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Novel single-bed and twin-bed pressure swing adsorption systems

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ABSTRACT

Pressure swing adsorption (PSA) is one of the promising technologies for separation of gas mixtures. Multi-bed (poly-bed) PSA units are used to get both raffinate and extract products of high purities. Any multi-bed PSA cycle can be carried out in a single bed (or in multiple beds connected in parallel to a common header) with a requisite number of holding tanks and a single set of compressors and vacuum pumps. The performances of single-bed systems have been studied operating on the molecular gate, duplex, modified and moving-bed emulation of 3-bed PSA cycles, which are known to yield both products of high purities and to have potential for process intensification. The sizes of holding tanks were found to be unwieldy for commercial applications. Twin-bed systems have been proposed in which an additional complementary bed replaced the holding tanks. The twin-bed system facilitates also the scale-up of molecular-gate PSA, which was considered difficult to scale up to commercial units. A process-intensification index has been used to compare the performance of different configurations. The studies show that the performances of the 3-bed and modified duplex PSA configurations are far superior to the other two for CO_2 capture from flue gas.

1. Introduction

Several PSA cycles have been proposed to separate a binary mixture into raffinate and extract products of high purities. Two or more beds are employed except in the case of a 'molecular-gate' (or piston) PSA. For processing large volumes of a gas mixture, as in the case of hydrogen recovery from refinery gas streams, as many as 16 beds have been employed. A large number of beds have also been used for the CO_2 capture from a flue gas [1,2]. These beds are interconnected. They require a vast interconnecting pipe network, a large number of valves and flow controllers and may require a number of compressors and vacuum pumps. The interconnected beds impose restrictions on the durations of individual steps in a cycle and pose difficulties if one of these beds needs to be disconnected.

In principle, any PSA cycle can be implemented with a single bed and a required number of tanks for holding the effluents (from intermediate steps), for the recycling in the subsequent steps in a cycle. Multiple beds, connected in parallel to common headers with a single set of compressors and vacuum pumps, can be used if a large volume of gas is to be processed. Such a unit permits to set the optimum duration of the individual steps to achieve high productivity. The associated pipe network would be less complex, and also the number of valves and flow controllers required would be less. Any bed can be disconnected, if required, with ease without interrupting the operation.

Keller and Kuo [3] proposed 'molecular gate' (also called 'piston') PSA (MGPSA) that employs a single bed with a piston-cylinder device (hereafter referred to as piston-cylinder) at each end of the bed for holding and recycling the gas to the bed. Feed enters the bed at some intermediate position along the bed. It is shown to yield high purities of both products and high productivity. However, its scale-up for industrial applications is difficult because of the required size of the piston-cylinders.

A duplex PSA (DPSA) is known to yield both products of high purities [4,6–8]. However, its productivity is low and energy requirement is high. To overcome this deficiency, a modified duplex PSA (MDPSA) has been proposed [7,8]). Like the MGPSA and DPSA, the MDPSA is also capable of yielding high purities at a desorption pressure above 1 bar with a moderate pressure ratio [3,7,8]. A '3-bed PSA' and a '4-bed PSA', which emulate moving bed process, have been proposed to get both products of high purities [9]. These may be considered as the variants of the Skarstrom cycle. The 3-bed PSA is suitable for the systems with one weakly adsorbed component (large separation factor), whereas the '4-bed PSA' is suitable for the systems in which the components exhibit competitive adsorption [10]. Both of them require deep vacuum for

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Nomenclature

b_i	Langmuir parameter of component i (m^3/mol)
c_i	Gas-phase molar concentration of component i (mol/m^3)
C_{AA}	Annual cost of adsorbent (US $/(mol/s of CO_2 captured))
C_{AC}	Annual capital cost of adsorber (US $/(mol/s of CO_2 captured))
C_{AE}	Annual cost of energy (US $/(mol/s of CO_2 captured))
C_{AL}	Annual cost of component loss (US $/(mol/s of CO_2 captured))
D	Diameter of bed (mm)
D_L	Axial dispersion coefficient (m^2/s)
$\mathcal{E}$	Energy requirement (kWh/ton CO_2 captured)
I_{PI}	Process-intensification index, cost of capture (US $/TPDc CO_2 captured)
I'_{PI}	Process-intensification index (US$/y(mol/s) of CO_2 captured)
K	Blake–Kozeny constant
k_i	Linear driving force mass-transfer coefficient of component i (1/s)
L	Bed length (m)
L_e	Equivalent length of valve (m)
N	Number of components
n	Number of moles (mol)
P	Pressure (atm)
PH	Adsorption pressure (atm)
PI	Intermediate blowdown pressure (atm)
P_L	Desorption pressure (atm)
$\mathcal{P}$	CO_2 productivity (L STP/h kg)
q_i	Amount adsorbed in solid phase (mol/m^3)
$q_{s,i}$	Saturation constant of component i (mol/m^3)
q_i^e	Amount adsorbed in solid phase at equilibrium (mol/m^3)
R	Universal gas constant (J/mol K)
R_{CO2}	Recovery of CO_2
R_R	Raffinate recycle ratio
T	Temperature (K)
t	Time (s)
t_b	Final blowdown time (s)
t_{ib}	Intermediate blowdown time (s)
t_f	Feed time (s)
t_{pr}	Pressurization time (s)
t_{pu}	Purge time (s)
t_s	Stripping time (s)
v	Superficial velocity (m/s)
W	Work done (J)
Wc	Weightage factor to get total annual cost
W_R	Weightage factor to get total running cost
x	Mole fraction in gas phase
y	Mole fraction in solid phase
x_i	Mole fraction of component i in gas phase
x_f	Mole fraction of CO_2 in feed stream
x'_f	Mole fraction of CO_2 in mixed feed stream
x_R	Mole fraction of CO_2 in the input stream used for pressurization, purge
x_E	Mole fraction of CO_2 in the recycle stream to feed step
z	Distance measured from bed inlet (m)
z_{F-}	Bed position just before feed inlet
z_{F+}	Bed position just after feed inlet

Greek symbols

ε_B	Bed voidage
γ	Ratio of heat capacities Cp/Cv
ρ_g	Density of gas (kg/m^3)
μ	Viscosity of gas (kg/m s)

Subscripts

$b-$	Start of blowdown
$b+$	End of blowdown
$f-$	Start of feed
$f+$	Start of feed
i	Component number
pr−	Start of pressurization
pr+	End of pressurization
pu−	Start of purge
pu+	End of purge
$s-$	Start of stripping
$s+$	End of stripping

the regeneration to get both raffinate and extract products of high purities.

The objective of this work is to study the efficacies of single- and twin-bed PSA systems operating on the MGPSA, DPSA, MDPSA and 3-bed PSA cycles for CO_2 capture.

2. Single-bed systems

Fig. 1 shows the MGPSA, DPSA, MDPSA and 3-bed PSA, their single-bed configurations (SC) MG-SC, D-SC, MD-SC and 3-bed-SC respectively, and their pressure histories in the bed. The compressors or vacuum pumps and holding tanks with the single-bed systems are also shown in the figure. However, additional tanks or compressor/vacuum pumps and mass-flow controllers could be used for the flexibility and ease of operation. We have considered only the bare minimum required for the withdrawal of products continuously. The headers are shown to indicate that additional beds could be connected in parallel.

2.1. MG-SC

In an MGPSA, the pressure swing in the bed is sinusoidal. It is induced by unequal stroke lengths of the pistons. Its amplitude is dictated by the displacement volumes of the pistons and by the phase lag or lead of the relative movement of two pistons [11,12]. The pressure drop across the bed is negligible compared to the amplitude of the pressure swing.

Two holding tanks are required to replace the two piston-cylinders for the implementation of the cycle in a single bed (i.e., in MG-SC). The sinusoidal pressure variation in the bed could be achieved with the help of programmable mass-flow controllers and a compressor. The feed is introduced in both steps of the cycle but at different rates. In the first half (Step-1) of a cycle, the raffinate held in Tank-1 is used to purge the bed and the extract is drawn from the other end while the bed is being evacuated from P_H to P_L. A part of the extract is drawn as extract product and the rest is held in Tank-2. In the other half of cycle (Step-2), the extract held in Tank-2 is being recycled through the bed, and a part of the raffinate is drawn as raffinate product and the rest is collected into Tank-1 while the bed is being pressurized from P_L to P_H.

In fact, Keller and Kuo [3] claimed that a set of tanks and compressors could be used in place of the piston-cylinders to carry out the MGPSA. The raffinate and extract recycle rates in the MG-SC can be set as desired with ease unlike in MGPSA. However, the energy requirement would be higher for the MG-SC than for the MGPSA since the recycling of the gas is almost in a reversible manner in the MGPSA unlike in the MG-SC.