

Thermodynamic Simulation of CO₂ – Adsorbent Based Sorption Refrigeration System

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Different materials like activated carbon, metal organic frameworks, silica, etc. have ability to adsorb (exothermic process) and desorb (endothermic process) CO₂. These heat interactions during adsorption and desorption processes can be utilized for the development of gas – adsorbent based sorption refrigeration system. Therefore, in the present work, this concept is employed to analyze the thermodynamic performance of CO₂ – adsorbent based sorption refrigeration system (CO₂-A SRS). The chosen adsorbents for thermodynamic simulation are Activated Carbon (Norit RB3), Pore Expanded Mesoporous Silica Materials (PE MSM 41), Amine Tethered Mesoporous Silica Materials (AT MSM 41) and Amine Functionalized Silica (AF Silica). The working pairs are developed based on the available pressure difference between coupled adsorbent to allow sufficient amount of CO₂ to flow between the coupled materials in the operating temperature range of 0°C (refrigeration output), 25°C (ambient) and 100°C (heat source). The thermodynamic performance of refrigeration system is compared for two adsorbent pairs. The thermodynamic performance includes refrigeration effect, specific refrigeration power, coefficient of performance, refrigeration capacity and second law of efficiency. The refrigeration effect of Activated Carbon – PE MSM 41 pair is observed double that of AT MCM 41 – AF Silica pair. In addition, the thermodynamic performance of CO₂-A SRS is compared with the performance of CO₂ – adsorbent based vapour adsorption refrigeration system (CO₂-A VARS) available in literature. The COP of CO₂-A SRS is observed higher than CO₂-A VARS.

Keywords: Adsorbent; COP; CO₂ adsorbent based sorption refrigeration system; CO₂ storage; Reaction enthalpy; Specific refrigeration power.

1. INTRODUCTION

Carbon dioxide has adverse effect on the environment, since Green House Gases contains 77% of CO₂ [1]. Therefore, the concept of storage and sequestration of CO₂ from environment or waste exhaust gases received much interest of researchers worldwide. It is observed from several studies that CO₂ can be captured by adsorption in different materials like activated carbon, zeolite, silica, etc. These technologies become promising solution for the benefit of future generations. Several studies on characterisation of adsorbent materials to identify its CO₂ storage capacity are available in literature [2-30]. Development of any sorption based thermodynamic system demands for the knowledge of adsorption/desorption characteristics, reaction kinetics and thermal stability of materials used.

Vinod and Anil [2] have experimentally and theoretically studied the CO₂ adsorption and desorption characteristics of three different type of activated carbons

namely Norit RB3 (steam activated rod), Norit Darco (100 mesh size), and Norit Darco (12 -20 US mesh size). They have observed that CO₂ adsorption capacity increased with increase in supply pressure. Later, the experimentally measured isotherm are simulated using D-A Model. Several researchers [12-14] theoretically studied the CO₂ adsorption phenomena on solid adsorbent. Young and Crowell [15] estimated the thermodynamic properties of solid adsorbents and revealed the importance of surface area and spreading pressure on the physical adsorption process. The development of several amine-tethered mesoporous silica materials to enhance the CO₂ adsorption capacity at lower partial pressures are presented by different researchers [16-20]. In other studies [28-30], novel pore expanded mesoporous silica materials are suggested as promising support for amine tethering. It allows exploitation of internal space, which is not possible with zeolite, MSM-41, SBA-15 and KIT-6 [21, 22]. On the other hand, Loganathan et al. [27] have investigated the CO₂ adsorption and desorption isotherms on PE-MSM-41 at different temperatures and at the pressure range of 0-25 bar and it was observed that the adsorption and desorption are reversible in nature as the isotherms coincide with each other.

The experimental investigation on CO₂ storage and reaction rates of pitch-based activated carbon at 303 to

Received: January 2019, Accepted: June 2019

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doi: 10.5937/fmet2001187S

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FME Transactions (200x) 48, 187-194 187

423 K temperature and 0-1 bar pressure is reported by Shen et al. [23]. Balsamo et al. [24] have reported that reaction kinetics directly proportional to supply pressures whereas inversely proportional temperatures. It is observed by Zhang et al. [25] on experimental investigation of CO₂ storage and reaction kinetics of activated carbon and zeolite 13X at 298, 308, 318 and 328 K, and up to 30 bar pressure that the adsorption rates of zeolite 13X at low pressures are comparatively more than activated carbon whereas at higher pressures the adsorption capacities are observed lower in zeolite 13X compared to activated carbon.

CO₂ storage capacities of different adsorbent materials are widely investigated for several operating conditions whereas less effort has been given on the development of CO₂ – adsorption based thermodynamic systems. CO₂ – adsorption based thermodynamic systems like cooling system can be operated using waste heat as input whereas the heat of desorption during endothermic process can be utilized as cooling output. The development of any solid – gas sorption thermodynamic system demands for the several thermodynamic and thermo physical properties like gas storage, reaction kinetics, thermodynamic properties, etc. of adsorbent materials [31]. The selection of suitable working pairs depends on the adsorption isotherms, kinetics, and heat of adsorption and desorption, specific heat capacity, internal energy, etc. In addition to high adsorption capacity and fast kinetics, activated carbon exhibits high surface area, better pore size distribution and thermal stability. Therefore, it is more suitable for adsorption of CO₂ compared to other solid adsorbents [3–6, 26]. It can also be adopted easily for many applications due to its economical suitability for large quantity use and non-reactive to moisture. Activated carbons are also studied for the suitability of different applications like separation and purification of CO₂; sorption based thermodynamic devices systems, cryo-coolers and energy storage systems [7–11]. Recently, thermodynamic analysis of CO₂ and activated carbon based cooling system has been conducted by Vinod and Anil [2] and obtained maximum COP of 0.09 with CO₂-Norit RB3, pair at driving source temperature of 80°C with the evaporator temperature of 15°C. On the other hand, Banjac et al. [32] have discussed about the geothermal ground source heat pump for low temperature hydronic heating system. Jitendra and John Rajan [33] have presented the recent advancement in cooling technologies for solar PV systems.

Though several adsorbent materials are used to study their CO₂ adsorption capacity, activated carbons are reported to be most suitable for CO₂ storage applications due to its high CO₂ storage capacity. Also, activate carbons are used to study the thermodynamic performance of CO₂ – adsorbent based vapour adsorption refrigeration systems (CO₂-A VARS) by several researchers. But, the observed COP and cycle efficiency of CO₂-A VARS are quite low that necessitates the further investigations on system performance improvement. Therefore, in the present study, the concept of gas – solid sorption is employed to propose a new thermodynamic cycle of CO₂ – adsorbent based sorption refrigeration system (CO₂-A SRS). The sorption refrige-

ration system works with the employment of working pairs (adsorption/absorption materials) of one high pressure type and one low pressure type materials [34–39]. The useful cooling effect can be produced through adsorption/desorption of gas to/from working materials. Such systems do not require mechanical moving parts. There is no need of compressor to increase gas pressure, this (pressure increase or decrease) can be done through sensible heating and sensible cooling of charged materials. In addition, sorption systems are environmental friendly due to absence of harmful refrigerants. The refrigeration effect in CO₂-A SRS can be obtained by utilizing the heat interactions involved during CO₂ transfer between coupled adsorbent materials. This type of gas – solid sorption refrigeration system is never studied in literature using CO₂ as working fluid. Therefore, we proposed a concept of gas – solid sorption refrigeration system to theoretically analysis (thermodynamic simulation) the thermodynamic performance of such sorption system using CO₂ as working fluid. In the present study, two pairs of adsorbent materials are used to estimate the performance of CO₂-A SRS and compared their suitability for the development of CO₂-A SRS. The adsorbent pairs used for thermodynamic simulation of CO₂-A SRS are “Activated Carbon - PE MSM 41” and “AT MSM 41 - AF Silica”. The performance of CO₂-A SRS is estimated in terms of refrigeration effect, refrigeration capacity, specific refrigeration power, COP and cycle efficiency.

2. WORKING PRINCIPLE OF CO₂ – ADSORBENT BASED REFRIGERATION SYSTEMS

2.1 CO₂ – Adsorbent based sorption refrigeration system (CO₂-A SRS)

Figures 1 and 2 show the thermodynamic cycle and scheme of CO₂ – A SRS respectively working in the temperature range of T_{ref} = 0°C (refrigeration output temperature), T_a = 25°C (ambient temperature) and T_{reg} = 100°C (heat source temperature). A CO₂ – A SRS consists of two CO₂ transfer processes; refrigeration process and regeneration process, and one sensible heating process and one sensible cooling process. CO₂ – A SRS needs a pair of two adsorbent materials that eliminates the requirement of expansion device, heat exchangers, etc., which are required in CO₂-A VARS (Fig. 3). The CO₂ – A SRS system utilizes the reaction heats involved during adsorption/desorption of CO₂ on /from adsorbent materials to produce refrigeration effect.

Refer to Figs. 1 and 2; A₁ and A₁' are adsorbents used at high-pressure side and A₂ and A₂' are adsorbents at low-pressure side. In refrigeration process, adsorbent A₁ at point 1 desorbs CO₂ at T_{ref}, which is adsorbed by adsorbent A₂ at point 2 at temperature T_a. The desorption (endothermic) heat absorb by adsorbent A₁ is responsible for producing refrigeration effect (Q_{ref}) at T_{ref}, and the adsorption (exothermic) heat (Q_a) released by adsorbent A₂ is rejected to ambient at T_a. Simultaneously, in regeneration process, the adsorbent A₂' desorbs CO₂ by taking the required heat (Q_{reg}) of desorption from waste heat source at T_{reg} that CO₂ is

adsorbed by adsorbent A_1 , by rejecting heat of adsorption (Q_a) to ambient at T_a . Thereafter, by sensibly cooling adsorbent A_1 from T_a to T_{ref} and adsorbent A_2 from T_{reg} to T_a , and sensibly heating of adsorbent A_1 from T_{ref} to T_a and adsorbent A_2 from T_a to T_{reg} , system can be ready for next cycle.

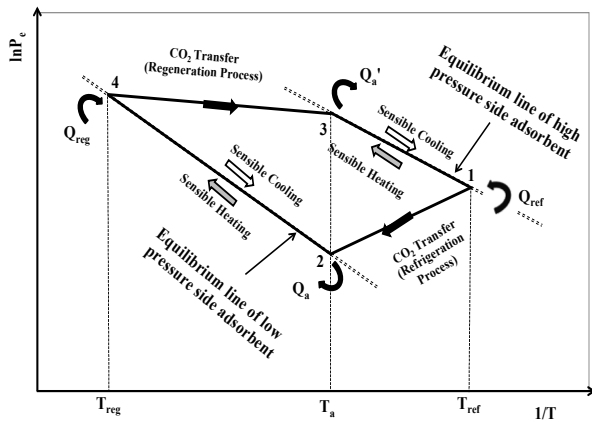


Figure 1. Thermodynamic cycle of CO_2 – adsorbent based sorption refrigeration system

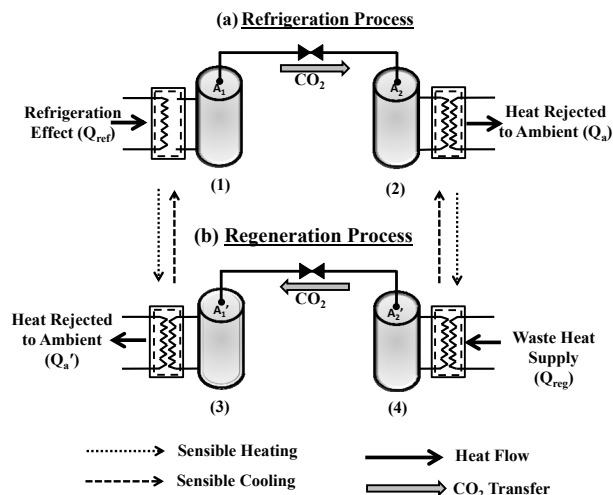


Figure 2. Scheme of CO_2 – adsorbent based sorption refrigeration system

2.2 CO_2 – Adsorbent based vapour adsorption refrigeration system (CO2-A VARS)

Figure 3 shows the scheme of CO_2 – adsorbent based vapour adsorption refrigeration system. This system consists of a condenser, an evaporator, an expansion valve and one sorption reactor. Firstly, CO_2 gets evaporated in an evaporator producing refrigeration effect (Q_{ref}). Then, the low-pressure CO_2 transferred to the adsorber and get adsorbed on adsorbent at low temperature. Since, the process of adsorption is exothermic, certain amount of heat (Q_a) is rejected to ambient. Adsorber is then disconnected from the evaporator heat exchanger and is sensibly heated to required condenser temperature and corresponding pressure. After reaching to equilibrium condition, CO_2 get desorbed from adsorbent using waste heat source (Q_s). The desorbed CO_2 condensed in the condenser by rejecting Q_c amount of heat. The operation completes by expansion of CO_2 through expansion valve between condenser and evaporator.

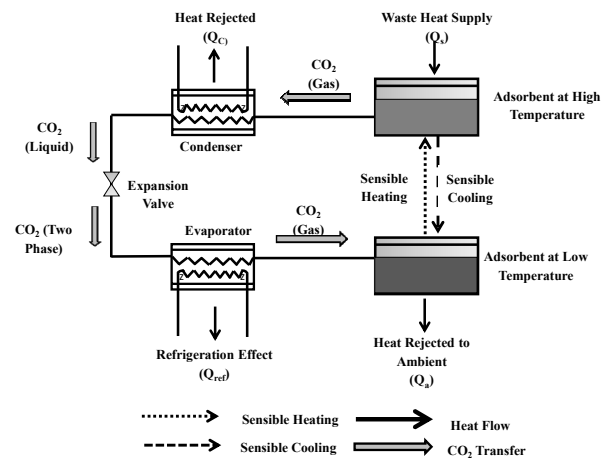


Figure 3. Scheme of CO_2 – adsorbent based vapour adsorption refrigeration system

3. SELECTION OF ADSORBENT PAIRS

Typically, the desirable properties of adsorbents suitable for CO_2 – A SR system are (a) high CO_2 storage capacity that increases the amount of CO_2 transmission, (b) fast reaction kinetics to reduce overall cycle time, (c) sufficient pressure difference between coupled sorption beds at operating temperature range, (d) and favourable thermodynamic properties, generally, high desorption heat for adsorbent at high pressure side to increase refrigeration output and low desorption heat for adsorbent at low pressure side to reduce regeneration input. In this view, different adsorbent materials characterised for CO_2 storage application available in literature are chosen to identify the best-suited adsorbent pairs of the development of CO_2 – A SRS. The chosen adsorbent materials are Activate Carbon (Norit RB3) (AC1), Activated Carbon (Norit Carco, 100 mech size) (AC2), Activated Carbon (Norit Darco, 12×20 US mesh size) (AC3) [2], Pore Expanded Mesoporous Silica Materials (PE MSM 41) [26], Amine Tethered Mesoporous Silica Materials (AT MSM 41) [30], Amine Functionalized Silica (AF Silica) [40], 13X Zeolite [41] and MIL 101 [42].

The isotherm data of above mentioned adsorbent materials are taken from respective references and van't Hoff plots are constructed for each adsorbent material. Van't Hoff plot is a relation between logarithmic equilibrium pressure and inverse of absolute temperature. The equilibrium pressures for all the adsorbent materials are chosen at fixed CO_2 concentration at different temperatures. For the selection of equilibrium pressure, CO_2 concentration was kept fixed to ensure the uniformity in measurements. The constructed plots are linear where its slope and intercept can be used to evaluate reaction enthalpy and reaction entropy respectively using van't Hoff equation. Fig. 4 shows the van't Hoff plots of all adsorbent materials chosen for present study. The equations of van't Hoff lines and, estimated reaction enthalpy and entropy are listed in Table 1.

As mentioned earlier, the working temperature range for CO_2 – A SRS is selected as $T_{ref} = 0^\circ C$, $T_a = 25^\circ C$ and $T_{reg} = 100^\circ C$. We have proposed the refrigeration system which can able to discharge the waste heat at ambient temperature. Therefore, the heat sink is chosen as $25^\circ C$ while the refrigeration output temperature ($0^\circ C$)

and heat source temperature (100°C) are chosen in such a way that there exist sufficient pressure difference between coupled reactors to allow sufficient CO₂ transfer between them. Also, high pressure difference increases rate and amount of CO₂ transfer. Therefore, to select the suitable working pair for CO₂ – A SRS, all adsorbent materials are examined on the basis of available pressure difference between coupled adsorbent beds for a given temperature range (see Fig. 4) because sufficient pressure differential is required to allow CO₂ transfer between them and also for fast kinetics. Based on van't Hoff data, out of eight adsorbents, only four adsorbent materials are found suitable for the development of CO₂ – A SRS. The selected adsorbent materials and their possible pairs are Activated Carbon – PE MSM 41 (pair 1) and AT MSM 41 – AF Silica (pair 2). Activated carbon and AT MCM – 41 are considered as high pressure adsorbents due to their higher equilibrium pressures relative to PE MCM – 41 and AF Silica equilibrium pressures respectively at given operating temperatures. In the proceeding sections, thermodynamic cycles and simulation are discussed for these selected adsorbent pairs.

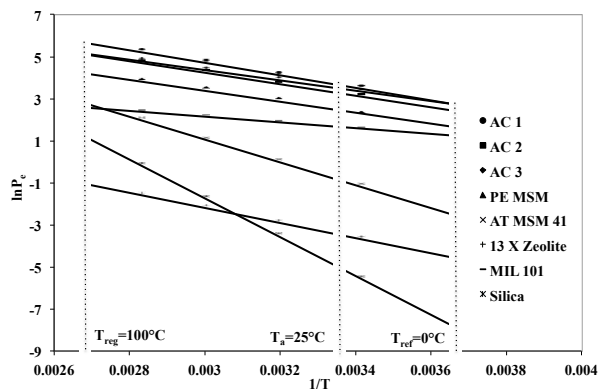


Figure 4. Van't Hoff plots for chosen adsorbent materials

As mentioned earlier, the working temperature range for CO₂ – A SRS is selected as $T_{ref} = 0^\circ\text{C}$, $T_a = 25^\circ\text{C}$ and $T_{reg} = 100^\circ\text{C}$. We have proposed the refrigeration system which can able to discharge the waste heat at ambient temperature. Therefore, the heat sink is chosen as 25°C while the refrigeration output temperature (0°C) and heat source temperature (100°C) are chosen in such a way that there exist sufficient pressure difference between coupled reactors to allow sufficient CO₂ transfer between them. Also, high pressure difference increases rate and amount of CO₂ transfer. Therefore, to select the suitable working pair for CO₂ – A SRS, all adsorbent materials are examined on the basis of available pressure difference

Table 1. Estimated reaction enthalpy and entropy values

Adsorbent Materials	Van't Hoff Equations	Reaction Enthalpy; ΔH (kJ/mol)	Reaction Entropy; ΔS (kJ/mol K)
Activated Carbon-1	$\ln P_e = -2971.4/T + 13.621$	24.7	0.113
Activated Carbon-2	$\ln P_e = -2733.8/T + 12.438$	22.7	0.103
Activated Carbon-3	$\ln P_e = -2457.4/T + 11.737$	20.4	0.098
Pore Expanded PE MCM-41	$\ln P_e = -1983.1/T + 8.7686$	16.5	0.073
Amine Tethered PE MCM-41	$\ln P_e = -5423.9/T + 17.329$	45.1	0.144
13X Zeolite	$\ln P_e = -3589/T + 8.5758$	29.8	0.071
MIL 101 Powder Form	$\ln P_e = -1367.3/T + 6.2506$	11.4	0.052
Amine Functionalized Mesoporous Silica	$\ln P_e = -9226.1/T + 25.939$	65.1	0.216

between coupled adsorbent beds for a given temperature range (see Fig. 4) because sufficient pressure differential is required to allow CO₂ transfer between them and also for fast kinetics. Based on van't Hoff data, out of eight adsorbents, only four adsorbent materials are found suitable for the development of CO₂ – A SRS. The selected adsorbent materials and their possible pairs are Activated Carbon – PE MSM 41 (pair 1) and AT MSM 41 – AF Silica (pair 2). Activated carbon and AT MCM – 41 are considered as high pressure adsorbents due to their higher equilibrium pressures relative to PE MCM – 41 and AF Silica equilibrium pressures respectively at given operating temperatures. In the proceeding sections, thermodynamic cycles and simulation are discussed for these selected adsorbent pairs.

3.1 Results and discussion

For operation of CO₂ – A SRS, a pair of high-pressure and low-pressure type adsorbent materials is required. In the present study, Activated Carbon and AT MSM 41 are considered as high-pressure type, and PE MSM 41 and AF Silica as low-pressure type adsorbent. The thermodynamic cycles for CO₂ – A SRS constructed based on van't Hoff plots for working pairs Activated Carbon – PE MSM 41 and AT MSM 41 – AF Silica are shown in Figs. 5 and 6, respectively.

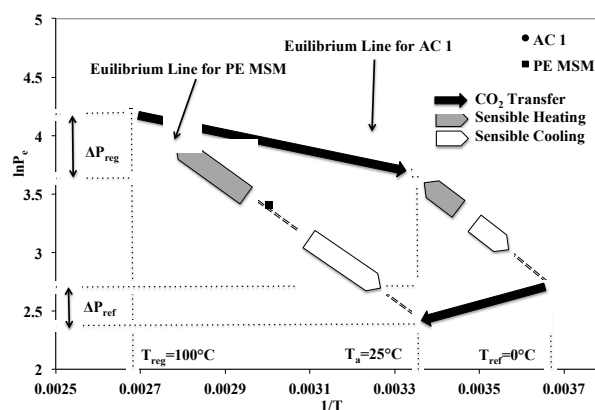


Figure 5. CO₂ – A SRS thermodynamic cycle using Activated Carbon – PE MSM 41 pair

In Fig. 5, ΔP_{ref} and ΔP_{reg} are the available pressure differences between the coupled adsorbent materials for refrigeration and regeneration processes respectively. The estimated pressure differences between coupled adsorbent materials are $\Delta P_{ref} = 4.14$ bar, $\Delta P_{reg} = 30$ bar, which are sufficient to allow CO₂ transmission during refrigeration and regeneration processes.

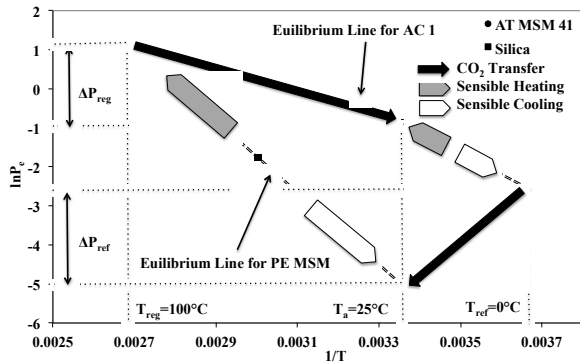


Figure 6. CO₂ – A SRS thermodynamic cycle using AT MSM 41 – AF Silica pair

On the other hand, in Fig. 6, for pair of AT MSM 41 – AF Silica materials, the refrigeration process occurs in sub atmospheric pressure whereas regeneration occurs at above atmospheric pressure and the pressure difference is $\Delta P_{reg} = 2.5$ bar. It is clear from Figs. 5 and 6 that both the pairs are suitable for the development of CO₂ – A SRS because there exist sufficient pressure difference between paired adsorbent materials to facilitate the CO₂ transfer for the working of sorption refrigeration system. The decrease in ΔP , in case of AT MSM 41 – AF Silica pair is responsible for decrease in CO₂ transfer rate, which significantly increases cycle time; it also decreases the transferrable CO₂ between paired adsorbents. On comparison, it is observed that the pair of Activated Carbon – PE MSM 41 materials is more suitable than AT MSM 41 – AF Silica pair due to its capacity of working on above atmospheric pressure with higher pressure differentials that improve system efficiency by reducing cycle time.

3.2 Thermodynamic analysis of CO₂ adsorption based sorption refrigeration system

The thermodynamic analysis of CO₂ – A SRS is carried out using Activated Carbon – PE MSM 41 and AT MSM 41 – AF Silica pairs to check their suitability for the development of CO₂ – A SRS. The adsorbent to reactor mass ratio is assumed to be 1:0.75, the specific heat of adsorbent and reactor as 0.7 kJ/kg K and 0.46 kJ/kg K respectively [2, 34]. The cycle time is assumed to be 30 minutes for 1 kg of each adsorbent. The thermodynamic properties and transferrable CO₂ of chosen adsorbent materials are available in Table 2.

The thermodynamic performance of CO₂ – A SRS are estimated using following equations:

Refrigeration effect

$$Q_{ref} = n\Delta H_{ref} - [(m_{ref}C_{ref} + m_{r,ref}C_{r,ref})(T_a - T_{ref})] \quad (1)$$

Regeneration heat supplied

$$Q_{reg} = n\Delta H_{reg} + [(m_{reg}C_{reg} + m_{r,reg}C_{r,reg})(T_{reg} - T_a)] \quad (2)$$

Coefficient of performance:

$$COP = \frac{Q_{ref}}{Q_{reg}} \quad (3)$$

Specific refrigeration power

$$SRP = \frac{Q_{ref}}{t_{half-cycle}(m_{ref} + m_{reg})} \quad (4)$$

Refrigeration capacity

$$RC = \frac{\text{Refrigeration load}}{\text{Cycle time}} = \frac{2Q_{ref}}{t_{cyl}} \quad (5)$$

Second law efficiency

$$\eta_E = COP \frac{(T_a / T_{ref}) - 1}{1 - (T_a / T_{reg})} \quad (6)$$

Upon thermodynamic simulation of CO₂ – adsorbent based sorption refrigeration system, the estimated thermodynamic performance viz. refrigeration effect (Q_{ref}), regeneration heat supplied (Q_{reg}), coefficient of performance (COP), specific refrigeration power (SRP), refrigeration capacity (RC) and second law efficiency (η_E) are listed in Table 3 for both the pairs. It is observed from the literature that the thermodynamic performance of any gas – solid sorption system significantly influences by reaction heat of the material employed. Also, for better refrigeration effect, the reaction heat of the refrigeration adsorbent material should be higher whereas the reaction heat of the regeneration adsorbent material should be lower. These together result in higher COP of the thermodynamic system. In the present study, it is observed that inspite of having higher reaction heat (AT MSM 41) than Activated Carbon, the refrigeration effect of CO₂ – A SRS using Activated Carbon – PE MSM 41 pair is higher than that of using AT MSM 41 – AF silica pair. This is due to the availability of higher transferrable CO₂ between Activated Carbon – PE MSM 41 pair (due to higher CO₂ storage capacity of these adsorbents) than AT MSM 41 – AF silica pair. Also, in Activated Carbon – PE MSM 41 pair, the reaction heat of regeneration materials i.e. PE MSM 41 is lower than that of refrigeration material i.e. Activate Carbon, which gives rise in COP whereas on the other hand, for AT MSM 41 – AF silica pair, the reaction heat of AF Silica (regeneration material) is higher than that of AT MSM 41 (refrigeration material).

Table 2. Properties of adsorbent materials [2, 27, 40, 43]

S. No.	Absorbent Materials	Reaction Enthalpy; ΔH (kJ/mol)	Transferrable CO ₂ (mol/gm)	Average Specific Heat (KJ/kgK)
1	Activated Carbon	18.63	0.02499	0.7
2	PE MSM-41	16	0.006	-
3	AT MSM-41	45	0.002	-
4	Amine Functionalized Silica	65	0.0012	-

Therefore, the SRP, cooling capacity and second law efficiency are also observed greater for the pair Activated Carbon – PE MSM 41. Based on the above observations for available pressure differential, reaction heat and transferrable CO₂ i.e. overall thermodynamic performance, the pair of Activated Carbon – PE MSM 41 is considered to be a best suited working pair for the development of CO₂ – adsorbent based sorption refrigeration system.

Table 3. Performance of CO₂ based solid sorption cooling system

Pairs →	Activated Carbon - PE MCM	AT MCM - AF Silica
CO ₂ Exchange (moles)	6	1.2
ΔH _{ref} (kJ/mol)	18.63	45
ΔH _{reg} (kJ/mol)	16	65
Q _{ref} (kJ)	98.65	40.87
Q _{reg} (kJ)	135.37	117.37
COP	0.72	0.34
SRP (W/kg)	54.8	22.7
RC (kW)	0.1	0.04
η _E (%)	33.18	15.86

It is also observed in the literature [2] that the performance of CO₂ – adsorbent based vapour adsorption refrigeration system have been analysed using adsorbent materials as Activate Carbon. The schematic and working principle of the CO₂ – adsorbent based vapour adsorption refrigeration system is given in Fig. 3 and section 2.2. The thermodynamic performance of CO₂-A VARS was reported as the maximum COP of 0.04, SRP of 7.4 W/kg and second law efficiency of 2.33% for evaporator temperature of 0°C and condenser temperature of 80°C. The thermodynamic performance was estimated using the same values of transferrable CO₂ and reaction heat presented in Table 2 for Activated Carbon. Whereas in the present study, authors have estimated the maximum COP of 0.72, SRP of 54.8 W/kg and second law efficiency of 33.18% for the temperature range of 0°C, 25°C and 100°C with adsorbent pair of Activated Carbon – PE MSM 41.

Based on the above observations, the basic criterion for the selection of adsorbent pair to achieve best refrigeration performance can be suggested. The selection of adsorbent pair depends on the adsorbent isotherms, thermal stability and reaction kinetics at the refrigeration system operating temperature range. The general properties required are high transferrable CO₂ capacity, fast reaction rates, good thermal stability. The adsorbent placed at refrigeration side should possess higher reaction heat to increase refrigeration effect and the adsorbent placed at regeneration side should possess low reaction heat to reduce the regeneration heat supplied consequently together increases COP. In addition, the pressure differences between the coupled adsorbent reactors strongly influence the CO₂ transfer rate and amount. The higher-pressure difference between coupled adsorbents is responsible for high refrigeration capacity and reduces cycle time.

4. CONCLUSIONS

The study on thermodynamic simulation of CO₂ – adsorbent based sorption refrigeration system and vapour adsorption system led to the following conclusions:

- The materials suitable for storage of CO₂ are considered to check their suitability for the development of gas-solid sorption refrigeration system.
- Out of several CO₂ storage materials, Activated Carbon, PE MSM 41, AT MSM 41 and AF Silica are found suitable for CO₂ – A SRS.
- The pair of Activated Carbon – PE MSM 41 is found best suitable for the development CO₂ – A SRS compared to AT MSM 41 – AF Silica pair, which can produce 197 kJ of refrigeration load with 33% of second law efficiency for 1 kg of absorbents and cycle time of 30 minutes.
- The refrigeration performance of CO₂ – A SRS can be improved with high transferrable CO₂ capacity, sufficient pressure difference between coupled adsorbents, high reaction heat of refrigeration adsorbent and low reaction heat of regeneration adsorbent.
- High refrigeration performance is observed for CO₂ – A SRS using the pair of Activated Carbon – PE MSM 41 compared to CO₂-A VARS using activated carbon as working material.

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NOMENCLATURE

A SRS	adsorbent based sorption refrigeration system
A VARS	adsorbent based vapour adsorption refrigeration system
COP	coefficient of performance
SRP	specific refrigeration power
RC	refrigeration capacity
C	specific heat; kJ/kg K

ΔH	reaction enthalpy; kJ/mol
m	mass of adsorbent; kg
n	moles of CO ₂ ; mol
P _e	equilibrium pressure; bar
ΔP	pressure differential; bar
Q	heat load; kJ
T	absolute temperature; °C
t	time; sec
η	efficiency

Subscripts

a	ambinet
cyl	cycle
ref	refrigeration
reg	regeneration
s	waste heat source
c	condenser
r	reactor

ТЕРМОДИНАМИЧКА СИМУЛАЦИЈА СИСТЕМА СОРПЦИОНОГ ХЛАЂЕЊА БАЗИРАНОГ НА АДСОРБЕНТУ CO₂

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Различити материјали као што су активни угљ, метално органски оквири, кварц и др. имају способност адсорпције и десорпције CO₂. Топлотна интеракција током ових процеса може да се користи за развој система сорпционог хлађења на бази адсорбента гаса. У раду је ова концепција примењена за анализу термодинамичких перформанси система сорпционог хлађења базираног на адсорбенту CO₂. Као адсорбенти су коришћени активни угаљ Norit RB3, PE MSM 41, AT MSM 41 и AF Silica. Од наведених адсорбентата направљени су парови на основу разлике у притиску која омогућава довољан проток CO₂ између два адсорбента на радној температури хлађења од 0⁰C, амбијенталној од 25⁰C и извора топлоте од 100⁰C. Термодинамичке перформансе система хлађења су упоређиване по паровима адсорбентата. Анализом су обухваћене следеће перформансе: ефекат хлађења, специфична снага хлађења, коефицијент перформансе, капацитет хлађења и други закон степена искоришћености. Ефекат хлађења код пара активни угаљ – PE MSM 41 је двоструко већи него код пара AT MSM 41 – AF-Silica. Такође је извршено поређење перформанси пара CO₂ – A-SRS и пара CO₂ – A-VARS што је доступно и у литератури. Утврђено је да је коефицијент перформансе код пара CO₂-A STS већи него код пара CO₂ – A VARS.