

# Investigation of carbon based adsorbents for the development of thermally-driven adsorption cooling systems

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**Abstract.** Adsorption cooling systems are considered as energy efficient and sustainable technologies from the perspective of environmental safety and thermal energy utilization. These systems possess zero potentials of ozone depletion and global warming. In adsorption cooling processes, knowledge of adsorbent-refrigerant pairs (e.g. adsorption equilibrium, kinetics and heat) is important. The system performance is directly related to interactions between the adsorbent and refrigerant. Thus, the overall thermodynamic performance of the system can be improved accordingly. In this study, numerous carbon based adsorbents are explored in detail with different types of refrigerants (e.g. ethanol, methanol, CO<sub>2</sub>, R134A etc.). In order to select the optimum adsorbent-refrigerant pair. The analyses in the study are based on the experimental data on various adsorbent-refrigerant pairs available in the literature. Various adsorption isotherms models including: Dubinin-Astakhov, Tóth, Freundlich etc. present adsorption equilibrium data. Consequently, overall system analyses have been conducted by means of pressure-temperature-adsorption equilibrium (P-T-W) diagram. The P-T-W diagram is also drawn from the ideal cycle analysis in order to explain the performance of adsorption cooling systems. The coefficient of performance of the system has been calculated accordingly for the studied adsorbent-refrigerant pairs.

**Keyword:** adsorption cooling; activated carbon; refrigerant; optimization

## 1. Introduction

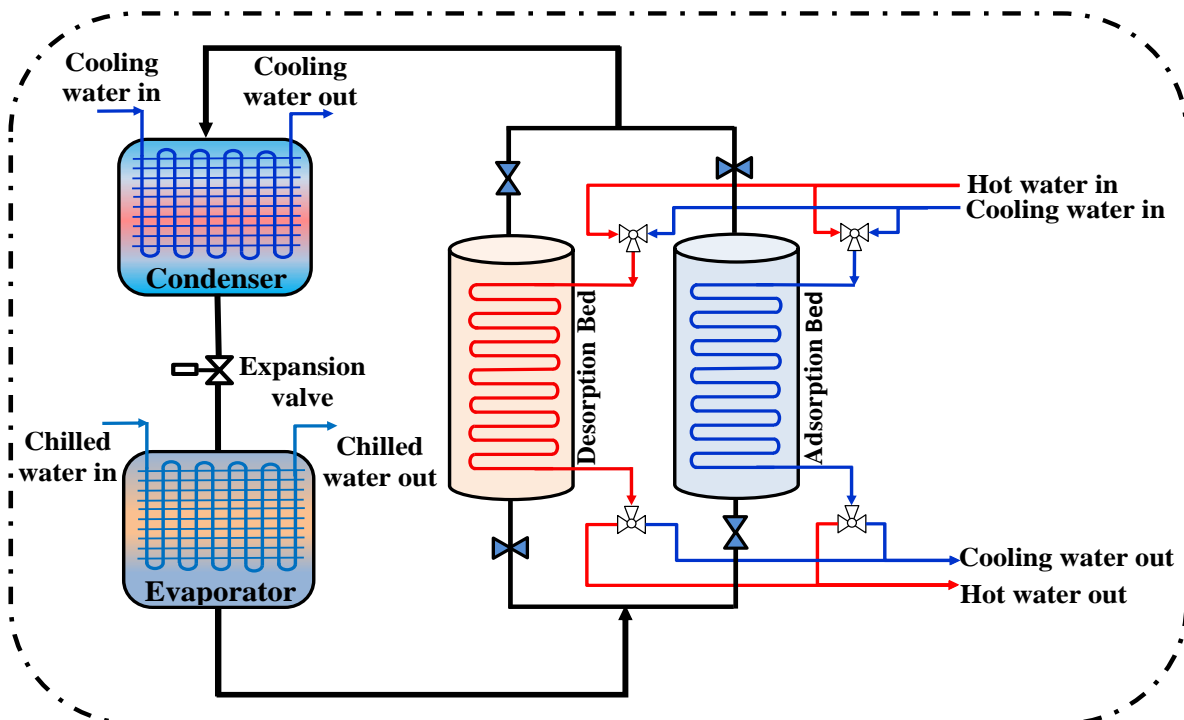
Thermally driven adsorption cooling systems are gaining much attention for the reason that, these systems are energy efficient and environmentally friendly. As the driving source of these systems could be solar energy or low grade waste heat [1]. Therefore, have a huge potential for adoption in those regions where there are more number of solar hours per year. Cooling load can be reduced in summer by utilizing adsorption cooling systems, where the vapor compression systems (VCS) cost a huge amount of energy. Also, thermally driven systems cause less deterioration of the ecosystem. As the refrigerant, they utilize (water, ethanol, CO<sub>2</sub> and HFCs etc.) gives a low threat for ozone depletion in contrast to the conventional refrigerants (CFCs) of VCS. Adsorbent-refrigerant pairs for the development of adsorption cooling systems are studied experimentally by many researchers. Some of them are activated carbon-CO<sub>2</sub> [2-3], activated carbon-ammonia [4], activated carbon fiber-ethanol [5], activated carbon-R134a [6], Silica gel-water [7-8], Zeolite-water [9], MOF-ethanol [10] and polymer-water [11-12]. Apart of cooling adsorption system can be utilized for other applications like water desalination [13], carbon capturing [14] and ice production [15] etc.

In this study, two carbon based adsorbent-ethanol pairs (Supersorbon HS4-ethanol and Dezorex DB1-ethanol) are selected in order to analyze their potential for the development of adsorption cooling system. Thermodynamic performance of cooling cycle is evaluated through the ideal cycle analysis. Hence Specific cooling energy (SCE) and coefficient of performance (COP) are evaluated for both assorted pairs.



## 2. Working of adsorption cooling system

A typical adsorption cooling system which clearly indicates that these systems are like vapor compression cooling system (VCS) except the compressor part is presented in Figure 1. In vapor compression systems, the compressor is electric driven, thus incurs high input cost for cooling and air conditioning. While in adsorption cooling system prime mover is the thermal compressor, therefore, the system economics are totally depending on low-cost thermal energy source. Thermal compressor usually consists of two beds packed with adsorbent material named as (i) adsorption bed and (ii) desorption bed. In adsorption cooling cycle, low-pressure refrigerant from the evaporator enters the adsorption bed, where the refrigerant gets adsorbed on to the adsorbent at a pressure equal to evaporator pressure. The exothermic nature of adsorption process causes adsorbent to release heat during the adsorption process. The heat of adsorption is removed by cooling water cycle around the adsorption bed. When the adsorbent becomes fully saturated with refrigerant the bed is switched to desorption mode by heating bed through the hot water cycle. At the end of desorption process, high-temperature and high-pressure refrigerant vapors will move toward the condenser. In the condenser, the temperature of refrigerant gets reduced by exchanging the heat through cooling water cycle. Also, the change in phase will occur, vapor refrigerant will be converted into liquid refrigerant. Hereafter it will pass through an expansion valve, where the drop-in pressure gives low pressure and low-temperature liquid refrigerant. That low-pressure refrigerant offers the required cooling effect, which will exchange by the evaporator and converted into the vapor phase. For continuous operation of adsorption cooling system, the adsorption and desorption beds are switched, after a specified switching time, by changing the cooling and heating water supplies through the valve accordingly.



**Figure 1.** Schematic of a typical adsorption cooling system.

## 3. Thermodynamic evaluation of adsorption cooling cycle

Adsorption isotherms of the two assorted pairs Supersorbon HS4-ethanol and Dezorex DB1-ethanol are reproduced by using Dubinin–Astakhov (D–A) adsorption equilibrium model (Eq.1) [16]. Values of adsorption isotherm parameters are listed in. The equation of the D-A isotherm model is given as:

$$W = W_0 \exp \left\{ - \left( \frac{A}{E} \right)^n \right\} \quad (1)$$

Where  $W$ ,  $W_0$ ,  $E$ ,  $n$  and  $A$  are the equilibrium adsorption uptake, maximum adsorption uptake, Characteristic energy, structural heterogeneity parameter and adsorption potential, respectively. Adsorption potential of the adsorbent-refrigerant pair can be evaluated as:

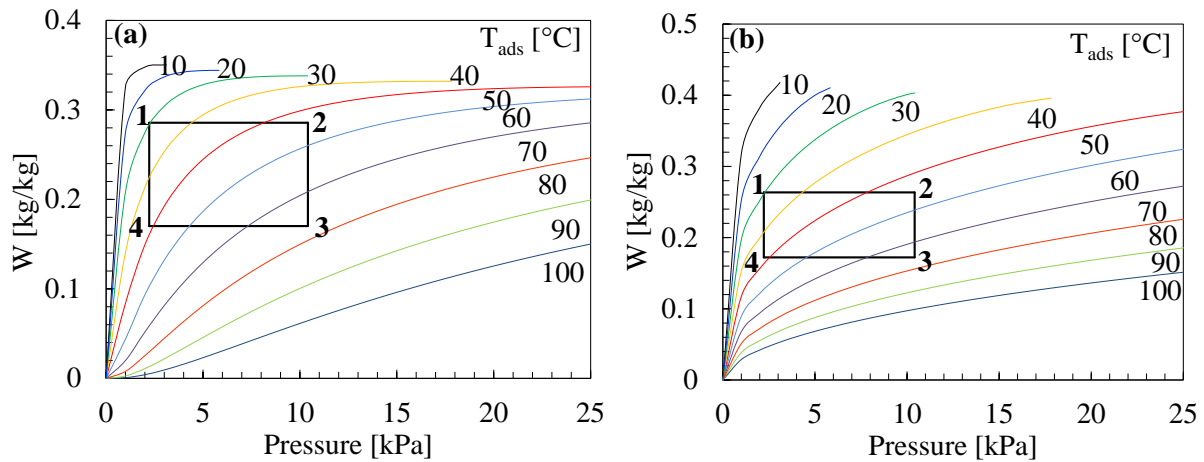
$$A = RT \ln \left( \frac{P_s}{P} \right) \quad (2)$$

Where  $P_s$  denotes the saturated pressure of refrigerant for a given temperature,  $P$  is the equilibrium pressure,  $T$  is the adsorption temperature and  $R$  is the gas constant.

**Table 1.** D-A adsorption isotherm model parameters

Adsorbent-Refrigerant Pair	D-A model Parameters			Reference
	$W_0$ [cm <sup>3</sup> /kg]	$E$ [kJ/mol]	$n$	
Supersorbon HS4-ethanol	426	8	2.4	[17]
Dezorex DB1-ethanol	508	7.8	1.2	[17]

Adsorption isotherms are outlined for different adsorption temperatures from 20-100°C with the difference of 10°C. The ideal adsorption Cooling cycle is traced along with these isotherms in Figure 2 for (a) Supersorbon HS4-ethanol and (b) Dezorex DB1-ethanol. The operating conditions for the ideal cycle are fixed at a regeneration temperature of 100°C. While evaporator and adsorption temperatures are set at 5°C and 30°C respectively.



**Figure 2.** Ethanol adsorption isotherms produced by D-A adsorption isotherm model for: (a) Supersorbon HS4, and (b) Dezorex DB1, reproduced from [17].

Performance of ideal cooling cycle can also be evaluated by dühring diagram or pressure-temperature-concentration (P-T-W) diagram. P-T-W diagram of adsorbent-refrigerant pair expresses a thermodynamic relation between equilibrium pressure, adsorbent temperature and equilibrium adsorbed concentration of refrigerant. Isothermic lines in the P-T-W lines are produced by simplifying the D-A isotherm equation (Eq.1) in the following equations;

$$\ln \left( \frac{W}{W_0} \right) = - \left( \frac{A}{E} \right)^n \quad (3)$$

$$A = E \left( - \ln \left( \frac{W}{W_0} \right) \right)^{\frac{1}{n}} \quad (4)$$

$$RT \ln \left( \frac{P_s}{P} \right) = E \left( - \ln \left( \frac{W}{W_0} \right) \right)^{\frac{1}{n}} \quad (5)$$

$$P = P_s / \exp \left[ \frac{E}{RT} \left( - \ln \left( \frac{W}{W_0} \right) \right)^{\frac{1}{n}} \right] \quad (6)$$

The adsorption cooling cycle consists of four consecutive processes 1-2 an isosteric heating process (pre-heating), 2-3 isobaric heating (desorption), 3-4 isosteric cooling process (precooling) and 4-1 isobaric cooling process (adsorption) Figure 3 [18]. P-T-W diagram of Supersorbon HS4-ethanol and Dezorex DB1-ethanol are shown in Figure 3 (a) and (b), respectively. The ideal cycle of both pairs is constructed for regeneration, evaporator and condenser temperatures of 100°C, 5°C and 30°C, respectively. To evaluate the performance of ideal cycle a thermodynamic model was employed, which is time independent [19]. Thus SCE can be defined as:

$$SCE = (W_{max} - W_{min}) \left[ LH_{T_e} - \int_{T_e}^{T_c} C_{P_{ref}} dT \right] \quad (7)$$

Whereby  $W_{max}$  is the maximum uptake of refrigerant evaluated for evaporation pressure and adsorption temperature and  $W_{min}$  is minimum uptake measured corresponding to the desorption temperature and condenser pressure.  $LH_{T_e}$  is the vaporization enthalpy at evaporator temperature and  $C_{P_{ref}}$  shows the specific heat capacity of refrigerant. Heat added to the adsorbent for the increase in temperature from  $T_1$  and  $T_3$ . is given as:

$$Q_{ads} = \int_{T_1}^{T_3} C_{P_{ads}} dT \quad (8)$$

Where  $C_{P_{ads}}$  is the specific heat capacity of adsorbent. Heat added to the refrigerant is given by:

$$Q_{ref} = W_{max} \int_{T_1}^{T_2} C_{P_{ref}} dT + \int_{T_2}^{T_3} W \cdot C_{P_{ref}} dT + \int_{W_{min}}^{W_{max}} q_{st} dW \quad (9)$$

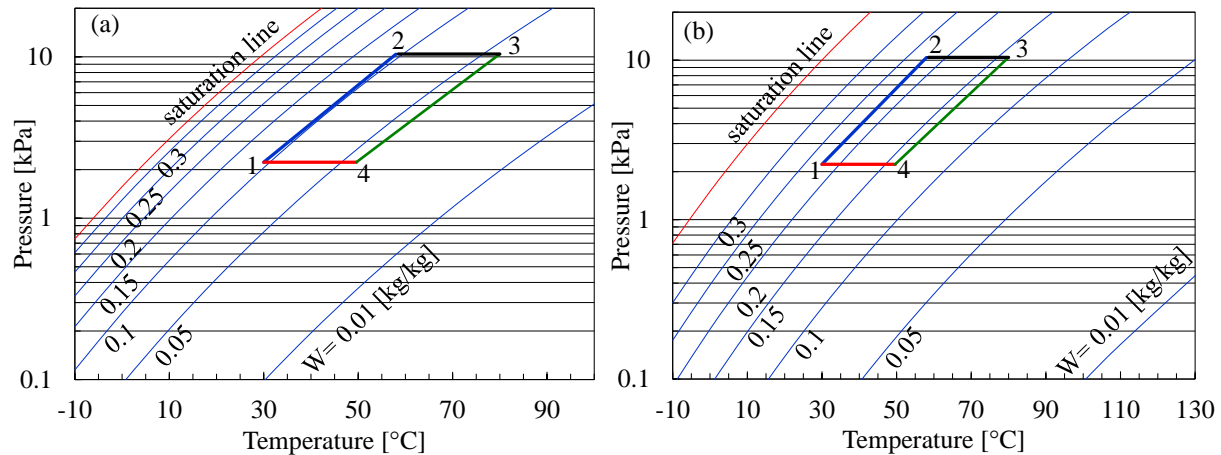
In Eq. (9), the first and second terms are sensible heats added to the refrigerant during pre-heating and desorption processes, respectively. Whilst third term is the heat of adsorption. Here the average values of  $q_{st}$  for Supersorbon HS4-ethanol and Dezorex DB1 ethanol Pairs are used 1126.05 kJ/kg and 1038.68 kJ/kg, respectively [17].

Thus, COP of the cycle can be described as:

$$COP = \frac{SCE}{Q_{ads} + Q_{ref}} \quad (10)$$

SCE and COP as a function of desorption temperature are found to increase with the increase in desorption temperature. SCP reach the maximum value of 180.1 and 128.8 kJ/kg for Supersorbon HS4-ethanol and Dezorex DB1-ethanol Pairs, respectively, at a regeneration temperature of 100°C. Minimum desorption temperature was found to be 58°C for corresponding evaporator temperature of 5°C. COP of Dezorex DB1-ethanol and Supersorbon HS4-ethanol pair, for the regeneration temperature range of 80-

0°C, was about 0.57 and 0.64, respectively. Therefore, these adsorbents could be an option for the utilization of low-grade waste heat.



**Figure 3.** P-T-W diagram of (a) Supersorbon HS4-ethanol and (b) Dezorex DB1-ethanol Pairs

#### 4. Conclusions

Adsorption isotherms of two assorted pairs reveal the higher adsorption uptakes for the Dezorex DB1-ethanol Pair as compared to Supersorbon HS4-ethanol pair. Ideal cycle analysis of adsorption cooling system of both activated carbon-ethanol pair is led at an evaporator temperature of 5°C and regeneration temperature of 100°C. It shows a higher specific cooling effect for Supersorbon HS4 is 180.1, while Dezorex DB1 give relatively lower values for SCE of 128.8. Similarly, the coefficient of performance of Dezorex DB1-ethanol and Supersorbon HS4-ethanol pairs are 0.57 and 0.64, respectively, for the regeneration temperature ranging from 80°C to 90°C. At an evaporator temperature of 5°C, minimum desorption temperature was found i.e. 58°C, which proves the applicability of these adsorbents for thermally driven adsorption cooling systems.

#### Nomenclature

VCS	Vapor compression systems
W	Equilibrium adsorption uptake [kg/kg]
$W_0$	Maxium adsorption uptake [kg/kg]
E	Chahracteristic energy [kJ/mol]
n	Structural heterogenity parameter [-]
A	Adsorption potential [kJ/kg]
$P_s$	Saturated pressure of refrigerant for given temperature [kPa]
P	Equilibrium pressure [kPa]
T	Adsorption temperature [°C]
R	Gas constant.[kJ/kg.K]
LH	Vaporization enthalpy [kJ/kg]
$C_p$	Specific heat capacity [kJ/kg.K]
Q	Heat energy [kJ/kg]
$q_{st}$	Isosteric heat of adsorption [kJ/kg]
SCE	Specific cooling effect [kJ/kg]
COP	Coefficient of performance [-]

*Subscripts*

max	Maximum
min	Minimum
c	Condenser
e	Evaporator
ref	Refrigerant
ads	Adsorption

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