Performance investigation of a waste heat driven pressurized adsorption refrigeration cycle

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Abstract. This article presents performance investigation of a waste heat driven two bed pressurised adsorption refrigeration system. In this study, highly porous activated carbon (AC) of type Maxsorb III has been selected as adsorbent while n-butane, R-134a, R410a, R507a and carbon dioxide (CO2) are chosen as refrigerants. All the five refrigerants work at above atmospheric pressure. Among the five pairs studied, the best pairs will be identified which will be used to provide sufficient cooling capacity for a driving heat source temperature above 60°C. Results indicate that for a driving source temperature above 60°C, AC-R410a pair provides highest cooling capacity while AC-CO2 pairs works better when the heat source temperature falls below 60°C.

1. Introduction
One of the most pestering environmental problems that the refrigeration industry is intrigued is ozone depletion. Thermally driven sorption based cooling systems are gradually emerging as environmentally friendly alternatives to conventional vapor compression based refrigeration cycles. Since the detection of ozone holes in the stratosphere, caused by the CFCs (chlorofluorocarbons) and HCFCs (hydrochlorofluorocarbons) of vapor compression based coolers, interest on adsorption cooling systems have increased a lot [1]. The attractive features of these systems are; they have the ability to operate by low temperature driving heat sources typically below 100°C, thus makes it is possible to use solar energy and industrial waste heat as the driving heat sources. The construction of these systems is simpler, as there are almost no moving parts, and they require low electricity usage. Furthermore, it is possible to operate these systems with heat source temperature as low as 50°C if multi-stage regeneration is performed and an improvement in the waste heat recovery efficiency can be attained by using multi-bed scheme [2].

Thermally powered adsorption cooling systems could be operated in both partial vacuum and pressurized conditions. Of the adsorbent-refrigerant pairs working at sub-atmospheric conditions are silica gel-water [2], zeolite-water [3], activated carbon-methanol [4], activated carbon fiber-ethanol [5] pairs etc. However, the main drawback of vacuum based adsorption cooling cycles is that the leakages will drastically reduce its performance. In addition, the high vacuum operation demands advanced technology and special designs. Several other studies have been conducted to investigate the possibility of using different types of adsorbent-refrigerant pairs for pressurized adsorption cooling systems [6-10]. For the above mentioned perspectives, the main objective of the study is to analyze the performance of a two bed adsorption cooling cycles at pressurized conditions employing highly porous activated carbon of type Maxsorb III as adsorbent paired with five different refrigerants namely...
n-butane, R-134a, R410a, R507a and carbon dioxide (CO₂) . The performance of the best pair will be investigated to analyze cooling capacity and COP variations by varying regeneration, cooling and chilled water temperatures.

2. Working principle of adsorption chiller
In the present study, a two bed adsorption cooling cycle has been studied. The schematic diagram of the adsorption cycle is shown in figure 1. The chiller is composed of four heat exchangers namely two adsorber/desorber heat exchangers, an evaporator and a condenser. Four refrigerant valves are used for the operation four pre-determined processes namely, adsorption, pre-heating, desorption and pre-cooling. As can be seen from figure 1, refrigerant evaporates from the evaporator and adsorbed by the adsorber bed through refrigerant valve V4. At the same time desorbed refrigerant goes to the condenser through refrigerant valve V2 which is known as the desorption-condensation process. The desorber bed is powered by solar thermal heat which is the only heat source of the studied system. The details of the working principle of adsorption chiller have been described in detail elsewhere [1].

3. Adsorbent-refrigerant pair
In the present study, activated carbon of type Maxsorb III has been selected as adsorbent while n-butane, R-134a, R410a, R507a and carbon dioxide (CO₂) are chosen as refrigerants. Table 1 lists the thermo-physical properties of some of the activated carbon used as adsorbents. It is observable from the table 1 that Maxsorb III has the highest surface area and pore volume compared with the others. Figure 2 shows the SEM photograph of Maxsorb III.

| Adsorbent          | BET Surface area (m²/g) | Pore volume (cc/g) | Source |
|--------------------|-------------------------|--------------------|--------|
| ACF (A-20)         | 1900                    | 1.028              | [7]    |
| Granular AC        | 1150                    | 0.43               | [8]    |
| AC of type Maxsorb III | 3120              | 1.7                | [9]    |

4. Mathematical modeling

4.1. Adsorption isotherms
Dubinin-Astakhov (D-A) model is used to estimate the equilibrium uptake of all the pairs.

\[
W = W_0 \exp \left[ - \frac{RT}{E} \ln \left( \frac{p_*}{p} \right) \right]^n
\]

with \( W = xV_a \), where \( x \) is the mass concentration (kg-kg⁻¹) and \( V_a \) is the adsorbed phase specific volume. Equation (1) is used to evaluate the adsorption uptake of AC-n-butane, AC-R134a, AC-R507a and AC-R410a pairs. For AC-CO₂ pair, equation (2) can be written without the adsorbed phase volume which is in the following form,

\[
x = x_0 \exp \left[ - \frac{RT}{E} \ln \left( \frac{p_*}{p} \right) \right]^n
\]

In the case of D-A, equation (2), the adsorbed phase volume is calculated as [11],

\[
V_a = V_b \exp \left[ \alpha(T_{des} - T_b) \right]
\]
\[
\begin{align*}
\ln \left( \frac{b}{V_b} \right) \\
\text{where, } \alpha = \frac{T_c - T_b}{T_c} \text{ and } b \text{ is the Van der Waal’s volume } (= RT_c/8 P_c)
\end{align*}
\]

The values of \( T_c, P_c \) and \( T_b \) of n-butane, R134a, R410a, R507a and CO2 can be found elsewhere [12]. Table 2 lists the adsorption characteristics of the various pairs studied.

In addition, the D-A model has to be modified to accommodate the pseudo-vapour pressure of carbon dioxide since its critical temperature is as low as 304.12K. Hence, the saturation pressure is given by [11],

\[
P_s = \left( \frac{T}{T_c} \right)^2 P_c
\] (4)

Figure 1. Schematic diagram of two bed adsorption chiller.

| Refrigerant | R134a [13] | R410a [13] | n-butane [14] | R507a [13] | CO2 [10] |
|-------------|------------|------------|---------------|------------|---------|
| \( W_0 \) (\( m^3/kg \)) | 2.22 | 2.07 | 0.8 | 2.05 | 1.67 |
| \( E \) (kJ/kg) | 71.87 | 72.37 | 300 | 76.34 | 94.502 |
| \( n \) | 1.29 | 1.36 | 1.05 | 1.34 | 1.18 |
4.2. Heat of adsorption

The heat of adsorption at a constant concentration can be expressed as:

$$\Delta h_{st} = -\frac{R \dot{\Delta} (\ln P)}{\partial \left(\frac{1}{T}\right)}$$  \hspace{1cm} (5)

The specific cooling capacity (SCC) is achieved at the evaporator and is given by,

$$SCC = \left( x_{\text{max}} - x_{\text{min}} \right) \left[ h_{fg} - \int_{T_{\text{eva}}}^{T_{\text{pfg}}} C_{p,\text{ref}} dT \right]$$  \hspace{1cm} (6)

where $x_{\text{max}}$ indicates the amount of refrigerant uptake on AC as a function of adsorption temperature and evaporator pressure, $x_{\text{min}}$ denotes the amount of refrigerant uptake on AC during desorption at the desorption temperature and condenser pressure, $h_{fg}$ represents the latent heat of evaporation at the cooling load temperature and $C_p$ shows the specific heat capacity of refrigerant.

The coefficient of performance (COP) of the adsorption cooling cycle can be defined as:

$$COP = \frac{SCC}{Q_h}$$  \hspace{1cm} (7)

where $Q_h$ is the summation of heat added to the adsorbent, $Q_{\text{adb}}$ and the heat added to the refrigerant, $Q_{\text{ref}}$, as represented below:

$$Q_h = Q_{\text{adb}} + Q_{\text{ref}}$$  \hspace{1cm} (8)

The heat added to the adsorbent and refrigerant are further derived as shown in equation (9) and equation (10) respectively:

$$Q_{\text{adb}} = \int_{T_{\text{eva}}}^{T_{\text{pfg}}} C_{p,\text{adb}} dT$$  \hspace{1cm} (9)

$$Q_{\text{ref}} = x_{\text{max}} \int_{T_{\text{eva}}}^{T_{\text{pfg}}} xC_{p,\text{ref}} dT + \int_{T_{\text{eva}}}^{T_{\text{pfg}}} xC_{p,\text{ref}} dT + \int_{x_{\text{min}}}^{x_{\text{max}}} \Delta h_{st} dx$$  \hspace{1cm} (10)

Figure 2. SEM photograph of Maxsorb III.
5. Results and discussion

5.1. Ideal cooling cycle

Using the isotherm data, the conceptual ideal adsorption cooling systems of AC-R134a, AC-R507A, AC-R410a, AC-n butane and AC-CO\textsubscript{2} are shown in figure 3. One can understand from figure 3 that for the same operating temperature conditions, the difference between the maximum and minimum uptake, $\Delta x = x_{\text{max}} - x_{\text{min}}$, of AC-R410a cycle is higher than that of other cycles. The $\Delta x$ values for AC-R410a cycle is 0.4 kg/kg, while for AC-n butane cycle the $\Delta x$ value is 0.08 kg/kg.

![Figure 3. Adsorption isotherms of AC-n butane, AC-R134a, AC-R410a, AC-R507a and AC-CO\textsubscript{2} pairs.](image)

5.2. Heat transfer fluids

Figure 4 shows the effect of regeneration temperature on the specific cooling effect (SCC) for all the pairs. From figure 4, it is apparent that the increasing regeneration temperature yields in a linear increase in the SCC for all five various adsorbent-refrigerant pairs. Maximum SCC value of 54 kJ/kg is achieved by AC-R410a pair at when the regeneration temperature is 80°C. For a temperature range of 60°C to 80°C, the AC-R410a pair shows the highest SCC followed by AC-R410a, AC-CO\textsubscript{2}, AC-R134a, AC-R507a and lastly AC-n butane. AC-n-butane pair shows the lowest SCC value of 9 kJ/kg at driving source temperature of 60°C.

Figure 5 illustrates the effect of regeneration temperature on COP for all the pairs. It is observed that the COP value of the refrigeration cycles increase sharply with increasing regeneration temperature up to 75°C. However, it can be seen that COP exhibits an asymptotic behaviour when the regeneration temperature approaches 80°C. This is due to the higher heat intake requirement when the difference between heat sink temperature and heat source temperature grows significantly large. From the figure, it is obvious that the AC -R410a pair provides the highest COP for regeneration temperature range of 70°C to 80°C. However, for a relatively lower regeneration temperature, the COP value drops lower than that of AC -CO\textsubscript{2} pair. For regeneration temperature lower than 70°C, the COP of AC -CO\textsubscript{2} pair is 0.1 compared 0.095 of AC -R410a pair.
Figure 6 shows the effects of cooling water temperature on the SCC of all the pairs. As opposed to the case of regeneration temperature and evaporator temperature, the increase in cooling water temperature results in a linear decrease in the SCC of the refrigeration cycle, as shown in figure 6. AC -R410a pair provides the highest SCC value among all assorted adsorbent-refrigerant pairs for a temperature range of 10°C to 30°C.

**Figure 4.** Effect of regeneration temperature on specific cooling capacity for all the pairs.

**Figure 5.** Effects of regeneration temperature on COP.
Figure 6. Effects of cooling water temperature on specific cooling capacity.

As for the case of COP, it is observed from figure 7 that the COP value of the refrigeration system decreases with increasing cooling water temperature but the decrement is insignificant as Tcw approaches 20°C. It is observable from figure 7 that AC - R410a pair provides the highest COP for cooling water temperature of 10°C to 30°C.

Figure 7. Effects of cooling water inlet temperatures on COP.

6. Conclusion
The aim of the present study is to analyse the performance of pressurized adsorption refrigeration cycle using activated carbon of type Maxsorb III as adsorbent and five various refrigerants. The main conclusions are as follows:

i. AC-R410a pair exhibits the highest adsorption uptake compared to the other pairs.
ii. AC-R410a pair shows higher values of cooling capacity with the variation of regeneration
temperature of 70°C to 80°C and evaporator temperature range of 5°C to 20°C.

iii. When the regeneration temperature and evaporator temperature drop below 70°C and 5°C
respectively, the pair of AC-CO$_2$ proves to be a better option.

iv. As for the case of varying cooling water temperature, the pair of AC-R410a provides the best
cooling capacity and COP value, for cooling water temperature ranging from 10°C to 30°C.

v. The present study may provide useful information in designing pressurized based adsorption
cooling cycles driven by solar energy or waste heat.

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