Adsorption of Carbon Monoxide-Nitrogen, Carbon Monoxide-Oxygen, and Oxygen-Nitrogen Mixtures on Synthetic Zeolites

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Experimental results for the adsorption of the binary gas mixtures oxygen-nitrogen, oxygen-carbon monoxide and nitrogen-carbon monoxide on two synthetic zeolites are reported. In all of these experiments the temperature was —200°F. and the total pressure was 1 atm. Also reported are the isotherms for the three pure gases on the two zeolites at —200°F. The results indicate that these zeolites have a surface selectivity which is independent of any sieving effect based on the size of the adsorbed molecules. It does not appear that the strong separations obtained can be explained in terms of the van der Waals forces which are generally believed to be dominant in physical adsorption. The available methods of predicting binary adsorption data from the pure gas isotherms have been examined.

Data on the adsorption equilibria of gas mixtures are important both from a practical viewpoint for the design of gas adsorbers and on a theoretical basis for the understanding of the interactions between gases and solid surfaces. Compared to the voluminous data in the literature on pure gas adsorption, very little data are available on the adsorption of gas mixtures. For a complete understanding of the behavior of gas molecules in the sphere of influence of a solid, the forces of molecular interactions must be quantitatively treated. Such a statistical mechanical treatment is unfortunately not yet available and, therefore, the description of adsorption has been in terms of simplified models and measurable experimental variables. Whereas considerable success has been achieved in the description of pure gas adsorption, the simplifying assumptions of many of these models cause them to fail when they are extended to gas mixtures. An excellent summary of the literature on adsorption up to about 1959 is given in the monograph of Young and Crowell (*32*).

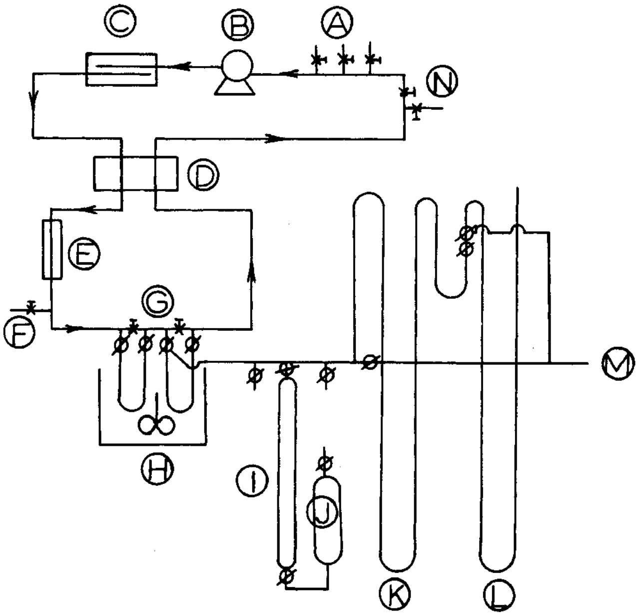

Fig. 1. Schematic flow diagram. A. gas inlets, B. gas pump, C. mixing cylinder, D. thermalconductivity cell, E. rotameter, F. chromatographic sample take-off, G. adsorption columns, H. constant temperature bath, I. graduated cylinder, J. mercury reservoir, K. balancing manometer, L. read-out manometer, M. to cold trap and vacuum pump, N. vent or recycle control valves.

More recently proposed theories for adsorption equilibria are those of Prausnitz and Myers (*24*, *30*), Cook and Basmadjian (*11*), and Grant and Manes (*19*). In the present paper experimental adsorption-equilibria data at —200°F. for six binary gas mixture-adsorbent systems are presented together with the corresponding pure gas data. The adsorbents used were Linde Molecular Sieves. On the basis of this data the applicability of the best known and more recently proposed gas-mixture adsorption prediction methods are compared.

DESCRIPTION OF THE APPARATUS

Figure 1 is a schematic flow diagram of the apparatus. Two pure gases in addition to helium could be admitted through the microregulating valves to the copper tube recycling loop. This loop contained a gas pump (automobile electric fuel

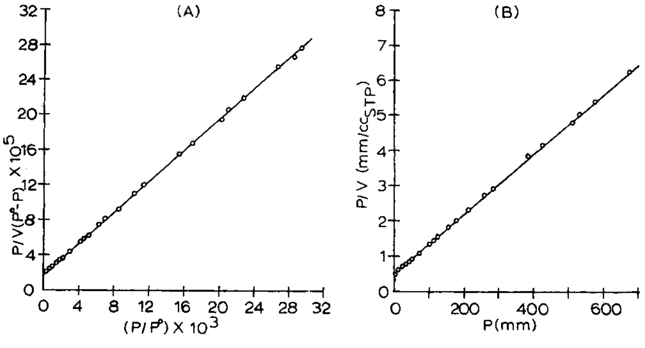

Fig. 2. Langmuir and BET correlations for the adsorption of oxygen and molecular sieve 5A at —200°F. (A) BET correlation, (B) Langmuir correlation.

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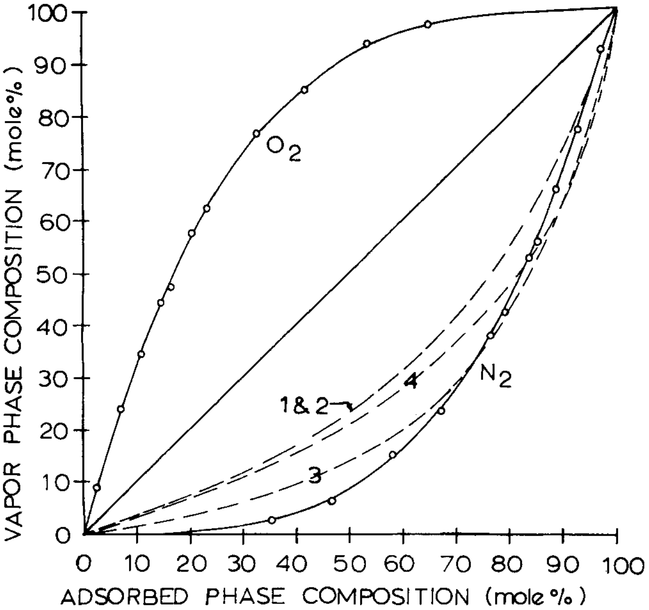

Fig. 3. Adsorption phase diagram. Oxygen-nitrogen on molecular sieve 5A at —200°F. and 1 atm. —○— Experimental, - - - nitrogen predictions: (1) Langmuir, (2) BET, (3) Prausnitz and Myers, (4) Cook and Basmadjian.

pump), a small mixing cylinder, a thermal conductivity cell, a rotameter, an outlet connection to the gas chromatograph, and a set of valves and stopcocks which allowed the gas to by-pass or be sent through the adsorption columns. These glass columns were provided with thermocouple wells to measure the temperature of the gas as it emerged from the adsorbent beds at the bottoms of the U-tubes. The adsorption columns were also connected to a glass system used to measure the pressure, volume and temperature of gas adsorbed or desorbed. The mercury level in the left-hand leg of the balancing manometer was always brought to the same reference level to yield a constant volume, and the pressure reading was obtained from the right-hand manometer. The adsorption columns were immersed in a constant temperature bath containing dichlorodifluoromethane. A proportional temperature controller in conjunction with an electric heater and a liquid nitrogen cold finger was used to regulate the temperature to better than 0.1°F. In order to ascertain when equilibrium was established a thermal conductivity cell constantly compared the gas entering the adsorption columns to the stream leaving the columns. When these streams were identical for the length of time required for one complete recycle the system was judged to be at equilibrium.

Experiments using gas mixtures were carried out as follows. The cold dead volume of each of the adsorption columns was determined by measuring the pressure change when helium was expanded into this space. Feed gas containing roughly the desired vapor phase composition was admitted to the system by regulating the pure gas inlet rates. This mixture was initially allowed to vent after passing through the adsorption columns. In a number of cases the adsorbent was first saturated with one of the pure gases before admitting the mixtures. The admission of gas was then stopped and the gas mixture was recycled until equilibrium was established. The columns were then sealed off, removed, and attached to the glassware manifold where the adsorbed phase was desorbed and the final pressure and glassware volume were recorded. Samples of the desorbed gas and the vapor phase were analyzed in the gas chromatograph. The dead volume of the columns at ambient temperature was then determined permitting equilibrium compositions and volumes adsorbed to be calculated. Small corrections were included for the residual adsorption at ambient temperature, which was determined experimentally. The composition data obtained are believed to be good to ±1% in the 10 to 90% composition range and the volume adsorbed to ±3% of the calculated values.

For the determination of the pure gas isotherms, the glassware, adsorption columns, and constant temperature bath served as a standard BET type of apparatus. A more detailed description of the apparatus and the calculations are given elsewhere (*12*).

CHARACTERISTICS OF ADSORBENTS

The adsorbents used in the study were synthetic zeolites (Linde molecular sieves, types 5A and 10X). These types of adsorbents are unique in that they have defined dimensions and pore structures which have been determined from X-ray diffraction data (*3, 7, 8, 14, 31*). Accessibility of adsorbate molecules to the porous structure is determined by the adsorbates critical diameter and the effective diameter of the windows of the zeolites. If the adsorbate molecules have critical diameters substantially less than those of the windows leading into the cavities of these crystals they are usually adsorbed reversibly and rapidly. Molecular sieve types 5A and 10X have effective window diameters of about 5Å. and 8Å. respectively. The adsorbates have critical dimensions (diameter of the circumscribed circle of the cross section of minimum area) as follows: oxygen, 2.8Å.; nitrogen, 3.0Å; carbon monoxide, 2.8Å. (*7*). Thus in all cases the adsorbate molecules have free access to the inner pore structure of the sieves and the same total surface area is available to each of the adsorbates.

The adsorbents were obtained in 1/16 in. diameter pellets containing an inert bonding material (20% by weight) which has been found to have an insignificant effect on the adsorptive properties (*16*). Regeneration consisted of heating the adsorbents in vacuum ($< 10^{-3}$ mm. Hg.) at 200°C. for a period of 14 hr. They were then stored in a desiccator in capped vials. For each run portions were weighed out by difference and then were held in the adsorption columns overnight under vacuum at room temperature. A fresh sample was used for every pure gas-isotherm determination and each mixture-point determination.

TABLE 1.

	Molecular Sieve 5A	Molecular Sieve 10X
Surface Area Σ (sq.m./g.)	572.2	676.2
Monolayer Volume V_m (cc.STP/g.)	130.9	154.7
Layers at Saturation *n*	1.25	1.27

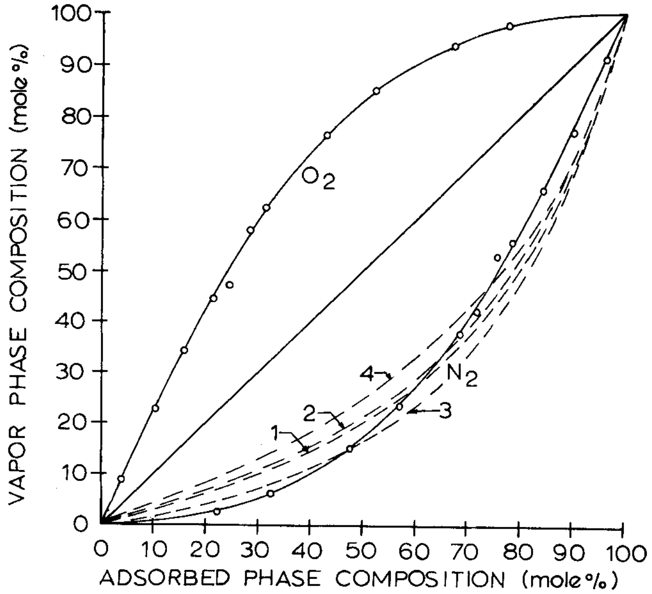

Fig. 4. Adsorption phase diagram. Oxygen-nitrogen on molecular sieve 10X at —200°F. and 1 atm. —○— Experimental - - - nitrogen predictions: see Figure 3.

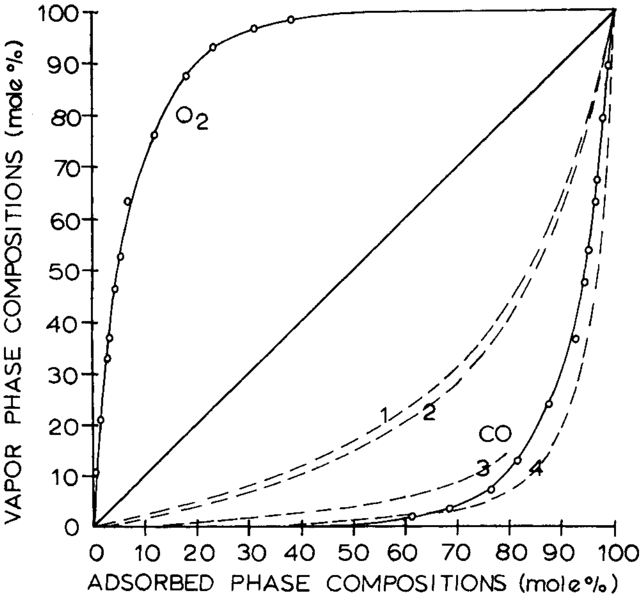

Fig. 5. Adsorption phase diagram. Oxygen-carbon monoxide on molecular sieve 5A at —200°F. and 1 atm. —○— Experimental - - - carbon monoxide predictions: see Figure 3.

TABLE 2. PURE GAS ADSORPTION DATA

$T = -200$°F.

P(mm. Hg.) V(cc.STP/g.)

oxygen		nitrogen		carbon monoxide	
P	*V*	*P*	*V*	*P*	*V*
		Molecular Sieve 5-A			
				0	46.3
2.6	8.2	0.8	25.9	1.7	53.9
9.0	18.1	3.0	44.8	2.9	78.1
17.2	28.4	10.2	61.9	3.9	81.7
29.3	41.1	28.2	77.6	4.8	87.4
47.0	54.6	40.8	82.4	8.0	89.5
54.7	60.4	50.2	84.6	11.9	94.5
76.0	69.6	62.1	87.0	32.3	99.7
116.7	79.8	105.9	92.9	49.9	101.8
160.7	86.9	166.1	95.6	82.0	103.6
215.9	92.5	200.9	95.9	141.7	105.3
288.0	98.6	297.0	98.9	211.1	107.0
389.8	100.9	405.5	99.8	252.7	107.9
513.1	106.7	490.7	101.2	367.6	108.7
578.8	107.0	604.8	102.1	468.1	110.0
720.6	111.0	643.4	102.1	522.4	110.4
881.1	112.1	783.1	103.1	653.0	111.4
1003.7	113.6			669.3	111.5
1153.8	116.3			828.5	111.7
1418.7	118.4				
1601.7	119.6				
		Molecular Sieve 10-X			
4.5	4.7	0.6	14.1	0.9	33.5
22.6	12.6	13.1	38.9	3.4	40.6
48.8	20.8	21.4	47.5	14.7	68.4
89.2	32.9	41.4	55.8	30.5	78.6
148.1	48.7	57.5	61.2	46.7	86.3
210.4	63.7	135.1	77.5	68.4	94.3
257.8	72.8	183.5	83.1	97.8	98.8
305.3	80.0	297.4	91.3	151.3	105.8
381.2	89.1	390.6	95.6	180.2	107.9
451.0	96.1	486.1	98.5	270.9	113.4
537.8	101.6	496.8	100.0	309.5	114.7
698.9	110.1	596.7	102.6	423.2	118.5
866.6	116.2	625.0	102.4	544.6	121.4
1335.7	126.4	772.4	106.0	638.1	123.4
		899.8	108.0	734.7	124.8
				902.2	127.6
				1129.1	130.1

The surface areas were determined by the adsorption of nitrogen at liquid-nitrogen temperature, using the n-layers B-E-T equation (9) as described by Joyer, et al. (22). This was necessary because the data did not give a satisfactory fit when correlated by the infinite layers B-E-T equation or the Langmuir equation. The areas (Σ), monolayer coverage (V_m) and corresponding number of adsorbed layers at saturation (n) are shown in Table 1.

PURE GAS ADSORPTION

Adsorption isotherms were determined for nitrogen, carbon monoxide, and oxygen on molecular sieve types 5A and 10X at —200°F. (Table 2). For all three adsorbents the adsorption appeared to be completely reversible as determined from the adsorption-desorption behavior. The B-E-T and Langmuir plots of Figure 2 were calculated from the data for oxygen on molecular sieve type 5A which was selected as a typical example of the relatively

TABLE 3. TOTAL MIXTURE VOLUME ADSORBED

$T = -200$°F. $P = 1$ atm.

Y — vapor phase mole per cent
X — adsorbed phase mole per cent
V_{tot} — total volume adsorbed (standard cc./g. of adsorbent)

Molecular Sieve Type 5A			Molecular Sieve Type 10X		
Y_1	X_1	V_{tot}	Y_1	X_1	V_{tot}
		Oxygen (1)—Nitrogen (2)			
0	0	103.0	0	0	105.8
8.8	2.6	102.1	8.8	4.0	104.2
22.9	7.1	100.7	22.9	10.2	105.7
34.2	11.0	103.1	34.2	15.8	103.0
44.4	14.6	103.6	44.4	21.7	107.4
47.2	16.4	100.1	47.2	24.5	106.8
57.7	20.5	102.1	57.2	28.3	106.8
62.3	23.6	104.5	62.3	31.4	106.6
76.4	32.7	104.5	76.4	43.0	107.0
85.0	41.9	103.8	85.0	52.2	107.3
93.8	53.6	101.7	93.8	67.2	108.9
97.5	64.8	103.6	97.5	77.7	107.3
100.0	100.0	110.7	100.0	100.0	113.0
		Oxygen (1)—Carbon Monoxide (2)			
0	0	111.8	0	0	125.5
10.9	0.8	109.7	10.9	1.9	122.6
21.0	1.7	106.1	21.0	3.7	122.5
32.9	3.0	109.7	32.9	7.0	123.3
37.1	3.4	109.6	37.1	7.8	122.7
46.5	4.6	109.9	46.5	10.3	123.9
52.7	5.6	108.2	52.7	12.6	121.4
63.7	7.2	109.3	63.7	16.7	120.8
76.2	12.4	105.4	76.2	23.0	118.7
87.4	18.5	107.5	87.4	32.8	118.4
93.0	23.5	106.3	93.0	39.5	114.6
96.7	31.6	103.4	96.7	47.0	113.0
98.2	38.6	104.2	100.00	100.00	113.0
100.0	100.0	110.7			
		Nitrogen (1)—Carbon Monoxide (2)			
0	0	111.8	0	0	125.5
13.0	0.7	109.6	13.0	1.5	125.6
27.0	3.1	109.3	27.0	6.7	122.8
33.1	3.8	109.4	33.1	7.4	121.5
42.2	6.1	109.5	42.2	10.4	123.0
48.5	6.3	106.9	54.8	14.7	119.2
54.8	7.9	108.3	65.2	20.0	119.4
65.2	11.0	107.8	77.5	30.3	116.1
77.5	19.4	106.4	87.9	42.5	111.4
83.3	24.7	104.6	94.3	58.2	109.6
87.9	27.9	104.4	97.9	75.7	106.8
94.3	41.3	104.5	100.00	100.0	105.8
97.9	55.6	100.8			
100.0	100.0	103.0			

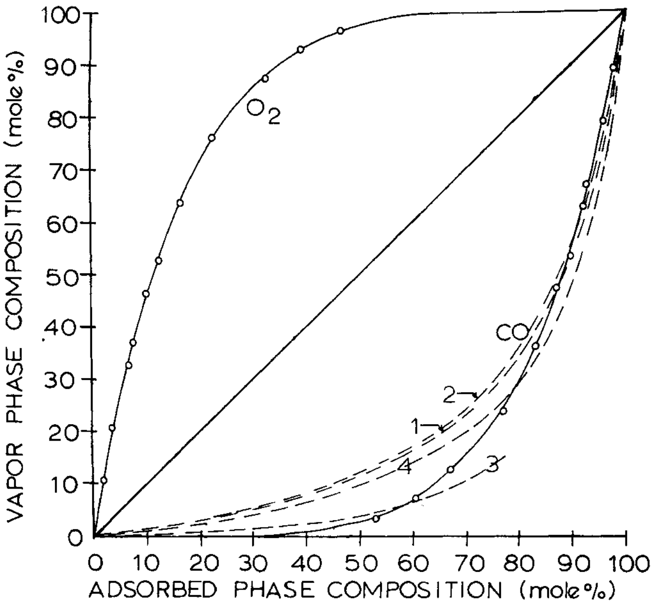

Fig. 6. Adsorption phase diagram. Oxygen-carbon monoxide on molecular sieve 10X at —200°F. and 1 atm. —○— Experimental - - - carbon monoxide predictions: see Figure 3.

good correlation of the —200°F. data obtained by either method. Attempts to correlate the data for these synthetic zeolites by modifications of the potential theory as proposed by Lewis and co-workers (*26*), Maslan, Altman, and Aberth (*28*) or by Dubinin, et al. (*5, 13, 16*) met with little success.

ADSORPTION OF GAS MIXTURES

Adsorption of the binary mixtures of oxygen-nitrogen, oxygen-carbon monoxide, and nitrogen-carbon monoxide on molecular sieve types 5A and 10X at 1 atm. and —200°F. was studied. On Figure 3 to 8 are plotted the adsorption phase diagrams for three mixtures on the two adsorbents. The data for the total volume of these mixtures adsorbed are given in Table 3.

It is interesting to note that for the oxygen-nitrogen system the condensed phase is enriched in nitrogen although in vapor-liquid equilibrium (at similar temperatures and pressures) oxygen is the less volatile of the two gases. On the basis of the pure gas isotherms, however, it is apparent that nitrogen exhibits a sharper and higher knee-bend than oxygen, suggesting that the interactions between the nitrogen molecules and the surface are stronger than the interactions between the oxygen molecules and the surface. Similarly, one might predict the selectivity of carbon monoxide over oxygen or nitrogen. The strong separation of the carbon monoxide-nitrogen systems, however, is surprising.

PREDICTION OF THE TOTAL VOLUME ADSORBED

In a study of the adsorption of hydrocarbons on both silica gel and carbon, Lewis, et al. (*25*) found that:

$$\frac{V_{a1}}{V^o_{a1}} + \frac{V_{a2}}{V^o_{a2}} = 1 \qquad (1)$$

where V_{ai} and V^o_{ai} denote the volumes of gas adsorbed from the mixture and pure gas, respectively, at the same total pressure and constant temperature.

This empirical relation has been found to correlate the low temperature adsorption of oxygen and nitrogen on activated carbon (*1*), and the adsorption of carbon dioxide and some low molecular weight hydrocarbons on silica gel and carbon (*21*). Kammermeyer, Kaser, and Rutz (*23*), on the other hand, found that the correlation did not hold for the adsorption of propane-carbon dioxide mixtures on porous glass. Figure 9 indicates that this empirical method should be of some value for low temperature adsorption on synthetic zeolites. The solid line is a plot of Equation (1) and the maximum deviation is approximately 10%.

Reasonable values for the total volume of mixture adsorbed were also obtained from the pure gas data by the Langmuir or B-E-T gas mixture adsorption equation (32) and by the method of Cook and Basmadjian (*11*).

PREDICTION OF THE RELATIVE VOLATILITY

The relative volatility (α) is defined as

$$\alpha = (Y_2/X_2)/(Y_1/X_1) = Y_2X_1/Y_1X_2 \qquad (2)$$

where Y and X are the vapor and adsorbed phase compositions, respectively. The Langmuir mixture equations as developed by Markham and Benton (*27*) and the B-E-T theory as extended to gas mixtures by Hill (*20*) were used to attempt to predict the behavior of the mixtures from pure gas adsorption parameters. On Figures 3 to 8, curves 1 and 2 show the results for the Langmuir and B-E-T predictions, respectively, for the six systems. In general the results are poor and for the nitrogen-carbon monoxide system the prediction is definitely unsatisfactory. Potential theory correlations as extended to gas mixtures by Lewis, et al. (*25*), by Maslan and co-workers (*28*), by Bering, et al. (*5*), and by Grant and Manes (*19*) also gave poor results when applied to the present systems.

Also investigated was the thermodynamic prediction method of Prausnitz and Myers (*30*) in which the basic concepts are that (a) in adsorption equilibrium the spreading pressures of the adsorbates will be equal and (b) in an ideal solution the partial pressure of an adsorbed component is given by the product of its mole fraction in the adsorbed phase and the pressure it would exert as a pure adsorbate at the same temperature and spreading pressure as those of the mixture. The results of this method are shown by curves 3 on Figures 3 to 8. The difficulty encountered in evaluating the spreading pressure in the low pressure region was handled by fitting a Langmuir equation to the low pressure data and using this equation to calculate the spreading pressures. The predictions are good for the oxygen-nitrogen systems, relatively poor for the nitrogen-carbon monoxide systems and reasonably good for that portion of the oxygen-carbon monoxide system

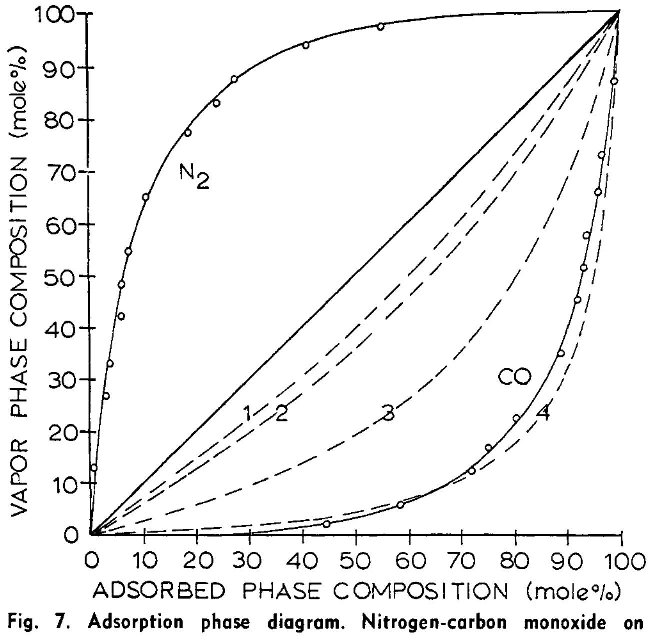

Fig. 7. Adsorption phase diagram. Nitrogen-carbon monoxide on molecular sieve 5A at —200°F. and 1 atm. —○— Experimental - - - carbon monoxide predictions: see Figure 3.

which could be calculated from the available pure gas data. A major disadvantage of this method is that it requires pure gas adsorption data far above the total binary mixture pressure in order to obtain equal spreading pressures for both components. In the present case where it was desired to predict data at 760 mm., experimental data were available only up to 1,200 mm. and an extrapolation was attempted to about 3,000 mm. Even so, the prediction of the oxygen-carbon monoxide systems could be made only to a vapor phase composition of about 15% carbon monoxide.

Cook and Basmadjian published in 1965 (*11*), a semi-empirical method of predicting binary adsorption equilibria from the pure component isotherms. They found their method was applicable to systems with variable relative volatilities, valid at low and high pressures, and not dependent upon the validity of Lewis' equation for predicting the total volume adsorbed [Equation (2)]. The method was reported to have been tested successfully on a large number of systems with charcoal as the adsorbent and one case in which molecular sieve type 5A was used ($H_2 - D_2$ adsorbed at 75 to 90°K. and pressures below 1 atm.). The approach failed, however, in the region of multilayer adsorption and for systems exhibiting azeotropes.

The predictions obtained by the method of Cook and Basmadjian for all six binary systems are plotted on their respective adsorption phase diagrams (line 4, Figures 3 to 8). Good agreement is obtained with the possible exception of the oxygen-nitrogen systems, both of which have isotherms that intersect below 1 atm. Cook and Basmadjian reported similar discrepancies when intersecting isotherms were encountered.

It is interesting to note that this method, when applied to the oxygen-nitrogen systems, would predict an adsorption azeotrope at some higher total pressure. This behavior would be in harmony with the suggestion of various investigators that only the first adsorbed layer is strongly affected by the solid's force field, in fact, that starting with the second layer, the adsorbed phase assumes the bulk liquid composition. Since oxygen is richer in the condensed phase for the vapor-liquid equilibria of oxygen-nitrogen one might picture the build up of oxygen-rich layers with increasing pressure to eventually overcome the effects of the nitrogen-rich first layer and thus arrive at an apparent azeotrope.

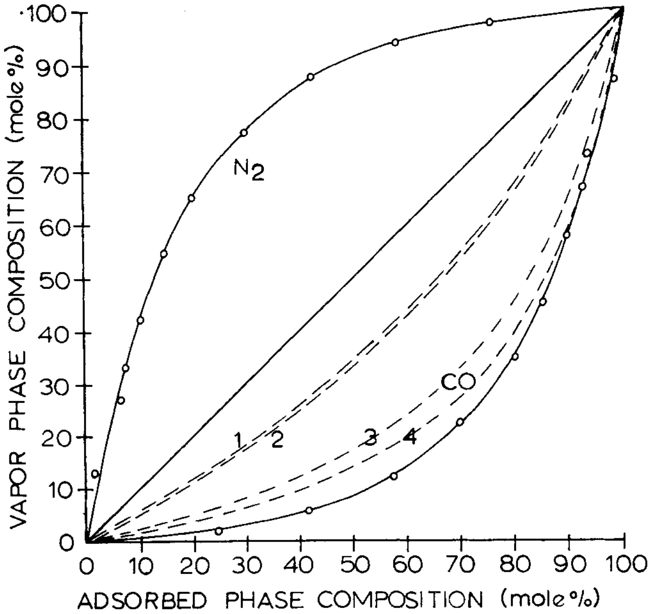

Fig. 8. Adsorption phase diagram. Nitrogen-carbon monoxide on molecular sieve 10X at —200°F. and 1 atm. —○— Experimental - - - carbon monoxide predictions: see Figure 3.

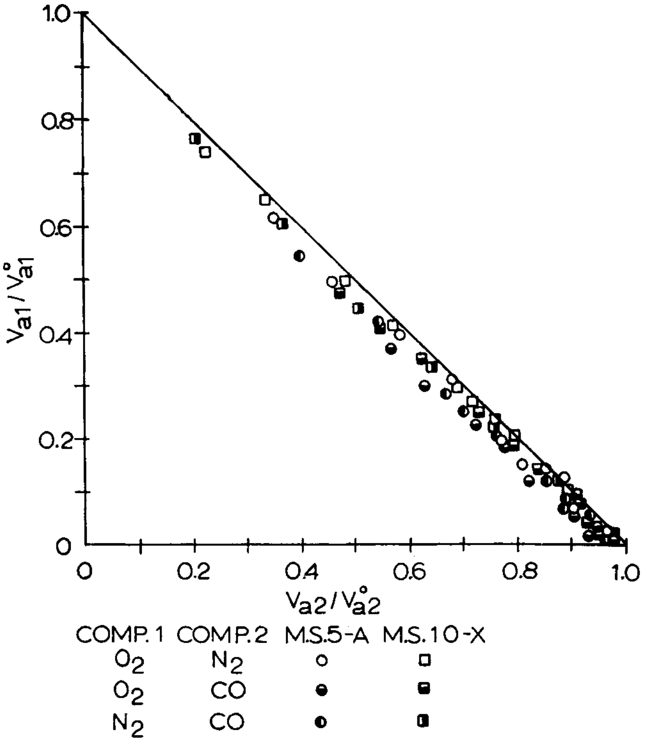

Fig. 9. Lewis correlation of the total volume adsorbed, $V_{a1}/V^{\circ}_{a1} + V_{a2}/V^{\circ}_{a2} = 1$.

This semi-empirical approach would be the recommended method for predicting gas mixture adsorption on zeolites at cryogenic temperatures, except perhaps for cases where the isotherms intersect. Although the thermodynamic approach of Prausnitz and Myers is somewhat better for the oxygen-nitrogen systems studied here, the semi-empirical method is much better for the nitrogen-carbon monoxide systems. Furthermore, the method of Cook and Basmadjian does not require pure component data far above the total pressure of the mixture.

DISCUSSION OF RESULTS

The synthetic zeolites studied have been shown to have strong adsorption selectivity which is not related to any sieving effect due to differences in molecular size of the adsorbates. In all the binary mixtures a stronger separation was obtained with the adsorbent having the smaller effective pore size. Although it may be that this effect cannot entirely be assigned to the pore size difference it seems likely that the pore size is an important factor. The smaller pores tend to restrict the number of layers that can be formed on the surface, thus producing an overall effect more closely allied to the separation in the first layer. In a detailed study of the adsorption of a mixture of acetone and chloroform vapors on silica gel Bering claimed (*15*) that adsorbent selectivity is manifested only within the first adsorption layer. The composition of the second and all subsequent layers assumed the composition of a normal bulk solution. The restricting of the number of adsorption layers in the case of synthetic zeolites suggests that adsorption models which tend to minimize the adsorbent's force field and assume bulk-liquid type of behavior are not likely to be as successful for these adsorbents as for other types of adsorbents.

The observed surface selectivity must be related to the interaction of the gas molecules with the solid surface and/or the interaction between adjacent adsorbate molecules. For the present systems such selectivity is not easily explained in terms of the nonspecific van der Waal's interactions. The best example of this is found in the nitrogen-carbon monoxide systems. The two adsorbates have very similar physical properties: normal boiling point, liquid density, latent heats, critical temperatures, and pressures, and show similar pure gas adsorption behavior on the zeolite. Although carbon monoxide does have a small permanent dipole moment ($\sim 0.1D$) the relative magnitude of the effect due to the permanent dipole compared to the effect due to the mutually induced dipole is 0.003 to 67 (*17*).

Mulliken (*29*) has suggested that charge-transfer forces may be comparable in importance to London's dispersion forces in some adsorption systems. These forces are believed to create molecular complexes by a complex resonance mechanism, meaning a quantum-mechanical resonance between a no-bond structure and a structure with a bond between the two molecules. Such a bonding, which falls intermediate between what are generally termed physical and chemical adsorption, would be most likely in a highly ionic system such as found with zeolites.

Other investigators have also found the process of physical adsorption to be inadequately described by dispersion interactions. Graham (*18*) made very careful measurements of the heats of adsorption on three different types of carbon crystals. He says "it seems probable that interaction energies other than those of dispersion forces may arise from the peculiar electronic properties of graphitic carbon. For example, nuclear magnetic resonance measurements have demonstrated an interaction of unpaired electrons in the surface of graphitic carbon with adsorbed molecules."

Another approach to the problem being discussed here is the structural model of physical adsorption presented by Cook, Pack, and Oblad (*10*). Like the no-bond charge-transfer theory this approach proposes the sharing of electrons in the formation of something less than a chemical bond. The adsorption potential is associated with the elimination of unbonded electron orbitals on the adsorbent surface and surface strains due to heterogeneities and impurities. According to this theory a more basic substance, that is one which can more easily donate an electron pair, will have the higher structural adsorption potential. In their paper the authors examined Arnold's data (*2*) for the adsorption of oxygen-nitrogen mixtures on anatase. Arnold found that mole fraction of nitrogen was the larger in the adsorbed phase at low pressures but was the smaller at higher pressures, which is also the predicted result for this mixture on synthetic zeolites. These low-pressure results are explicable in terms of the structural-adsorption theory in so far as nitrogen, due to its electronic structure, would be expected to have a greater tendency to coordinate with the atoms in an unsatisfied crystal surface than oxygen. Cook, Pack, and Oblad (*10*) applied this theory quantitatively to Arnold's data for the well defined anatase surface and obtained excellent agreement.

Recently Benson and King (*4*) published a report on the electrostatic aspects of physical adsorption. Since the work of Brunauer, Emmett, and Teller (*9*) electrostatic forces have not generally been considered important in physical adsorption. Benson and King, however, claim electrostatic interactions are quite important for many adsorbents, and in particular for zeolites. They present evidence that suggests these adsorbents have strong electric fields which are dominant in determining their adsorption properties.

At present, there is not enough experimental evidence to determine which, if any, of the above approaches is correct in its description of the adsorption mechanism. However, the results of the present study do confirm the fact that consideration of van der Waals dispersion and induction forces alone is not adequate for interpretation of physical adsorption on synthetic zeolites.

NOTATION

n = number of adsorbed layers
P = equilibrium adsorption pressure (mm. Hg.)
P^o = vapor pressure (mm. Hg.)
V_{ai} = volume of gas i adsorbed from mixture (stand. cc./g.)
V^o_{ai} = volume of pure gas adsorbed (stand. cc./g.)
V_m = volume of gas for adsorbed monolayer (stand. cc./g.)
X = mole fraction in adsorbed phase
Y = mole fraction in vapor phase
Σ = surface area (sq. m./g.)

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Manuscript received November 29, 1967; revision received April 12, 1968; paper accepted April 24, 1968.