 28.6 cm length to throttle the condensed methanol of 2L volume into the evaporator.

(a)


(b)


Figure 7. Samples of the activated carbon used in the experiments

Temperatures are to be measured at different positions in the bed, in the condenser, in the evaporator as well as the pressures. Also measuring the amount of condensed methanol is necessary in order to determine the practical C.O.P. of the cycle. Figure 8 shows the complete circuit of the unit presented in the Engineering Day of Senior project of Beirut Arab University. PV panels are used to drive the circulating pumps for hot and cold water.

THEORITICAL COP

In our design the adsorber is consisted of two beds each containing 5 kg of activated carbon. If heated to 110^{o}C, then the sensible heat needed to raise its temperature from room temperature to 110 ^{o}C would be around 900 kJ. This amount should be added to the heat needed to release the Methanol to the vapor state. Since the activated carbon adsorbs around 55% of its weight by Methanol, then the total heat would be 7300 kJ. While the Methanol is expanding in the capillary tube from 0.17 bar to 0.07 bar, it will evaporate to the vapor state releasing a heat amounts to 6350 kJ. The solar energy used during the regeneration would be 43400 kJ and the theoretical C.O.P would be 0.146. Details of the thermodynamics analyses and investigating the performance are under preparation and will be a subject of future publication.

CONCLUSIONS AND FUTURE WORK

The project presents a prototype design of an air-conditioning unit which is driven by solar energy using the adsorption technique. In this paper, the current status of the project is presented. Literature review of the various applications of adsorption techniques in refrigeration and air-conditioning are presented. The proposed design of the working circuit and how it works is explained. Activated carbon-Methanol pair is selected mainly due the availability in the local market with reasonable prices. Some difficulties have been arisen during the setup of the prototype such as; maintaining the vacuum inside the entire circuit; charging the evacuated circuit with methanol; and insensitivity of the multi-way valves to such low pressure in the circuit. In the second phase of the project, such difficulties will be dealt with, full measurements of temperature and pressure, thermo-dynamical analysis, and complete proposal for the circuit driven by solar energy for heating and driving the circulating pumps and fans will be presented.

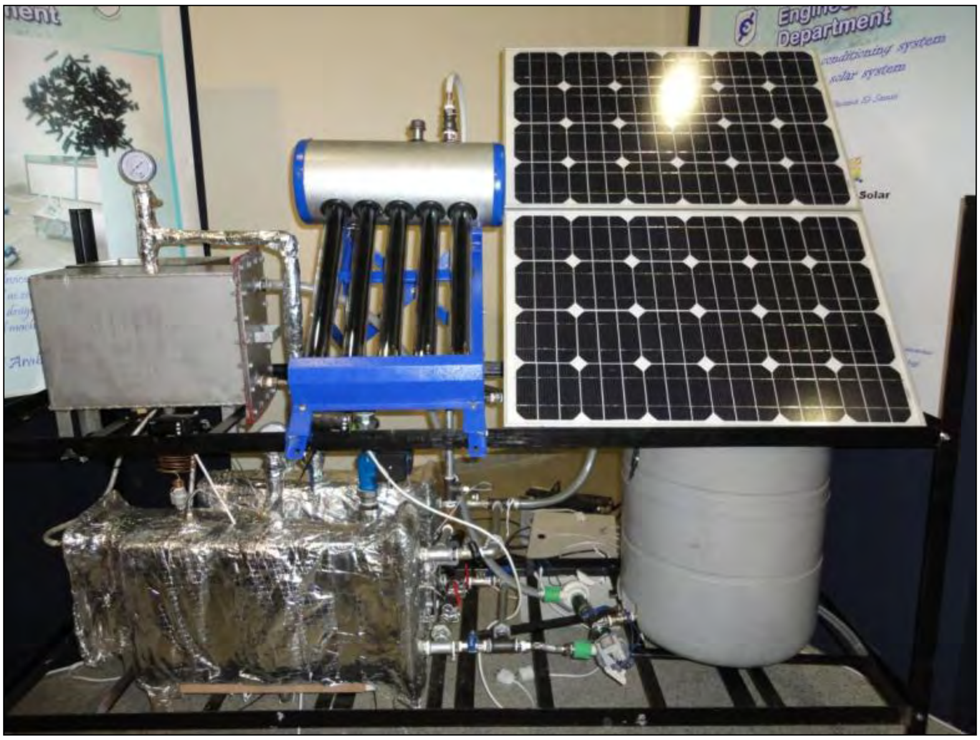

Figure 8. Adsorption air-conditioning solar assisted unit, BAU 2010 senior project.

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