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Application of Renewable Energy Options—The Role of Solar Adsorption Cooling Technology

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Abstract

High energy requirement of vapor compression cooling systems in addition to harmful refrigerants further necessitates the increasing need for more reliable, flexible, environmentally friendly, and cost-efficient cooling systems options. Adsorption cooling technology could be a better option in terms of huge energy saving potential, Carbon emission reduction, flexibility, and waste heat utilization. There are, however, some setbacks that hindered adsorption cooling technology from real mass production and commercialization. This work seeks to study, evaluate and compare the energy requirement and coefficient of performance of solar-powered adsorption cooling system (as an application of renewable energy) in relation to vapor compression system. Adsorbate/adsorbent equilibrium test (using a test rig) was used to predict the performance of thermal driven adsorption cooling system using methanol/activated carbon (as adsorbate/adsorbent pair) in relation to similar data obtained from laboratory vapor compression refrigeration test rig (same mass of refrigerant). For the adsorption cooling system and vapor compression system, the energy requirements were found to be 1913.57 kJ and 8932.02 kJ while the coefficient of performance (COP)s were found to be 0.39 and 1.2 respectively. Presumably, the adsorption cooling system has an energy requirement that could be powered by direct solar thermal heating using a flat plate collector, however, the COP is relatively lower indicating lower cooling capacity, and hence takes a longer period of time to overcome the same cooling load as vapor compression system. It is recommended among other things that research should focus on developing better adsorbate/adsorbent pairs for an increased adsorption/desorption time.

Keywords

Adsorbate, Adsorbent, Adsorption Cooling, Solar Energy, Vapor Compression

1. Introduction

Serious concerns for the environment have focused almost everyone's attention on the future of our planet. From retailers to manufacturers, small scale to large scale industries, domestic to commercial buildings, and the public to private organizations, the race is on towards optimizing energy usage and greening the environment and the economy in general [1].

Currently, a substantial proportion of Nigeria's energy supply is generated from fossil fuels such as oil and gas. Combustion of oil and gas resources results in ozone layer depletion and hence global warming. It is now universally accepted that fossil fuels are finite and it is only a matter of time before their reserves become exhausted [2]. Extended use of these reserves, worldwide, in a current manner will continue for no more than some decades to come. The need for supplementary or even alternatives that ideally will be non-depleting energy sources has since been recognized. These non-depleting sources are also referred to as renewable energy sources as they are available on a cyclic or periodic basis [3].

A significant proportion of energy consumption in our world is from refrigeration and air conditioning systems. In 1988, the International Institute of Refrigeration (IIR) estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air conditioning processes of various kinds [4]. Overpopulation and hence increase in thermal comfort requirements and global warming keep this value on the increase. In 2012, a study shows refrigeration and air conditioning systems consume around 30% of total worldwide energy [5].

Adsorption refrigeration and air conditioning systems could be better options in terms of huge energy saving potential, carbon emission reduction, and waste heat utilization. An adsorption refrigeration system is a thermal-driven refrigeration that uses a solid adsorbent to adsorb and desorb a refrigerant vapor in response to changes in the temperature of the adsorbent [6].

Currently, most of the world's energy demand for refrigeration and air conditioning is met by mechanical vapor compression systems driven by high-grade electrical power inputs which utilize environmentally harmful refrigerants. Vapor compression systems still dominate almost all application areas [4]. This is because of certain setbacks, which hinder adsorption systems from real mass production and commercialization, they are: 1) Long adsorption/desorption time; 2) Small refrigeration capacity per unit mass of adsorbent, *i.e.*, low Specific Cooling Power (SCP), which leads to a bulky system; and 3) Low Coefficient of Performance (COP) of the system [6].

The aim of this work is to study, evaluate and compare solar-powered adsorption cooling technology (as a sustainable and emerging renewable energy application) in relation to the conventional vapor compression cooling system.

2. Review of Solar Powered Adsorption Cooling System

2.1. Solar Thermal Heating

Sun radiates its energy at the rate of about 3.8×10^{23} kW per second [1]. Solar energy, being the most promising among all the renewable energy sources is transmitted radially as electromagnetic radiation. Solar energy touches the boundary of the atmosphere at about 1.5 kW/m^2. After traversing the atmosphere, the earth's surface receives about 1 kW/m^2 of solar radiation [3]. According to [3], Nigeria receives about 5.08 × 10^{12} kWh of energy per day from the sun and if solar energy appliances with just 5% efficiency are used to cover only 1% of the country's surface area, then 2.54 × 10^6 Mwah of electrical energy can be obtained from solar energy. This amount of electrical energy is equivalent to 4.66 million barrels of oil per day.

Heat energy from the sun is one of the best renewable energy options for use in adsorption cooling applications, especially in remote and rural locations. Based on the energy requirement of the adsorption cooling system, a flat plate collector may be used because the temperature needed is not very high [4]. In Solar thermal applications, solar energy as electromagnetic waves is first converted into heat energy. The heat energy is then used directly or transferred through a medium (mostly water) to the point of application. Heat is needed in the adsorption refrigeration system to remove the adsorbate (refrigerant) from the adsorbent [7]. Different sources of heat such as industrial heat waste, electrical heating elements, and solar radiation can be used [2].

2.2. Adsorption Cooling Technology

The adsorption cooling system consists of four major components; adsorber, condenser, expansion device, and evaporator [8]. The arrangement of the major components is represented in **Figure 1**.

Adsorption refrigeration systems use solid materials like Celica gel, Zeolite, Activated-Carbon, and some specially prepared composite materials as absorbents while the refrigerant fluid (adsorbate) could be Water, Ammonia, Ethanol, or Methanol [9]. The adsorption system does not use mechanical energy but only small heat energy and can either be an intermittent or continuous cycle [8]. According to [10], the important considerations influencing the choice of a suitable adsorbent are:

1) Adsorption of large amounts of adsorbate under low-temperature conditions to yield good COP.
2) Desorption of most of the adsorbate when exposed to thermal energy.
3) Possession of high latent heat of adsorption compared to sensible heat.
4) No deterioration with age or use.
5) Non-toxic and non-corrosive.
6) Low cost and widely available.

Choice of adsorbate depends to a large extent on the following properties [11]:

1) Evaporation temperature below 80˚C.
2) Small molecular size to enable it to be adsorbed into the adsorbent.
3) High latent heat of vaporization and low specific volume.
4) Thermally stable with the adsorbent at the cycle operating temperature ranges.

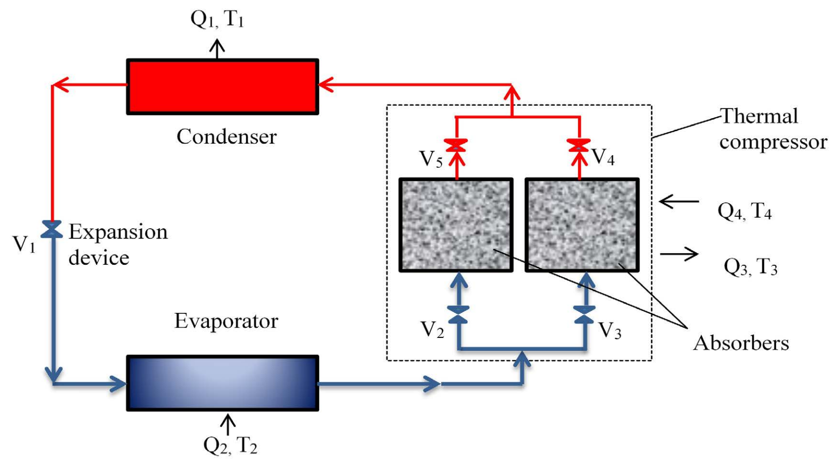

Figure 1. Adsorption refrigeration cycle [1].

5) Non-toxic, non-corrosive and non-flammable.

6) Low saturation pressures (slightly above atmospheric) at normal operating temperature.

Performance limitations of adsorption cycles with different adsorbates for solar cooling were investigated by Critoph (2000), concluding that, in general, the activated-carbon/methanol combination was preferable for solar cooling, giving the best COP in a single-stage cycle.

There are other reasons that make activated-carbon/methanol the most favored pair as was reported by [12]. These are briefly outlined below:

1) Activated-carbon is cheaper than zeolite.

2) Activated-carbon can be produced with varying properties by varying the activation time and temperature to suit particular applications.

3) Activated-carbon can be produced from biomass.

The predominant adsorbent/adsorbate pairs are zeolite/water and activated-carbon/methanol. Zeolite/water is usually used for cooling systems while activated-carbon/methanol is used in ice-making systems [13].

2.3. Adsorbent/Adsorbate Equilibrium

In particular, the solid-vapor (adsorbent/adsorbate) equilibrium is obtained from the Clausius-Clapeyron equation [14], this is stated in Equation (1).

$$\frac{dP}{dT} = \Delta H\left(T\left(V_v - V_l\right)\right) \tag{1}$$

where:

P is the vapor pressure.

T is the absolute temperature.

ΔH is the isosteric heat of adsorption per unit mass of adsorbent for the transition, kJ/kg.

V_v and V_l are the specific volumes of the vapor and liquid phases of the refrigerant respectively, m^3/kg.

In practice, $V_v \gg V_l$ and also it may be assumed that the perfect gas law is obeyed approximately by the vapor, thus (1) becomes:

$$\frac{dP}{dT} = \frac{\Delta H}{RT^2} \tag{2}$$

where:

R is the Universal gas constant.

Hence by integrating (2):

$$\log P = \frac{\Delta H}{RT} + \text{Constant} \tag{3}$$

This linear relationship between $\log P$ and $\frac{1}{T}$ is determined in practice to a first approximation. From the plot, we can estimate the isosteric heat of adsorption from the gradient of the equilibrium line [14].

3. Methodology

The adsorption equilibrium test rig was used to determine the energy requirement of the system. The pressure, temperature, and concentration data obtained were used to estimate the COP of the adsorption cooling system. Activated carbon/methanol pair was used as adsorbent/adsorbate pair. A laboratory vapor-compression refrigeration test rig was used to obtain energy requirement and COP for the corresponding vapor compression cooling system (with the same mass of refrigerant as in the adsorption system).

3.1. Adsorbent/Adsorbate Equilibrium Test

The test rig as shown in **Figure 2** consists of:

1) 12.5 mm brass pipe and accessories;
2) 0.01 - 2.0 bar pressure gauge;
3) 0˚C - 140˚C temperature gauge;
4) 0.75 Hp electric Vacuum pump;
5) 200 W electric heating element.

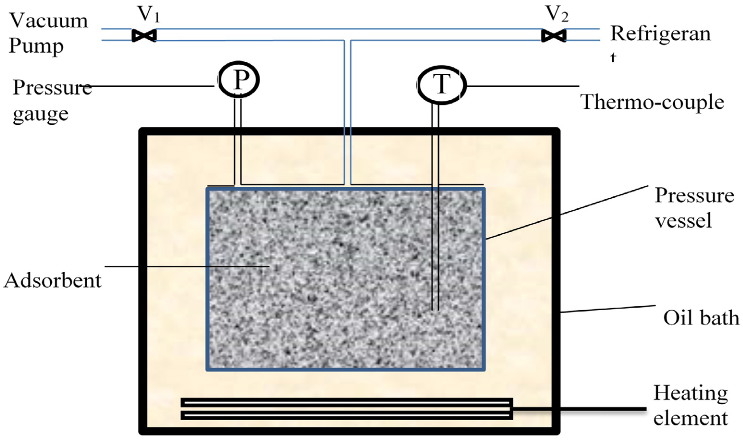

Figure 2. Adsorbent/Adsorbate Equilibrium test rig [1].

A standard equilibrium test was carried out as performed by [15]. The refrigerant (Methanol) cylinder was first weighed. The pressure vessel containing 1 kg of activated-carbon was immersed in oil contained in the constant temperature bath. The adsorbent is heated by heating the oil bath through an electrical heating element. Valve one (V1) was open while valve two (V2) was closed and the pressure vessel was first evacuated at a high temperature using a vacuum pump. The pressure vessel was later allowed to cool. Valve one (V1) was closed and a known mass of adsorbate was administered by opening valve two (V2). The temperature of the vessel was varied between 30˚C to 160˚C and the corresponding pressure was measured at each stage. With the concentration, pressure, and temperature known, the P-T-X data for each of the samples of adsorbent were obtained.

3.2. Energy and Performance Evaluation

Energy input per unit time for the vapor compression system was obtained from the vapor compression test rig. Also, the coefficient of performance of the system was determined using the data obtained from the vapor compression test rig.

For the adsorption cooling system, using (3) as stated in the preceding section $\log P = \frac{\Delta H}{RT} + \text{Constant}$ from the plot of the linear relationship between $\log P$ and $\frac{1}{T}$, isosteric heat of adsorption (ΔH) was estimated from the gradient of the equilibrium line as performed by [12].

Coefficient of performance, COP is given by:

$$COP = \frac{Q_c}{Q_{in}} \tag{4}$$

where:

Q_c is the useful cooling in kJ/kg of adsorbent. Q_c given by:

$$Q_c = L(DX) - C_{PR}\left(T_{con} - T_{eva}\right) \tag{5}$$

Q_{in} is the heating input per kilogram of adsorbent. Q_{in} given by:

$$Q_{in} = Q_{sen} + \Delta H \tag{6}$$

Q_{sen} is the sensible heat needed to heat the adsorbent and its containing vessel to the maximum temperature.

(ΔH) is the isosteric heat of adsorption.

The range of solar flat plate collectors' thermal energy output (from literature) was analyzed for possible application in the adsorption system based on the adsorption system energy requirement obtained. The COPs obtained for the two systems were also analyzed.

4. Results, Discussion and Conclusions

4.1. Results and Discussion

The energy required by the vapor compression test rig and the COP of the system was obtained as 8932.02 kJ/h and 1.2 respectively. These results agreed closely with the results obtained by [11].

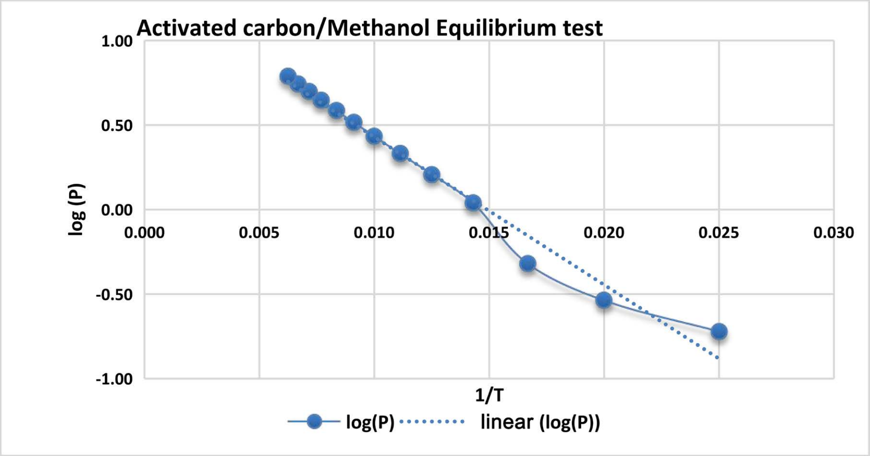

Figure 3. Plot of Log(P) vs. 1/T for activated carbon/Methanol Equilibrium.

The energy required by the adsorbent/adsorbate equilibrium test (adsorption cooling system) and the COP of the system were estimated as 1913.57 kJ/h and 0.39 respectively. This closely agreed with the results obtained by [1], the difference being due to the fact that the mass of the refrigerant slightly differs.

Figure 3 shows a linear plot of log(P) Vs 1/T for the adsorbent/adsorbate (activated carbon/methanol) equilibrium test.

The gradient of the linear plot for activated carbon/Methanol Equilibrium was found to be −61.8. This shows that adsorption is exothermic and that it requires a low amount of thermal energy to induce desorption of the adsorbate adsorbed thus can be derived by low-grade energy. The Clapeyron equation assumes that the vapor phase behaves like perfect (ideal) gas and that the molar volume of the liquid phase is much smaller than the molar volume of the gas phase [12].

From the table of properties, the specific gas constant for Methanol, $R_{\text{methanol}} = 8.3145/32.0 \times 10^{-3} = 259.83$ J/kg·K. Therefore, the Isosteric heat of adsorption for activated carbon/methanol was estimated to be a first approximation to be 16.058 kJ/kg.

From the linear plot, it was observed that at a pressure above atmospheric, the plot is perfectly linear obeying the Clapeyron-Clausius equation. This corresponds to temperatures above the melting point of methanol. However, below this point (1 atm and 64.85˚C) the plots tend to slightly disobey the linearity (Clapeyron-Clausius equation). This is because of the presence of a partial vacuum created initially before raising the temperature of both adsorbate/adsorbent pairs. This is further indicated by the occurrence of negative values of log(P) below atmospheric pressure (partial vacuum). At one atmospheric (1 atm), log(P) becomes zero and gradually positively increases with further addition of heat.

4.2. Conclusions

A review of adsorption cooling technology was carried out. Energy requirements and COPs of both the adsorption system and vapor compression system were obtained, evaluated, and compared. Solar flat plate collectors' thermal energy output (from literature) was analyzed for possible application in the adsorption system based on the adsorption system energy requirement obtained.

Overall, the energy required by the adsorption cooling system for the period (1913.57 kJ) is relatively much lower than that required by the vapor compression system (8932.02 kJ) indicating the huge energy savings potential of the adsorption cooling system.

The COPs of the adsorption cooling system (0.39) are much lower than that of the corresponding vapor compression system (1.2) indicating a relatively higher cooling capacity by the vapor compression system. In adsorption systems, this can be compensated by running the system for a relatively long period of time while yet maintaining the energy-saving potential.

It is also recommended that further work should be carried out towards producing composite adsorbent or adsorbate (like ionic liquids) from two or more different materials with the aim of playing around with some suitable properties of the materials to get adsorbent with better properties.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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