Experimental Study on Vapor Adsorption Refrigeration System with Carbon-Methanol Pair

Praveen Alok, Debjyoti Sahu*
Department of Mechanical Engineering,
Amrita School of Engineering, Bengaluru,Amrita VishwaVidyapeetham, India.

*corresponding author: debjyoti@blr.amrita.edu

Abstract: Adsorption systems may find its application in refrigeration and air-conditioning, ice-making, water chiller etc. In conventional vapor compression refrigeration system, compressor is the main power consuming component. A vapor adsorption systemcan be feasible replacement for vapor compression refrigeration system. The main objective of this project is to design, fabricate and test a cost effective and laboratory scale vapor adsorption refrigeration system. An intermittent type vapor adsorption system is fabricated using some common stainless steel utensils, copper tube, an electric heater and a laboratory vacuum pump. The Refrigeration effect and COP of the system is determined from basic thermodynamic relations. Though COP is ~0.175 but it's able to bring down temperature of circulating water by more than 10 ^{o}C.
Keywords: Adsorption refrigeration, Activated charcoal, Adsorption cycle efficiency.

1.Introduction

Due to rapid industrialization and fast growing population energy demand is increasing drastically. The living standard of the people is also increasing. Refrigeration and air-conditioning systems play a major role in electrical energy demand. According to energy consumption data, refrigeration and air-conditioning sector consumes almost 17 % of the global grid power [1]. Refrigeration and air-conditioning systems consume high quality energyvis-a-vis domestic and industrial appliances. According to data from the US Department of Energy, HVAC systems are responsible for using 18.62%, 16.20%, and 2.34% of the total energy consumed in the residential, commercial and industrial sectors respectively [2]. The energy consumption in the automotive air conditioning is also increasing. In a typical passenger car, the AC compressor can add up to 6 kW of power consumption to the engine thus increasing fuel consumption. Vapor compression refrigeration systems are technically sound and convenient to use. Vapor compression systems have high C.O.P, very low startup time, robust and compact in structure. However the refrigerants used in this system are mainly Chlorofurocarbon (CFC), Hydrochlorofluorocarbon (HCF), Hydrocarbon or mixtures of these compounds which causes depletion in ozone layer and has global warming potential. On the other hand it is easy to use environment friendly refrigerant in vapor adsorption refrigeration system. Moreover, a vacuum pump which will consume comparatively less power (Fig. 1) than a refrigerantcompressor as the refrigerant to be handled at low pressure has less specific volume.

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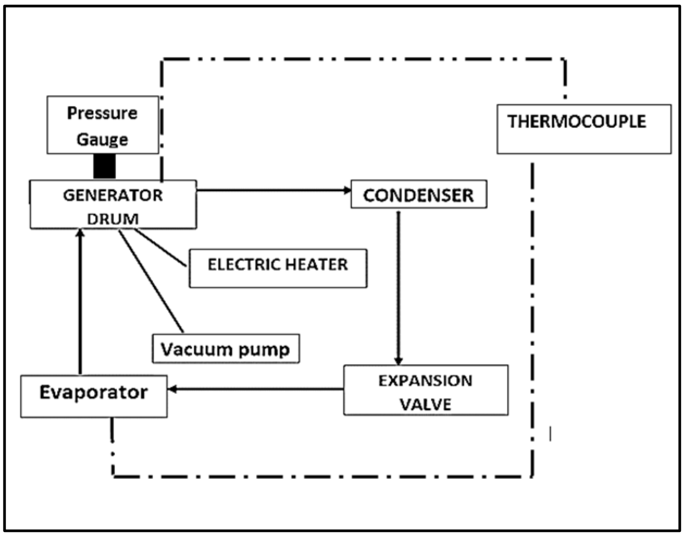

Fig. 1 Schematic diagram of Single drum vapor adsorption system

When the gas or vapor molecules get attached to the surface of solid, it is known as adsorption. The adsorbed molecules (adsorbates) would stick to adsorbent surface due to van der Waal electrostatic interaction. The adsorption cooling cycle consist of desorption-condensation-expansion-evaporation followed by adsorption. Unlike vapor compression systems which are driven by mechanical energy, vapor adsorption refrigeration systems are heat driven systems. It can also work with solar energy with a suitable adsorbent-adsorbate pair. In last decade, many researchers worked on adsorption systems and reported satisfactory cooling effect. Miles obtained an experimental COP of 0.8 for the activated carbon-ammonia system with the condensation and evaporation temperature of 35 ^{o}C and 5^{o}C respectively [3]. Pons *et al.* investigated the zeolite and water adsorption system under the fixed test temperature system that offers the best possible theoretical maximum COP of 1.5[4]. Baiju and Muraleedharan [5], have developed a two stage solar-adsorption refrigeration system using activated carbon-R134a pair at National Institute of Technology Calicut, India. They have discussed some performance characteristics of their experimental model and used artificial neural network model to predict other performance characteristics of their system. The theoretical COP obtained was 0.9. Pons and Crenier demonstrated that activated carbon and methanol can serve as a suitable pair for a solar powered vapor adsorption refrigeration system [6]. Critoph studied the performance of vapor adsorption refrigeration cycle with different adsorbates and reported that activated carbon – methanol combination gives best COP in a single stage cycle [7]. Headley *et al*. fabricated a carbon-methanol adsorption refrigeration system powered by concentrating solar collectors. The solar COP obtained was low, near to 0.02. Anyanwu (2001), wrote the review of solid adsorption solar refrigeration cycles where the classification according to the adsorbates used are introduced, such as, water based, fluorocarbon based, ammonia based and alcohols based systems [8]. Tchernev used water as refrigerant with zeolite as adsorbent, observed that the quantity of water adsorbed is strongly dependent on temperature and during night water adsorption rate is high [9]. When water is used as refrigerant, it mainly depends on temperature, not vapor pressure. For the solar energy input of 6 kW the refrigeration effect produced was 900Wh per square meter of collector area with a COP of 0.15. Critoph used fluorocarbon R114 as refrigerant with the adsorbent of activated carbon for the operation of solar adsorption cycle [7]. They built a small scale refrigerator to result ~300 kJ of cooling. The solar collector/generator/absorber component comprised thick steel tube containing 24.2 kg of activated carbon. In this process the refrigerant cooled from 300^{o}C to 130^{o}C before adsorption was completed. Noteworthy recent development in Byelorussia is the development of a refrigerator prototype with ACF-ethanol and ACF–acetone pairs [10]. Wang *et al.* reported that Activated carbon fiber (ACF) has greater adsorption capacity than regular activated carbon, and estimated adsorption time is 0.2 to 0.1 times than that of normal activated carbon [11].

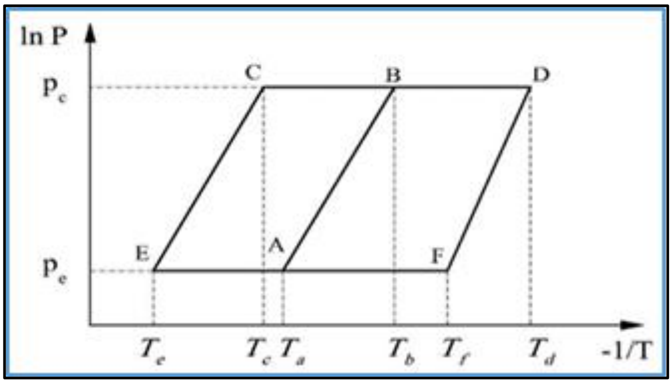

Fig. 2 Clapeyron diagram

Adsorption refrigeration cycle: The cooling effect in an adsorption chiller is generated due to the adsorption (weak van-der Waal electrostatic interaction) while the adsorbent bed is connected to the refrigerated space. The adsorption cycle can be understood following the Clapeyron diagram, which is represented in Fig. 2. There are two main steps in an ideal adsorption cooling cycle: the heating-desorption- condensation step and the cooling-adsorption-evaporation step [12]. During the first step, the adsorbent bed is exposed to the heat source (state A). The source heat increases the temperature of the bed to a certain temperature T_b (state B), which raises the vapor pressure of the desorbed refrigerant to the condensing pressure (P_c). Any low grade heat like solar or industrial waste heat that can be utilized in the generator. Desorption occurs at a constant pressure, and the desorbed refrigerant vapor is condensed in the condenser and flows towards the refrigerated space or evaporator. As heat is being supplied to the adsorbent bed, the maximum temperature, T_d of the cycle is achieved at the end of this period (state D). During the second step, which is cooling-adsorption-evaporation, the adsorbent bed is cooled down to a lower temperature, T_f. This decrease in temperature is associated with a drop in pressure to the evaporation pressure (P_e). Then adsorption and evaporation take place while the adsorbent bed is cooling down. Therefore coefficient of performance can be calculated by using Eq. 1 and it can be compared with maximum/theoretical COP, also known as Carnot COP (Eq. 2).

$$COP = Refrigeration\ effect/\ heat\ input \qquad \text{(Eq.1)}$$

$$CarnotCOP = \frac{\text{Tdesorption - Tcondensation}}{\text{Tdesorption}} \text{X} \frac{Tevaporator}{Tdesorption - Tevaporator} \qquad \text{(Eq.2)}$$

Working pair: Activated carbon is a common material in adsorption systems due to its high pour volume and surface area [13]. The specific surface area of commercial activated carbon is between 500 and 1500 m^2/g however a laboratory developed one can have surface area ~3000 m^2/g. Activated carbon can be found in different size chunks, powder, granular and extruded form. The pores of activated carbon is composed of irregular channels with a larger pore size at the surface and narrow pores within the grain [14].

2.Experimental Methodology

A lab scale model of vapor adsorption refrigeration cycle as an experimental apparatus has been designed and fabricated [15]. The main components are Generator drum, condenser, expansion valve and evaporator. Generator is made up of steel drum of thickness 1.3 mm. The generator drum is filled with 6 kg of Activated charcoal derived from coconut shell. Activated charcoal is treated with hydrogen peroxide (H_2O_2) and then washed with 4M nitric acid solution to open the pores. After the acid wash, activated charcoal is washed with distilled water multiple times. 2.5 liters of methanol is used as refrigerant. Three thermocouples are used; one in evaporator section, second one in condenser section and the third one in generator section (accuracy ±0.1 ^oC). An analog pressure gauge is used at the top of the generator drum to record the pressure in the generator and a vacuum gauge is used in evaporator.

Table 1: Refrigerant Properties

Properties	
Density of Methanol	790 kg/m^3
Specific heat capacity of methanol	2534 kJ/kg
Latent heat of vaporization of methanol	1102 kJ/kg
Specific heat of activated charcoal	920 J/kgK
Density of activated charcoal	420 kg/m^3
Adsorption capacity of Activated charcoal for methanol	0.32 kg/kg

Capillary tubes – Capillary tubes are small diameters coiled shaped tubes which are used to bring down the pressure and temperature of the refrigerant [16]. The tube diameter of capillary tube here is 1.17 mm and the total length of the capillary tube is 3.15 m optimized for minimum refrigerant required [15].

Fig. 3 Capillary tube used in this work

Evaporator box – The dimensions are 0.75×0.48×0.62 m^3. The evaporator box is made up of 20 mm thick polyurethane. Evaporator box contains evaporator coil located inside the evaporator box. 1.2 L of methanol is filled inside the evaporator coil before sealing. The evaporator box contains water which will experience the refrigeration effect.

Electric heater – A 1 kW electric heater is used to heat the adsorbent bed in order to produce thermal compression effect inside the generator bed.

Vacuum pump – A 0.5 HP vacuum pump is used to create vacuum inside the setup. The vacuum pump is used to lower the boiling point of the refrigerant inside the vessel in order to produce refrigeration effect. The boiling point of methanol at atmospheric pressure in 65℃. Creating vacuum inside the vessel lowers the boiling point of methanol and methanol boils inside the evaporator to produce refrigeration effect. Vapor adsorption refrigeration system with carbon and methanol pair could only work below atmospheric pressure which requires creating vacuum and sustaining vacuum inside the set up.

3. Results and discussion

Operation: First the valve between evaporator and the generator is turned off then generator is evacuated using the vacuum pump (Fig. 4). The evaporator coil is then heated with heating source for about 15 min. After heating, water is poured inside the evaporator box. Then the valve between the evaporator and generator is turned on hence methanol vapor inside the evaporator starts flowing to the generator drum. The adsorbent bed in the generator adsorbs the methanol vapor coming from the evaporator side. The whole set up is left for few hours. After few hours the generator is again heated for about 30 min. The pressure inside the generator drum increases and when the pressure increases to 40 kPa the valve which connects generator and the condenser is turned on. Methanol vapor inside the condenser condenses to liquid and enters the capillary tube. The pressure and temperature of the refrigerant decreases through the capillary tube and enters the evaporator tubes. The refrigerant inside the evaporator vaporizes after absorbing heat from the water kept in the evaporator box. The change in temperature of the evaporator box is being recorded using thermocouple.

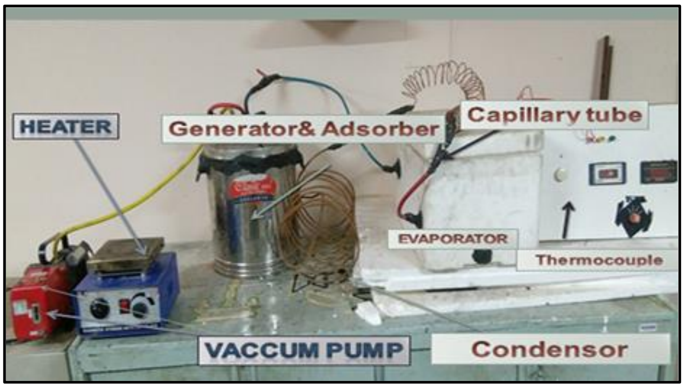

Fig. 4 Experimental setup

The temperature of the heating source was set to 125^{o}C. The adsorbent bed was heated up to 95 min. The temperature of the adsorbent bed started to rise and the valve which connects condenser to the generator was disconnected when the adsorbent temp. reached 95 ^{o}C. The temperature rise and decrease of adsorbent with respect to time is given in Fig. 5. When the heating source was disconnected the temperature of the adsorbent bed remained at almost same temperature for some time and when the temperature of the adsorbent bed reached '~50 ^{o}C the decrease in the temperature of the adsorbent bed became slow. When the pressure of the adsorbent rises up to a pressure which causes the vapor pressure of the refrigerant to rise up to the condensing pressure the valve which connects generator to the condenser is opened. As soon as the valve was opened the pressure in the generator decreases suddenly because the refrigerant vapor in the generator starts to move quickly towards the condenser tubes due to pressure difference which results the further decrease in pressure inside the generator. The decrease in pressure of the generator is quicker than decrease in temperature of the generator bed. The pressure decrease of the generator bed is much faster because de-adsorbed refrigerant vapors go inside the condenser as soon as the valve is opened.

The increase and decrease in temperature and pressure of the adsorbent bed with respect to time is shown in Fig 5. At 85 minute, the valve which connects generator to the condenser is opened. As soon as the valve is opened pressure inside the generator starts to decrease, however the electric heater is not disconnected and continued to heat the generator drum till 95th min. After 95 min electric heater was switched off. The temperature of the generator bed almost remained at same temperature for some time. The decrease in temperature of the generator drum was gradual as compared to the pressure drop. The experiment has been carried out by heating the generator drum with electric heater at constant temperature. The maximum temperature in the generator was set to 95 ^{o}C because it is not feasible to heat activated charcoal and methanol beyond 120 ^{o}C. Activated carbon will react with methanol beyond the temperature of 120°C. So generator bed temperature is not allowed to be go beyond 100 °C. The maximum pressure obtained in the generator drum is 23 kPa. Observed parameters are as recorded in Table 2.

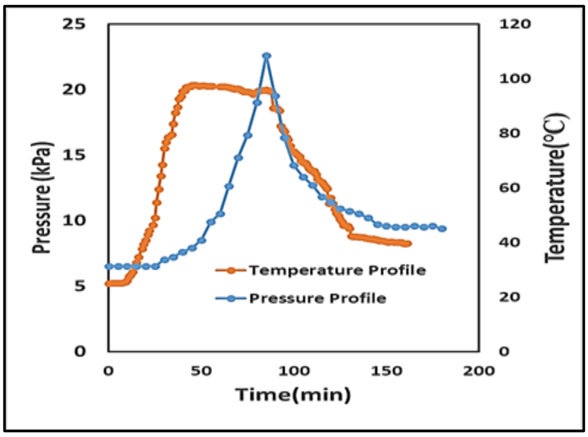

Fig. 5: Variation of adsorbent temperature and pressure

TABLE 2: Observation Table

Sl. no	Gen temp. max, °C	Gen temp. min	Water temp. in	Water temp. out	Generator pressure max	Generator pressure min
1	97.5	27.4	26.2	16.2	23 kPa	5.9 kPa
2	98.2	26.6	25.8	17.1	24.4 kPa	6.5 kPa

Calculation: To calculate coefficient of performance, refrigeration effect and input energy were calculate. The refrigeration effect is calculated by measuring drop in temperature of the water in the evaporator section.

Input energy = Power of the heater (kW)×3600s.
Refrigeration effect = $m_w \times C_{pw} \times \Delta T_w$.
C.O.P = Refrigeration effect/ Input energy.
Electric heater power = 1 kW
Specific heat of water (pressure const.) C_p = 4180 J/kg
ΔT_w = temperature drop in water.
Mass of water in the evaporator box = 23.4 kg

Table 3: Coefficient Of Performance

Trial no	Input energy, J	Refrigeration effect, J	COP	Carnot COP	efficiency
1	5700	978.12	0.1716	2.2025	7.7%
2	5700	997.682	0.175	2.4986	7%

Calculated results are shown in Table 3. COP obtained is ~0.17. Habib and Sitoi calculated a COP of ~0.18 for activated carbon and n-butane pair from their adsorption isotherm under controlled environment [17]. Mass of activated charcoal (6 kg) used in the experiment here is 30% higher than the required mass of activated charcoal. So amount of heat energy required to heat activated charcoal in order to increase the temperature and pressure of the generator bed increased which led to the decrease in COP. However in general COP obtained in vapor adsorption refrigeration system is usually very less as compared to vapor compression refrigeration system because in vapor adsorption refrigeration heat is used to compress the refrigerant, trapped inside the pores of the adsorbent [18]. In vapor compression refrigeration system refrigerants are compressed mechanically rather than thermally. The system is able to bring down temperature of circulating water by more than 10 ^{o}C which is encouraging compared to reported literature [19].

Saha *et al.* introduced the concept of adsorption cycle efficiency [20]. It is the ratio of actual COP to Carnot COP. Average generator temperature is assumed to be near to desorption temperature and adsorption temperature is assumed to be near to evaporator minimum temperature. As can be seen from the Table 3 efficiency of this system is ~7 to 8% which is interesting for system developed in a laboratory from cheapest possible material available.

4.Conclusions

Adsorption refrigeration is an eco-friendly technology which can address ozone depletion and global warming problem as it uses safe and benign refrigerants. In general vapor adsorption system consumes less grid power as it is a heat driven system and starting does not require high surge current like vapor compression system. Experimental study on vapor adsorption characteristics and performance of adsorption refrigeration cycle with generator filled with activated charcoal has been carried out in laboratory. It's able to bring down temperature of circulating water by more than 10 ^{o}C. This system can be even improved and studied with many more refrigerant adsorbent pair.Basic setup here, is an intermittent system because it has only one generator bed. To overcome this problem more than one adsorbent-generator bed can be used to make it a continuous system.

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