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T. Victor Lee[a]; Jan-Chan Huang[ab]; Daniel Rothstein[a]; Richard Madey[a]
[a] Department OF PHYSICS, KENT STATE UNIVERSITY, KENT, OHIO [b] General Electric Co., Schenectady, New York

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Adsorption of Binary Mixtures of Ethane and Acetylene on Activated Carbon

T. VICTOR LEE, JAN-CHAN HUANG,* DANIEL ROTHSTEIN, and RICHARD MADEY

DEPARTMENT OF PHYSICS
KENT STATE UNIVERSITY
KENT, OHIO 44242

Abstract

Dynamic measurements of the adsorption of binary mixtures of ethane and acetylene (and also of each gas alone) in a helium carrier gas were made on an (Columbia 4LXC 12/28) activated carbon adsorber bed at 25°C. The adsorption capacities of the activated carbon for the pure gases and for each component in the mixtures are extracted from the transmission curves by the use of a mass balance equation. Transmission is the ratio of the concentration at the outlet of the adsorber bed to that at the inlet. The adsorption isotherms for pure ethane and acetylene can be represented by a modified Langmuir isotherm known as the Chakravarti-Dhar isotherm at gas concentrations up to at least 4.2×10^{-7} mol/cm^3 (viz., 7.8 mmHg). The gas–adsorbate equilibrium composition and the adsorption capacity of each component in the binary mixture of ethane and acetylene are estimated from the corresponding single-component isotherms by applying ideal adsorbed solution theory (IAST). The fact that the estimated values of the adsorption capacities and the gas-adsorbate equilibrium compositions are in good agreement with those extracted from the measurements for the binary mixtures of ethane and acetylene confirms that the ethane–acetylene system forms an ideal adsorbed phase on activated carbon at a pressure of about 7.3 mmHg and a temperature of 25°C.

INTRODUCTION

Gas adsorption on solid adsorbents is an important process for the separation of gases. In the field of gaseous separations, adsorption is used to

*Present address: General Electric Co., Schenectady, New York 12308.

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dehydrate natural gases (*1, 2*), to dehumidify air (*3*), to remove impurities (e.g., carbon dioxide, water, methane) from industrial gases such as hydrogen (*4, 5*), to recover valuable solvent vapors from dilute mixtures with air and other gases (*6*), and to fractionate mixtures of low-molecular-weight hydrocarbon gases (*7–9*) containing such substances as methane, ethylene, ethane, propylene, and propane. A better understanding of the role of adsorption phenomena in chemical processes and mechanisms of physical separation has become increasingly important in recent years.

The design of large-scale adsorption separators requires a knowledge of both the adsorption capacity of the adsorbent for individual components and the gas–adsorbate equilibrium compositions in binary mixtures. In most practical cases the desired equilibria are for gaseous mixtures rather than for a pure gas. Thus, the development of a technique for estimating the equilibrium behavior of the adsorption of gaseous mixture from the known adsorption isotherms of the corresponding pure components is of particular interest.

Meyers and Prausnitz (*10*) pointed out that the concept of an adsorbed phase clarifies the meaning of an ideal solution behavior among components adsorbed at low coverage on adsorbents such as activated carbon. The ideal adsorbed solution theory (IAST) assumes that components in adsorbed mixtures have the same thermodynamic state as the pure adsorbed components at the same temperature and spreading pressure. Spreading pressure in a two-dimensional system is analogous to pressure in a three-dimensional system.

Huang and Madey (*11*) showed that potential theory offers a method for testing the interaction between the adsorbed species of binary or multi-component mixtures, and found that the adsorbed phase of binary mixtures of ethane and acetylene at low concentrations on activated carbon at 25°C behaves as an ideal solution. In this paper we apply IAST to estimate the adsorption equilibrium properties (viz., the adsorption capacity, the gas–adsorbate equilibrium composition, and the activity coefficients) for ethane–acetylene binary mixtures from the corresponding single-component (ethane and acetylene) isotherms. We compare the estimated values with those extracted from measurements of the time-dependent transmission of binary mixtures of ethane and acetylene and also of each gas alone in a helium carrier gas flowing through an activated carbon adsorbed bed at 25°C. Transmission is the ratio of the outlet concentration to that at the inlet of the adsorber bed. We calculate the adsorption capacities of the activated carbon for the pure gases and for each component in the mixtures from the transmission curves by the use of a mass balance equation.

THERMODYNAMICS OF THE ADSORBED PHASE

For a three-dimensional homogeneous fluid phase, the fundamental equations for the internal energy and the Gibbs free energy are (*12, 13*)

$$d(nU) = Td(nS) - Pd(nV) + \Sigma\mu_i dn_i \tag{1}$$

$$d(nG) = -(nS)dT + (nV)dP + \Sigma\mu_i dn_i \tag{2}$$

where U, G, S, V, and P are the molar internal energy, Gibbs free energy, entropy, volume, and pressure, respectively; μ_i is the chemical potential of component i, n_i is the number of moles of component i per unit volume of the fluid, and the total number of moles per unit volume of the fluid is given by $n = \Sigma n_i$. The summation is over all chemical species.

In gas–solid adsorption the adsorbed phase on the solid adsorbent is considered as a two-dimensional phase with thermodynamic properties analogous to those in a three-dimensional phase. Meyers and Prausnitz (*10*) proposed expressions analogous to Eqs. (1) and (2) for the internal energy and Gibbs free energy of the adsorbed phase:

$$d(n^a U) = Td(n^a S) - \pi d(n^a a) + \Sigma\mu_i^a dn_i^a \tag{3}$$

$$d(n^a G) = -(n^a S)dT + (n^a a)d\pi + \Sigma\mu_i^a dn_i^a \tag{4}$$

Since the pressure P and the volume V in Eqs. (1) and (2) are not appropriate coordinates for a two-dimensional phase, the pressure P is replaced by the spreading pressure π and the molar volume V by the molar area a. In Eqs. (3) and (4), the superscript a denotes the adsorbed phase.

The intensive variables for the Gibbs free energy are the temperature, spreading pressure, and composition. Upon application of Euler's theorem (*14*) to Eq. (4), the Gibbs free energy may be expressed as

$$n^a G = \Sigma n_i^a \mu_i^a \tag{5}$$

or

$$G = \Sigma x_i \mu_i^a \tag{6}$$

where μ_i^a represents the chemical potential of component i in the adsorbed phase, and x_i ($\equiv n_i^a/n^a$) is the mole fraction of component i in the adsorbed

phase. Differentiation of Eq. (5) provides an alternative expression for $d(n^a G)$:

$$d(n^a G) = \sum \mu_i^a dn_i^a + \sum n_i^a d\mu_i^a \tag{7}$$

Comparison of Eq. (7) with Eq. (4) reveals that

$$(n^a S)dT - (n^a a)d\pi + \sum n_i^a d\mu_i^a = 0 \tag{8}$$

Equation (8) is the Gibbs-Duhem Equation for the two-dimensional phase. We can obtain the Gibbs adsorption isotherm from Eq. (8) at constant temperature:

$$-(n^a a)d\pi + \sum n_i^a d\mu_i^a = 0 \qquad (\text{constant } T) \tag{9}$$

In gas–solid adsorption equilibrium, the two-dimensional adsorbed phase is always in equilibrium with the gas phase. The condition for equilibrium is that the chemical potentials of each component in both the adsorbed and gaseous phases are the same; that is,

$$\mu_i^a = \mu_i^g \tag{10}$$

where μ_i^g represents the chemical potential of component i in the gas phase. For any change in the equilibrium conditions, one must have

$$d\mu_i^a = d\mu_i^g \equiv RTd(\ln f_i^g) \tag{11}$$

In an ideal gas, the fugacity f_i^g of component i is equivalent to its partial pressure P_i $(= y_i P)$, where y_i is the mole fraction of component i in the gas phase and P is the total pressure in the gas phase (*13*); therefore, the chemical potential can be written

$$d\mu_i^g = RTd(\ln y_i P) \tag{12}$$

The use of Eqs. (11) and (12) in Eq. (9) gives

$$-n^a a d\pi + RT\sum n_i^a d(\ln y_i P) = 0 \qquad (\text{constant } T) \tag{13}$$

Now the product of the molar area a and n^a, the number of moles of adsorbate in a unit mass of the adsorbent, is a constant equal to the specific area A of the adsorbent; that is,

$$A = n^a a \tag{14}$$

Substitution of Eq. (14) into Eq. (13) gives

$$-\frac{A}{RT}\, d\pi + n^a d \ln P + \Sigma n_i^a d(\ln y_i) = 0 \tag{15}$$

Integration of Eq. (15) for fixed mole fractions y_i of the gases in the mixture gives

$$\frac{\pi A}{RT} = \int_0^P n^a d(\ln P) \equiv \int_0^P \frac{n^a}{P}\, dp \qquad (\text{constant } T \text{ and } y_1, \ldots, y_n) \tag{16}$$

Equation (16) is valid also for a single component.

Since the specific surface area A for a particular adsorbent is an unknown constant, evaluation of the integral in Eq. (16) at a constant temperature T yields a quantity that is proportional to the spreading pressure π.

IDEAL ADSORBED SOLUTION THEORY

Meyers and Prausnitz (*10*) developed a number of thermodynamics relations for the two-dimensional adsorbed phase which are analogous to the ones normally encountered in solution theory (*15*). An activity coefficient γ_i^a for the ith component in the adsorbed phase is defined by (*10*):

$$\mu_i^a(T, \pi, x_i) = \mu_i^0(T, \pi) + RT \ln \gamma_i^a x_i \tag{17}$$

where $\mu_i^0(T, \pi)$ is the chemical potential of the pure component i adsorbed at the same spreading pressure as the mixture. If $P_i^0(\pi)$ is the equilibrium pressure of the pure adsorbed component i at a spreading pressure π, the chemical potential of the standard state may be rewritten assuming an ideal gas phase:

$$\mu_i^0(T, \pi) = G_i^0(T) + RT \ln P_i^0(\pi) \tag{18}$$

The standard state Gibbs free energy $G_i^0(T)$ is defined as the molar Gibbs

free energy of component i at the perfect gas state and at a pressure of 1 atm. The chemical potential of component i in the gas mixture is given by (*15*):

$$\mu_i^g(T,P,y_i) = G_i^0(T) + RT \ln Py_i \tag{19}$$

At equilibrium the chemical potential of component i in the adsorbed phase and the gas phase are equal. Substitution of Eqs. (17) through (19) into Eq. (10) results in the following equation:

$$Py_i = \gamma_i^a x_i P_i^0(\pi) \tag{20}$$

The ideal adsorbed solution theory proposed by Myers and Prausnitz assumes that γ_i^a is unity; thus,

$$Py_i = x_i P_i^0(\pi) \tag{21}$$

Equation (21) is similar to Raoult's law with the important difference that $P_i^0(\pi)$ is the pressure of the pure component adsorbed at the same spreading pressure as the mixture rather than the vapor pressure of the pure component.

In general, an extensive molar thermodynamic property of a mixture is not a simple additive function of that property for each component of the mixture; for example, there is a difference in the molar surface area a in a mixture and the summation of the product of the mole fraction x_i of each component in the mixture and the corresponding molar surface a_i^0 for a single component. Mixing accounts for this difference; thus, the change a^m in a because of mixing is (*10*):

$$a^m(T,\pi,x_1,\ldots) = a(T,\pi,x_1,\ldots) - \sum x_i a_i^0(T,\pi) \tag{22}$$

Here a_i^0 is the molar surface for pure component i at a spreading pressure π and temperature T, a is the molar surface for the mixture of composition x_1, $x_2, \ldots, x_n$, and a^m is the change in a because of mixing. For an ideal adsorbed solution, there is no change in the molar surface upon mixing at constant temperature and spreading pressure; that is,

$$a^m = 0 \qquad (\text{constant } T \text{ and } \pi) \tag{23}$$

Thus, for a binary mixture that obeys IAST, we have

$$a = x_1 a_1^0 + x_2 a_2^0 \tag{24}$$

As expressed in Eq. (14), the molar surface a is inversely proportional to the amount n^a of adsorbate on the adsorbent; thus, Eq. (24) can be rewritten as

$$\frac{1}{n^a} = \frac{x_1}{n_1^0} + \frac{x_2}{n_2^0} \tag{25}$$

EXPERIMENTAL PROCEDURES

Transmission measurements were conducted by a gas chromatographic method using a finite input concentration. Since the flow system used in the present study was described elsewhere (*16*), only a brief description is given here. The flow system was constructed of stainless-steel tubing and valves with Teflon seats and gaskets. Calibrated hydrocarbon–helium mixtures (with a nominal concentration of 1%) were prepared by the Matheson Gas Co. (East Rutherford, New Jersey). The calibrated gases were mixed with pure helium in different proportions. Gas flow rates were measured with an accuracy of ±0.5% by flowmeters. The concentration of the hydrocarbon at the downstream side of the column was measured at regular time intervals by a Varian 3700 gas chromatograph.

The cylindrical stainless-steel adsorber bed (10.02 cm long and 0.459 cm i.d.) was packed with 0.588 g of "Columbia" type 4LXC 12/28 activated carbon. This carbon has intrinsic density 1.560 g/cc (*17*), surface area 1130 m^2/g (*18*), and pore volume 0.51 cc/g (*18*). Before measuring the mass of the carbon, the adsorber bed was desorbed at 200°C with helium flowing through the adsorber bed at a rate of 200 cc/min for 36 h. Also between each run, the bed was desorbed for 12 h under the same temperature and helium flow conditions as above. The bed was immersed in a constant-temperature water bath which maintained the temperature within ±0.02°C at 25°C. Repeated experiments verified the reproducibility of the results.

The equilibrium solid-phase concentration q_0 can be calculated from a mass balance equation (*11*) when the time-dependent transmission C/C_0 is known.

$$q_0(1 - \varepsilon)L + C_0 \varepsilon L = u C_0 \varepsilon \int_0^\infty (1 - C/C_0)dt \tag{26}$$

Here the adsorbent void fraction ε includes the voids within the carbon granules, L is the length of the column, u is the superficial flow velocity, and C is the concentration of the trace component measured at the column exit.

In our experiment, helium is used as the carrier gas. Since the adsorption capacity of helium is negligible at room temperature, the partial pressure of helium is not included for further data manipulations.

RESULTS

A. Pure-Component Isotherms

The experimental pure-component adsorption isotherms for ethane and acetylene on (Columbia 4LXC 12/28) activated carbon at 25°C are plotted in Fig. 1. For each of these gases, the equilibrium adsorbed-phase concentration q_0 is not linearly proportional to the equilibrium gas-phase concentration C_0; however, the adsorption isotherms can be represented by a modified Langmuir isotherm known as the Chakravarti-Dhar isotherm (*19*); that is,

$$\frac{q_0}{q_0^s} = \frac{(K_m C_0)^\upsilon}{1 + (K_m C_0)^\upsilon} \tag{27}$$

Here q_0^s is the adsorbed-phase concentration for a monolayer coverage, and K_m and υ are constants. Equation (27) simplifies to the Langmuir isotherm when $\upsilon = 1$ and to the Freundlich equation when K_m is small. Values of the parameters for the acetylene and ethane isotherms are listed in Table 1. The parameters for ethane were obtained previously by Huang et al. (*20*). The isotherms, shown as solid lines in Fig. 1, agree with the experimental points.

The reduced spreading pressure ($\pi A/RT$) is calculated from Eq. (16) and plotted in Fig. 2 versus the equilibrium gas pressure (P_i^0) of ethane and

TABLE 1
Parameters for Isotherms of Acetylene and Ethane on Columbia 4LXC 12/28 Activated Carbon at 25°C

Gas	K_m (10^5 cm^3/mol)	q_0^s (10^{-3} mol/cm^3)	υ
Acetylene	7.18	1.13	1.00
Ethane[a]	10.6	1.9	0.927

[a]From Ref. 20.

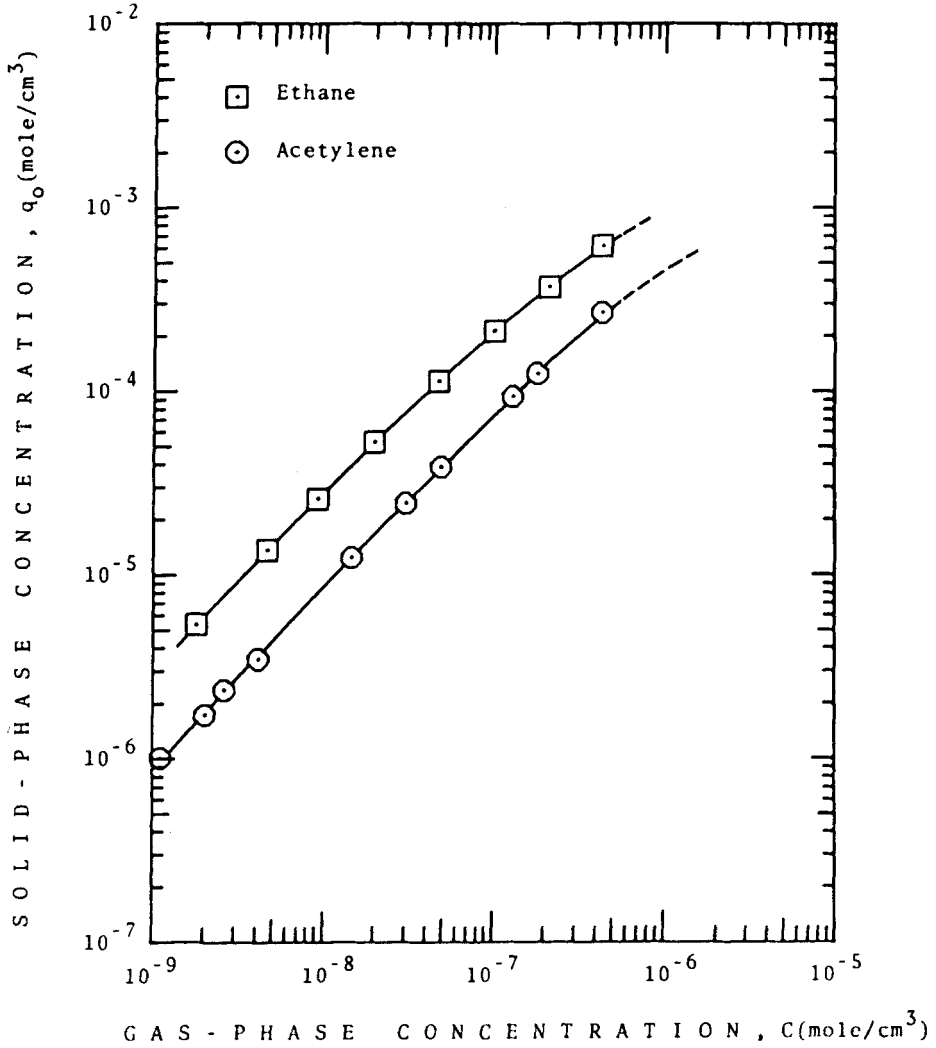

FIG. 1. Pure component isotherms for ethane and acetylene on Columbia 4LXC 12/28 activated carbon at 25°C.

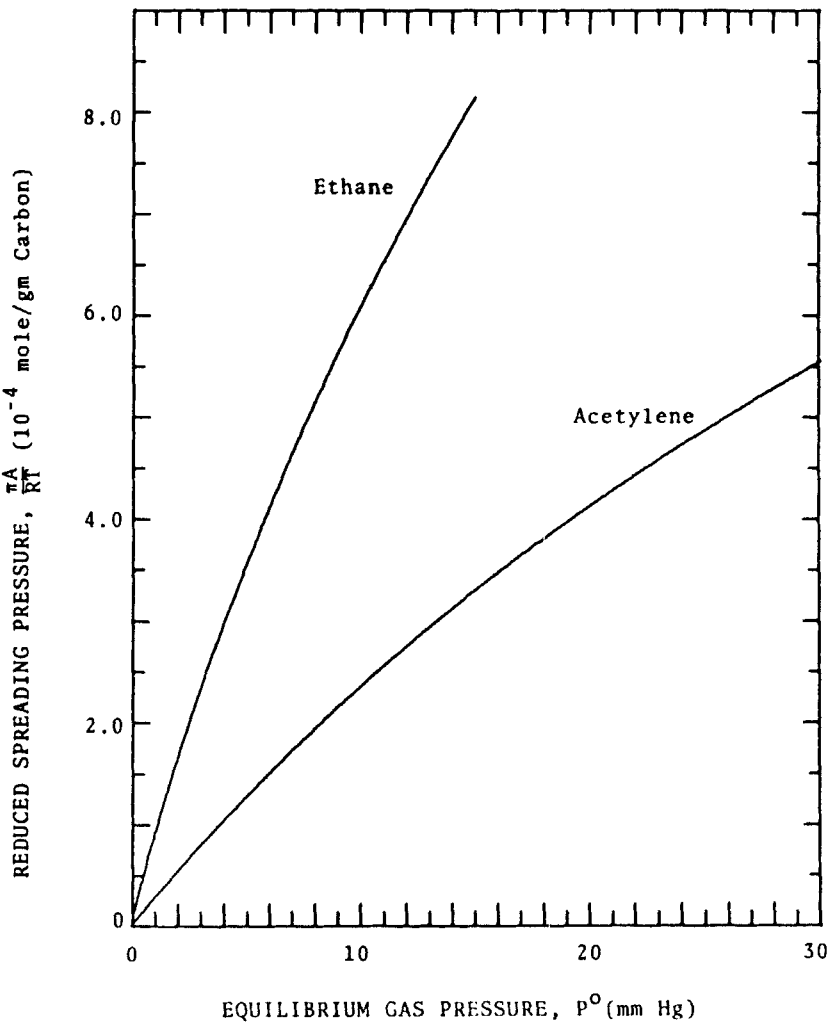

FIG. 2. Reduced spreading pressure as a function of gas pressure for the adsorption of ethane and acetylene on Columbia 4LXC 12/28 activated carbon at 25°C.

acetylene. The gas concentration extends to 1.6×10^{-6} mol/cm^3 (i.e., 30 mmHg) for acetylene and to 7.5×10^{-7} mol/cm^3 (i.e., 15 mmHg) for ethane.

B. Binary Mixtures Isotherms

Figure 3 is a plot of the gas-phase mole fraction of acetylene versus the adsorbed-phase mole fraction of acetylene. The five symbols in Fig. 3 represent the experimental mole fractions of acetylene in the adsorbed phase at five different known gas compositions with gas pressure 7.3 mmHg. The solid curve is the gas–adsorbate equilibrium composition calculated by IAST at 25°C and 7.3 mmHg. Numerical values for the adsorbed-phase mole fractions are listed in Table 2. Absolute deviations between the experimental and calculated mole fractions in the adsorbed phase are smaller than 0.013 as shown in the last column of Table 2.

Plotted in Fig. 4 as a function of the adsorbed-phase concentrations (in mol/cc) for each component and for the sum of the two components in the ethane–acetylene mixtures. The solid curves are the calculated values from IAST at a mixture pressure of 7.3 mmHg. The symbols represent the experimental results. Also, the adsorbed-phase concentrations for each component and for the sum of the two components in the mixture are listed in Table 3. As shown in the last column of Table 3, the calculated adsorbed-phase concentrations for the mixtures are within a 6% deviation of that obtained from experiments.

In our experiment the gas mixtures are mixed with the carrier gas (helium) while flowing through the adsorber bed. It is difficult to maintain the partial pressure of gas mixtures at a fixed value. As shown in Tables 2 and 3, two of the experimental data points do not have a gas pressure exactly equal to 7.3 mmHg; however, note that a slight change in the total gas pressure does not alter significantly the calculated values for the adsorbed-phase mole fractions and the adsorbed-phase concentrations. For simplicity, but without the sacrifice of accuracy, all of the experimental values in Figs. 3 and 4 are compared with the solid curves calculated by IAST at 7.3 mmHg only. In Table 4 the activity coefficients are calculated from Eq. (20). The fact that the values of the activity coefficients are near unity (viz., $0.966 < \gamma_1^a < 1.004$ and $0.975 < \gamma_2^a < 1.021$) supports the assumption that IAST is applicable to ethane–acetylene mixtures at low concentrations on activated carbon at 25°C.

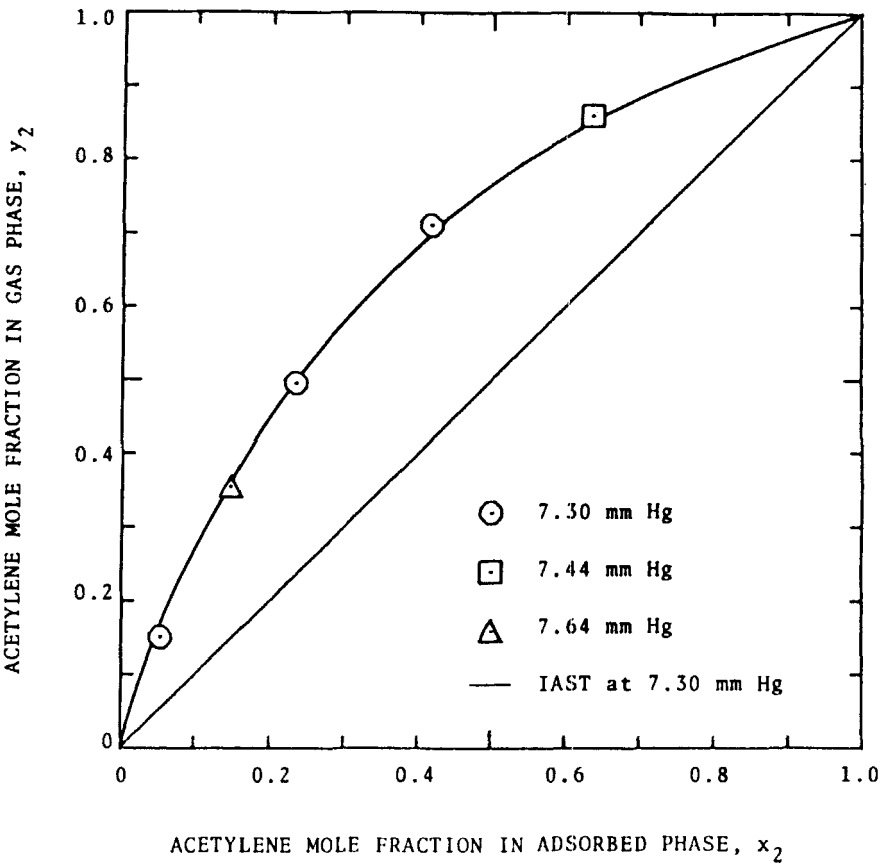

FIG. 3. Equilibrium phase diagram for adsorption of binary mixtures of ethane (Component 1) and acetylene (Component 2) on Columbia 4LXC 12/28 activated carbon at 25°C.

CONCLUSION

We measured the transmission of pure gases (viz., ethane and acetylene) and binary mixtures of these gases in a helium carrier gas flowing through an (Columbia 4LXC 12/28) activated carbon adsorber bed at 25°C. The adsorption isotherms for both single-component gases are nonlinear and can be represented by a modified Langmuir isotherm known as the Chakravarti-Dhar isotherm.

TABLE 2
Adsorbed-Phase Mole Fractions for Mixtures of Ethane (Component 1) and Acetylene (Component 2) at a Pressure of about 7.3 mmHg on Columbia 4LXC 12/28 Activated Carbon at 25°C

Gas-phase pressure P (mmHg)	Gas-phase mole fraction		Adsorbed-phase mole fraction				
			Experimental		Calculated		
	Ethane, y_1	Acetylene, y_2	Ethane, x_1	Acetylene, x_2	Ethane, $\bar{x}_1$	Acetylene, $\bar{x}_2$	Deviation, $\lvert(x_1 - \bar{x}_1)\rvert$
7.30	0.849	0.151	0.946	0.054	0.947	0.053	0.001
7.64	0.645	0.355	0.852	0.148	0.854	0.146	0.002
7.30	0.504	0.496	0.765	0.235	0.767	0.233	0.002
7.30	0.289	0.711	0.583	0.417	0.573	0.427	0.010
7.44	0.140	0.860	0.363	0.637	0.350	0.650	0.013

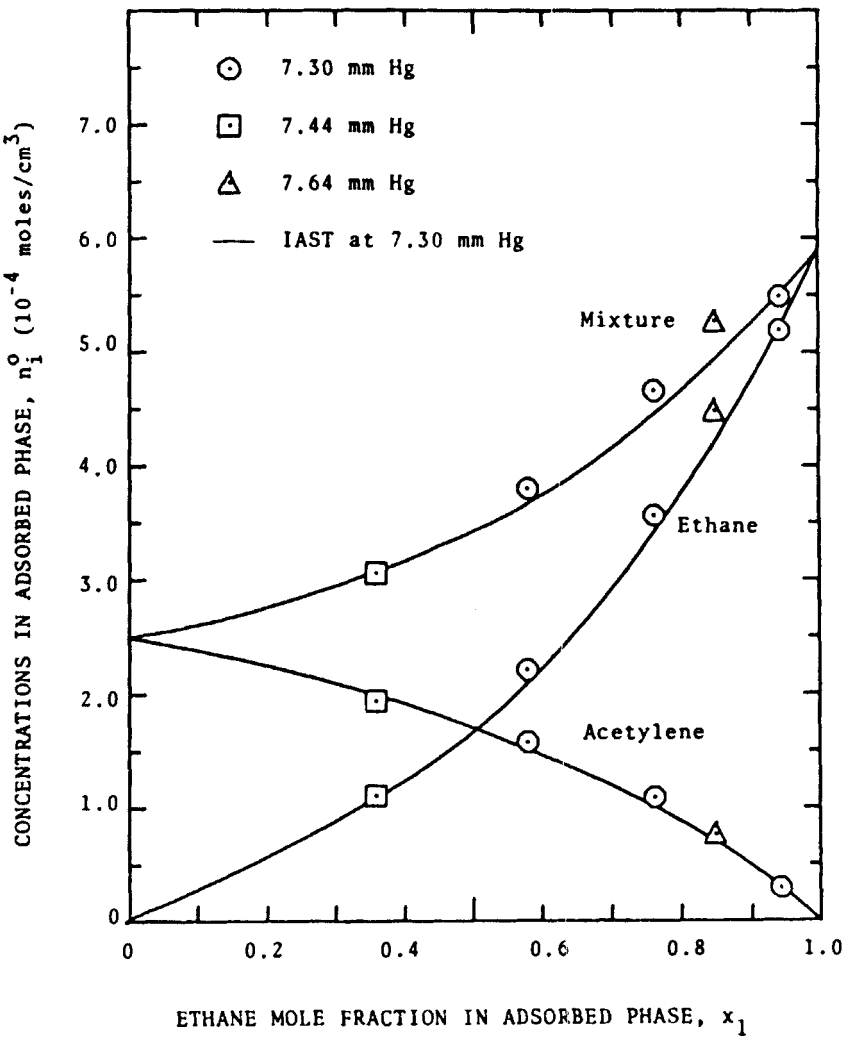

FIG. 4. Adsorption capacities of Columbia 4LXC 12/28 activated carbon for binary mixtures of ethane (Component 1) and acetylene (Component 2) at 25°C.

TABLE 3
Adsorption Capacities for Mixtures of Ethane (Component 1) and Acetylene (Component 2) at a Pressure of about 7.3 mmHg on Columbia 4LXC 12/28 Activated Carbon at 25°C

Gas-phase pressure (mmHg), P	Gas-phase concentration (10^{-7} mol/cm^3)		Adsorbed-phase concentration						Percentage deviation,[a] Δ
			Experimental (10^{-4} mol/cm^3)			IAST method (10^{-4} mol/cm^3)			
	Ethane, C_1	Acetylene, C_2	Ethane, n_1^0	Acetylene, n_2^0	Total, n_t^0	Ethane, $\bar{n}_1^0$	Acetylene, $\bar{n}_2^0$	Total, $\bar{n}_t^0$	
7.30	3.34	0.59	5.20	0.30	5.50	5.14	0.29	5.43	1.3
7.64	2.65	1.46	4.50	0.78	5.28	4.24	0.73	4.97	5.9
7.30	1.98	1.95	3.57	1.10	4.67	3.40	1.03	4.43	5.1
7.30	1.14	2.79	2.22	1.59	3.81	2.08	1.55	3.63	4.7
7.44	0.56	3.45	1.12	1.95	3.07	1.09	2.02	3.11	1.3

[a]Percentage deviation $\Delta \equiv 100|n_t^0 - \bar{n}_t^0|/n_t^0$

TABLE 4
Activity Coefficients for Mixtures of Ethane (Component 1) and Acetylene (Component 2) at a Pressure of about 7.30 mmHg on Columbia 4LXC 12/28 Activated Carbon at 25°C

Gas-phase pressure (mmHg), P	Gas-phase mole fractions		Adsorbed-phase mole fractions		Corresponding spreading pressure (10^{-3} mol/g), $\frac{\pi A}{RT}$	Equilibrium gas-pressure (mmHg)		Activity coefficient	
	Ethane, y_1	Acetylene, y_2	Ethane, x_1	Acetylene, x_2		Ethane, $P_1^0(\pi)$	Acetylene, $P_2^0(\pi)$	Ethane, γ_1^a	Acetylene, γ_2^a
7.30	0.849	0.151	0.946	0.054	0.438	6.54	20.9	1.002	0.975
7.64	0.645	0.355	0.852	0.148	0.396	5.76	18.7	1.004	0.981
7.30	0.504	0.496	0.765	0.235	0.340	4.80	15.6	1.002	0.987
7.30	0.289	0.711	0.583	0.417	0.276	3.71	12.2	0.977	1.021
7.44	0.140	0.860	0.363	0.637	0.232	2.97	9.87	0.966	1.017

We applied ideal adsorbed solution theory (IAST) to calculate the equilibrium behavior of gas–solid adsorption for binary mixtures of ethane and acetylene at a pressure of about 7.3 mmHg on activated carbon at 25°C from experimental single-component isotherms. Comparison between the experimental results and the calculated values shows that the activity coefficient obtained are close to unity, the calculated values of the mole fraction in the adsorbed phase are within a 0.013 absolute deviation of the experimental ones, and the adsorbed-phase concentrations calculated for the mixtures are within a 6% deviation of the experimental values. Since the equilibrium adsorbed-phase concentrations and the adsorbed-phase mole fractions of binary mixtures of ethane and acetylene can be predicted with accuracy from experimental adsorption isotherms of the pure gases, we conclude that the ethane–acetylene system at a pressure of about 7.3 mmHg forms an ideal adsorbed phase on activated carbon at 25°C.

Consistency between the calculated values from the IAST and experimental results for mixtures indicates, though implicity, that neglect of the effect of the carrier gas on the adsorption is a practical and justified assumption.

Acknowledgment

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SYMBOLS

A	specific surface area for an adsorbent (cm^2/g)
a	molar surface area (cm^2/mol of adsorbate mixture)
a^m	change of molar surface area because of mixing (cm^2/mol of mixture adsorbate)
a_i^0	molar surface area for the pure component i (cm^2/mol of ith component)
C	concentration of the trace component at the exit of the column (mol/cm^3)
C_0	concentration of the trace component at the inlet to the column (mol/cm^3)
f_i^g	fugacity of component i in the gas phase (mmHg)
G	molar Gibbs free energy (cal/mol)
G_i^0	molar Gibbs free energy for the pure component i at the standard state (cal/mol of ith component)
K_m	constant in Eq. (29) (cm^3/mol)
L	length of the adsorber column (cm)

n	total number of moles per unit volume of a fluid (mol/cm^3)
n_i	number of moles of component i per unit volume of a fluid (mol/cm^3)
n^a	total number of moles of adsorbate per unit mass of adsorbent (mol/g)
n_i^a	number of moles of component i per unit mass of adsorbent (mol/g)
n_i^0	adsorbate concentration of pure component i in the adsorbed phase (mol/cm^3)
n_t^0	total number of moles of adsorbates per unit volume of adsorbent (mol/cm^3)
P	pressure (mmHg)
P_i^0	equilibrium pressure for pure component i in an adsorption isotherm (mmHg or mol/cm^3)
$P_i^0(\pi)$	equilibrium pressure for pure component i corresponding to the spreading pressure π (mmHg or mol/cm^3)
P_m^0	equilibrium pressures for mixtures (mmHg or mol/cm^3)
q_0	equilibrium adsorbed-phase concentration (mol/cm^3)
q_0^s	adsorbed-phase concentration for a monolayer coverage (mol/cm^3)
R	universal gas constant (1.987 cal/°K·mol)
S	molar entropy (cal/°K·mol)
T	temperature (°K)
t	time (s)
U	molar internal energy (cal/mol)
u	superficial flow velocity (cm/s)
V	molar volume (cm^3/mol)
x_i	molar fraction of component i in the adsorbed phase (dimensionless)
y_i	molar fraction of component i in the gas phase (dimensionless)

Greek Letters

ε	adsorbent void fraction (dimensionless)
γ_i^a	activity coefficient of component i in the adsorbed phase
μ_i	chemical potential of component i in the fluid phase (cal/mol)
μ_i^a	chemical potential of component i in the adsorbed phase (cal/mol)
μ_i^g	chemical potential of component i in the gas phase (cal/mol)
$\mu_i^0(T,\pi)$	chemical potential of pure component i at the spreading pressure π and temperature T (cal/mol)

$\mu_i^g(T,\pi,x_i)$ chemical potential of component i in the adsorbed phase corresponding to a spreading pressure π, temperature T, and molar fraction x_i (cal/mol)

π spreading pressure (dyn/cm)

υ constant in Eq. (27) (dimensionless)

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