

ACTIVATED CARBON ADSORPTION CAPACITIES FOR VAPORS

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(Received 16 April 1991; revised 3 September 1991)

Abstract—It is sometimes desirable to estimate the adsorption capacity of an activated carbon bed for a chemical vapor at a selected concentration. The laboratory measurement of such a capacity (one point on an adsorption isotherm) may be hindered due to toxicity, availability, cost, time, etc. Therefore, an adsorption isotherm equation with general parameters based on physical properties of the adsorbate would be very useful. Equilibrium adsorption isotherm data and affinity coefficients for wide varieties of vapors and activated carbon have been collected from reports and publications. The Dubinin/Radushkevich equation was used for a correlation of these data based on readily available molar polarizations. The correlations for 123 affinity coefficients and 1350 adsorption capacities resulted in standard deviations of 0.18 and 0.029 g/g, respectively.

Key Words—Adsorption, capacities, affinity coefficients, vapors, carbon.

1. INTRODUCTION

Activated carbon is the most universal sorbent for purifying breathing air by adsorbing organic vapors. Packed beds of activated carbon (i.e., gas mask canisters, organic vapor respirator cartridges, test beds, etc.) are usually tested for service life using one chemical. The question often arises as to how long they will be effective for other adsorbates. Carbon bed breakthrough (service life) is determined by the bed design, adsorption kinetics, and carbon capacity for the vapor. This capacity, which depends on environmental conditions, is described by an adsorption isotherm. Both adsorbate vapor and carbon properties determine the isotherm. Ideally, one would be able to combine known or easily measured vapor properties, carbon properties, environmental (i.e., use) conditions, and bed design descriptors to estimate service life. A capacity (adsorption isotherm) equation and a rate (kinetic) equation are required to combine the effects of these parameters.

This paper focuses on estimating capacities, which are often the major determinants of service life. Only adsorption, characterized by reversible and non-reactive interaction with carbon, will be considered. Reactions with impregnants, impurities, or the carbon itself are more specific and complicated, and are usually preceded by physical adsorption. Furthermore, since liquid density will be an input parameter, capacity estimates in this paper will be limited to vapors of organic compounds that exist as liquids at ordinary temperatures and pressures. However, one of the parameter correlations includes gases, and extension of capacity estimates to gases is planned in future work. A final limitation is to relatively dry, ordinary activated carbons, produced by standard mass production activation processes. Capacities on carbons with enhanced macropore structures require separate consideration. A relatively dry carbon is

one in its original manufactured condition, dried by heating or evacuation, or equilibrated with air at 50% relative humidity or less.

2. BACKGROUND

Several adsorption isotherm equations have been commonly used to describe the effects of vapor concentration on adsorbed capacity[1]. The Dubinin/Radushkevich (D/R) equation[2] was selected from among these because it has the following desirable characteristics: (a) good fits of data, often over wide concentration ranges; (b) inclusion of temperature as a parameter; (c) parameters with physical interpretation; and (d) ease of application[1]. The D/R equation, based on the micropore volume filling theory and the Polanyi concept of adsorption potential and characteristic curves, can be expressed as:

$$W_g = W_o d_L \exp[-(KR^2 T^2/\beta^2)\{1n(P/P_{sat})\}^2] \quad (1)$$

where:

- W_g = gravimetric adsorption capacity (g/g),
- W_o = micropore volume (cm³/g),
- d_L = density of condensed liquid in micropores,
- T = absolute temperature,
- P/P_{sat} = partial vapor pressure relative to that at saturation,
- R = ideal gas constant,
- K = carbon structural constant, and
- β = affinity (similarity) coefficient.

The parameters in this equation can be further identified as: (a) vapor parameters (d_L , P_{sat} , and β); (b)

carbon parameters (W_o , K); and (c) environmental and use parameters (T , P).

The carbon structural constant K and the vapor affinity coefficient β appear as a ratio, K/β^2 . These coefficients are usually separated by using a reference compound, often benzene, for which β is defined as equal to 1.0[2]. There has been some debate, based on experimental measurements of isotherms and derivation of β , as to whether reference compounds should be of similar polarity to those being referenced[3–5]. The use of a reference compound introduces two problems. First, the suspected carcinogenicities of benzene and carbon tetrachloride, common capacity reference compounds, preclude their routine use. Second, the reference measurement has its own uncertainty, often ignored.

Another debate has concerned which parameter β correlates best with—molar polarizations, molar liquid volumes, or molecular parachors[3–5]. It has always been assumed that β is proportional to one of these measurable properties. As shown below, molar polarization is easily calculated for a wide variety of gases and vapors from tabulated physical data or correlations; therefore, it was the one chosen for this study.

3. AFFINITY COEFFICIENT CORRELATION

For the first database, 123 values of β^2 were compiled and calculated from 14 published and unpublished sources[1,4–16]. (The square of β was selected for correlations, since this is the form appearing in the D/R equation.) These values were for gas and vapor adsorbates ranging from argon to perchlorocyclopentadiene, including nonpolar, polar, and hydrogen bonding compounds. Values for aliphatic acids and amines, which apparently are special cases due to vapor phase association[7], were not included. Those from questionable data for 2,2,4-trimethylpentane[12,3], 1,1,2,2-tetrachloroethane[12], and 2,5-nonbornadiene[8] were also excluded. Any β values based on single isotherm points[4] were not used. When available, reported values were simply squared[6–11]. In other cases, reported fits of adsorption isotherm data to the D/R equation were used to calculate β^2 [4,14]. A third option was first to fit capacity data obtained from reported equilibrium measurements[5,12–13,15,22] or breakthrough curves[1,16,23] to the D/R equation. Initially, a reference compound was selected from among those used by each experimenter, and a tentative reference value for β^2 was assigned to it. This potential source of biases was later eliminated, as discussed below. Table 1 lists the values obtained from the references and the tentative relative values.

Molar polarizations (P_e , also called molar refraction, and proportional to electric dipole polarizability) were calculated for each of the compounds for which β^2 values were available. Where a liquid density, a refractive index, n_D , and a molecular weight, M_w , were listed at about 20° C in a handbook[17],

molar polarizations were calculated using the equation

$$P_e = \left(\frac{n_D^2 - 1}{n_D^2 + 2} \right) \frac{M_w}{d_L}$$

For organic compounds where they were not listed, the additive structural contributions were used to calculate molar polarizations[17]. A third alternative, used for inorganic gases, was to calculate molar polarizations from tabulated values of average electric dipole polarizabilities by dividing the latter by the conversion constant $0.3964308 \times 10^{-24} \text{ cm}^3$ [17].

Resulting values of P_e in units of cm^3/mole are also listed in Table 1. Figure 1 shows a log-log plot of β^2 vs P_e . The apparent linearity of this plot indicates that β^2 is a power function of P_e . However, since the slope of the plot on a log-log scale is less than 2.0, represented by the solid line, the power is smaller than 2 and β is less than directly proportional to P_e .

At this point, it was realized that the value of this slope may be affected by the tentative reference values included in the data. Therefore, an alternate procedure was used for data fitting. Each set of data from the 14 sources was allowed its own "floating" reference value:

$$\beta^2 = \sum_i \delta_{ii} a_i P_e^m \quad (3)$$

where the a_i and m are adjustable curvefit parameters and the delta function isolates the data sets i . Nonlinear curvefitting of this equation was done using a commercial program, SYSTAT (SYSTAT Inc., Evanston, Illinois), on a PC-compatible 386SX computer. It produced individual normalization values of a_i for each of the 14 data sets, but a common m , representing the general effect of P_e on β^2 , independent of selected reference values of β^2 . The value of m that best fit the data (minimum sum of squares of residuals) by this procedure was 1.8. Standard deviation of the 123 β^2 values from this data fit was 0.18. Best fit estimates of β^2 and normalization values are listed in Table 1. Figure 2 shows the agreement between estimates using this correlation and the experimental β^2 values.

4. STRUCTURAL CONSTANT CORRELATION

The effects of vapor differences on adsorption capacity can be factored out of the K/β^2 ratio using the above correlation, resulting in this form of eqn (1):

$$W_g = W_o d_L \exp[-BP_e^{-1.8} R^2 T^2 \{\ln(P/P_{\text{sat}})\}^2] \quad (4)$$

where B represents a relative carbon structural constant. It can be obtained from fitting adsorption isotherm data to the D/R equation. For example, in ref. 3, regression analysis of $\log_{10}(W_g/d_L)$ vs $(RT \ln\{P_{\text{sat}}/P\})^2$ for carbon tetrachloride data gave an

Table 1. Affinity coefficients and molar polarizations

Compound	Beta squared values				Molar polarization	Normalization factors $\times 1000$	Ref
	Reported beta	Tentative	Correlation	Residual			
Ammonia	0.28	0.08	0.071	0.009	5.460	3.478	7
Methanol	0.40	0.16	0.150	0.010	8.236	3.478	7
Methyl chloride	0.56	0.31	0.274	0.036	11.521	3.478	7
Ethanol	0.61	0.37	0.337	0.033	12.922	3.478	7
Methylene chloride	0.66	0.44	0.514	-0.074	16.338	3.478	7
Carbon disulfide	0.70	0.49	0.842	-0.352	21.494	3.478	7
Ethyl chloride	0.78	0.61	0.504	0.106	16.158	3.478	7
Acetone	0.88	0.77	0.505	0.265	16.177	3.478	7
Chloroform	0.88	0.77	0.839	-0.069	21.462	3.478	7
Benzene ^b	1.00	1.00	1.208	-0.208	26.274	3.478	7
Cyclohexane	1.04	1.08	1.377	-0.297	27.735	3.478	7
Carbon tetrachloride	1.07	1.14	1.221	-0.081	26.435	3.478	7
Diethyl ether	1.09	1.19	0.913	0.277	22.493	3.478	7
Pentane	1.12	1.25	1.127	0.123	25.278	3.478	7
Chloropicrin	1.28	1.64	1.293	0.347	27.289	3.478	7
Toluene	1.28	1.64	1.632	0.008	31.054	3.478	7
Heptane	1.50	2.25	1.978	0.272	34.552	3.478	7
Nitrogen	0.33	0.11	0.050	0.060	4.390	3.446	6
Krypton	0.37	0.14	0.094	0.046	6.267	3.446	6
Xenon	0.50	0.25	0.226	0.024	10.202	3.446	6
Methyl bromide	0.57	0.32	0.421	-0.101	14.393	3.446	6
Tetrafluoroethylene	0.59	0.35	0.218	0.132	9.997	3.446	6
Ethyl chloride	0.71	0.50	0.518	-0.018	16.158	3.446	6
Propane	0.72	0.52	0.507	0.013	15.967	3.446	6
Hexafluoropropylene	0.76	0.58	0.411	0.169	14.208	3.446	6
Chloroform	0.87	0.76	0.864	-0.104	21.462	3.446	6
Butane	0.87	0.76	0.804	-0.044	20.624	3.446	6
Benzene*	1.00	1.00	1.243	-0.243	26.274	3.446	6
Pentane	1.08	1.17	1.159	0.011	25.278	3.446	6
Hexane	1.29	1.66	1.568	0.092	29.898	3.446	6
Heptane	1.46	2.13	2.035	0.095	34.552	3.446	6
Methylene chloride	0.66	0.44	0.453	-0.013	16.338	3.026	8
Benzene*	1.00	1.00	1.066	-0.066	26.274	3.026	8
Cyclohexane	1.04	1.08	1.175	-0.095	27.733	3.026	8
Carbon tetrachloride	1.05	1.10	1.077	0.023	26.435	3.026	8
Chlorobenzene	1.19	1.42	1.448	-0.028	31.150	3.026	8
α -pinene	1.70	2.89	2.694	0.196	43.984	3.026	8
Perchlorocyclopentadiene	1.91	3.65	3.675	-0.025	52.266	3.026	8
Ammonia	0.26	0.07	0.059	0.011	5.460	2.773	9
Argon	0.26	0.07	0.036	0.034	4.140	2.773	9
Benzene*	1.00	1.00	1.005	-0.005	26.274	2.773	9
Argon	0.31	0.10	0.036	0.064	4.140	2.733	10
Methane	0.35	0.12	0.081	0.039	6.541	2.733	10
Sulfur hexafluoride	0.56	0.31	0.429	-0.119	16.497	2.733	10
Ethane	0.57	0.32	0.214	0.106	11.225	2.733	10
Pyridine	0.92	0.85	0.846	0.004	24.074	2.733	10
Neopentane	0.96	0.92	0.916	0.004	25.149	2.733	10
Benzene*	1.00	1.00	0.991	0.009	26.274	2.733	10
Methanol	0.39	0.15	0.140	0.010	8.236	3.156	11
Ethanol	0.62	0.38	0.316	0.064	12.922	3.156	11
Acetone	0.81	0.66	0.473	0.187	16.177	3.156	11
Chloroform	0.89	0.79	0.787	0.003	21.462	3.156	11
Methyl ethyl ketone	0.99	0.98	0.736	0.244	20.681	3.156	11
Ethyl acetate	1.00	1.00	0.841	0.159	22.267	3.156	11
Benzene*	1.00	1.00	1.133	-0.133	26.274	3.156	11
Carbon tetrachloride	1.08	1.17	1.146	0.024	26.435	3.156	11
Trichloroethylene	1.15	1.32	1.064	0.256	25.369	3.156	11
Nitrobenzene	1.15	1.32	1.697	-0.377	32.886	3.156	11
Toluene	1.26	1.59	1.531	0.059	31.054	3.156	11
<i>o</i> -xylene	1.40	1.96	1.978	-0.018	35.806	3.156	11
Butanol		0.67	0.950	-0.280	22.154	3.657	4
Methyl isobutyl ketone		1.76	1.657	0.103	30.179	3.657	4
Heptane*		2.18	2.113	0.067	34.552	3.657	4
Acetone		0.60	0.529	0.071	16.177	3.516	5
Trichloroethylene		1.00	1.189	-0.189	25.369	3.516	5
Pyridine		1.00	1.082	-0.082	24.074	3.516	5

Table 1. (Continued)

Compound	Beta squared values						Ref
	Reported beta	Tentative	Correlation	Residual	Molar polarization	Normalization factors $\times 1000$	
Benzene*		1.00	1.266	-0.266	26.274	3.516	5
Ethyl acetate		1.05	0.940	0.110	22.267	3.516	5
Carbon tetrachloride		1.14	1.280	-0.140	26.435	3.516	5
Toluene		1.27	1.711	-0.441	31.054	3.516	5
n-butanol		1.49	0.931	0.559	22.154	3.516	5
p-xylene		2.18	2.233	-0.053	36.005	3.516	5
Tetrachloroethylene		2.23	1.639	0.591	30.326	3.516	5
Methanol	0.34	0.14	0.160	-0.020	8.236	3.570	3
Nitromethane	0.43	0.23	0.338	-0.108	12.484	3.570	3
Acetonitrile	0.41	0.32	0.272	0.048	11.069	3.570	3
Acetaldehyde	0.66	0.54	0.293	0.247	11.528	3.570	3
Propionaldehyde	0.70	0.60	0.531	0.069	16.046	3.570	3
1,4-dioxane	0.72	0.62	0.913	-0.293	21.672	3.570	3
Acetone	0.72	0.63	0.539	0.091	16.177	3.570	3
Ethyl acetate	0.85	0.87	0.958	-0.088	22.267	3.570	3
Chloroform	0.87	0.92	0.897	0.023	21.462	3.570	3
Benzene	0.92	1.00	1.291	-0.291	26.274	3.570	3
Fluorobenzene	0.99	1.18	1.281	-0.101	26.158	3.570	3
Carbon tetrachloride*	1.00	1.20	1.305	-0.105	26.435	3.570	3
Hexane	1.20	1.75	1.629	0.121	29.898	3.570	3
1,1,2,2-tetrachloroethane	1.31	2.07	1.702	0.368	30.630	3.570	3
Methylene chloride		0.58	0.546	0.034	16.338	3.560	13
Acetone		0.63	0.536	0.094	16.177	3.560	13
Chloroform		0.84	0.886	-0.046	21.386	3.560	13
Methyl ethyl ketone		0.90	0.835	0.065	20.681	3.560	13
Benzene*		1.00	1.284	-0.284	26.274	3.560	13
Carbon tetrachloride		1.17	1.298	-0.128	26.435	3.560	13
Hexane		1.88	1.620	0.260	29.898	3.560	13
Heptane		2.11	2.102	0.008	34.552	3.560	13
Ethanol		0.31	0.299	0.011	12.922	2.990	1
Acetone		0.67	0.449	0.221	16.177	2.990	1
Chloroform		0.77	0.915	-0.145	21.462	2.990	1
Carbon tetrachloride*		1.16	1.086	0.074	26.435	2.990	1
Hexane		1.22	1.355	-0.135	29.898	2.990	1
Methane		0.23	0.108	0.122	6.541	3.743	14
Ethylene		0.28	0.263	0.017	10.726	3.743	14
Ethane		0.32	0.285	0.035	11.225	3.743	14
Methane		0.35	0.108	0.242	6.541	3.743	14
Ethylene		0.43	0.263	0.167	10.726	3.743	14
Ethane		0.46	0.285	0.175	11.225	3.743	14
Propylene		0.59	0.527	0.063	15.791	3.743	14
Propane		0.62	0.537	0.083	15.967	3.743	14
Butane*		0.76	0.852	-0.092	20.624	3.743	14
Nitromethane		0.29	0.310	-0.020	12.484	3.292	15
Ethyl chloride		0.54	0.492	0.048	16.158	3.292	15
Benzene*		1.00	1.181	-0.181	26.274	3.292	15
Carbon tetrachloride		1.05	1.194	-0.144	26.435	3.292	15
Chlorobenzene		1.47	1.605	-0.135	31.150	3.292	15
Heptane		2.24	1.934	0.306	34.552	3.292	15
Isopropanol		0.56	0.599	-0.039	17.623	3.422	16
Dichloromethane		0.61	0.523	0.087	16.338	3.422	16
Methyl acetate		0.72	0.592	0.128	17.502	3.422	16
Carbon tetrachloride		0.92	1.243	-0.323	26.435	3.422	16
Benzene*		1.00	1.230	-0.230	26.274	3.422	16
Methyl chloroform		1.28	1.200	0.080	25.918	3.422	16
Toluene		1.67	1.661	0.009	31.054	3.422	16
Hexane		1.86	1.552	0.308	29.898	3.422	16

*Units of molar polarization are cm^3/mole .

^bAsterisk (*) indicates the reference compound in each set.

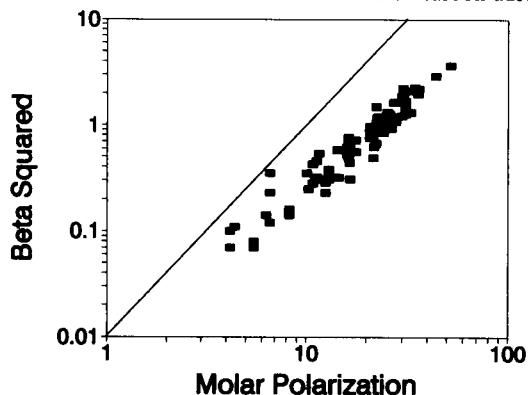


Fig. 1. Affinity coefficient correlation with molar polarization. Straight line slope represents direct proportionality between B and P_e .

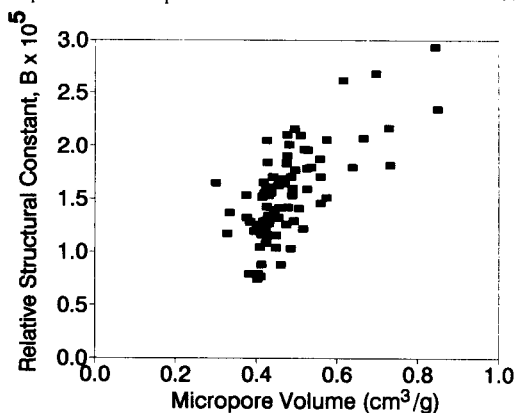


Fig. 3. Relative carbon structural constant vs micropore volume for activated carbons.

intercept of -0.37715 and a slope of -1.9839×10^{-8} . The molar polarization is 26.453 . From eqn (4), $\log_{10}(W_g/d_t) = \log_{10}(W_o) - (BP_e^{-1.8}/2.303)(RT \ln\{P_{sat}/P\})^2$. Therefore, B and W_o can be obtained by:

$$B = (1.9839 \times 10^{-8})(26.453)^{1.8}(2.303) \\ = 1.66 \times 10^{-5} (\text{cm}^3/\text{mole})^{1.8}(\text{mole}/\text{cal})^2 \\ W_o = \exp[(-0.37715)(2.303)] = 0.420 \text{ cm}^3/\text{g}$$

where the 2.303 comes from the use of logarithm base 10 .

Eighty sets of isotherm data[1,4-5,11-13,15,16,18,23] were fit to eqn (4) by nonlinear regression using SYSTAT to obtain B and W_o values for each set. These are plotted against one another in Fig. 3.

Figure 3 shows a general trend of increasing B as W_o increases. Such trends have been reported previously for a wide variety of adsorbates, a wide range of temperatures, and two activated carbons[19]. Due to the scatter of the data (also seen in ref. 19), it is not possible to define precisely the relationship between B and W_o ; however, it can be assumed to be

approximately linear. The scatter in the data may be in part due to the indirect method by which B is determined and sensitivity to experimental errors.

5. ADSORPTION ISOTHERM CORRELATIONS

A database was developed containing 1350 capacity data sets from 10 sources[1,4-5,11-13,15-16,18,20] for about 140 different compounds and 15 activated carbons by seven techniques over 20° - 200° C. The techniques and temperatures used to acquire these data are listed in Table 2. The Barneby Cheney carbon in ref. 15 was not included since it was specially treated to enhance macropore structure. The database exclusions were the same as those listed above for affinity coefficient correlations. Aliphatic acids and amines will be considered as special cases in future work.

With the further assumption that the relative structural constant B is related to micropore volume W_o by the proportionality constant b , eqn (4) becomes

$$W_g = W_o d_t \exp[-b W_o P_e^{-1.8} R^2 T^2 \{ \ln(P/P_{sat}) \}^2]. \quad (5)$$

Handbook values of liquid density at or near 20° C were used, except for one set of experiments with carbon tetrachloride at 200° C, where the liquid density was taken as 1.19 [18]. Saturation vapor pressures at experimental temperatures, easily calculated from tabulated parameters[21], were used. Molar polarizations were calculated as discussed above. With these inputs, eqn (5) became gravimetric capacity, W_g , as a function of temperature, T , concentration, P , and micropore volume, W_o , with one "universal" constant, b .

All the 1350 data were fit to eqn (5), allowing different adjustable curve fit parameters W_o s for each of the 15 carbons, but requiring the same b for all. The database was too large for SYSTAT to handle, so it was separated into five sections for nonlinear regressions. The sum of the squares of the

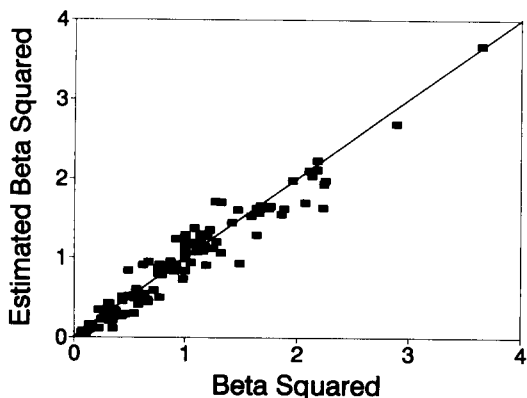


Fig. 2. Comparison of β^2 values estimated by the correlation with experimental β^2 values.

Table 2. Isotherm data sources and techniques

Technique	Temperature Range (°C)	Numbers of			Refs.
		Carbons	Compounds	Data	
Vapor equilibrium adsorption	25	1	8	103	13
Vapor equilibrium desorption	20-60	1	14	397	3,12
Vapor equilibrium desorption	20	3	6	440	15
Adsorption from flowing air	25	1	14	30	4
Adsorption from flowing nitrogen	30	2	13	23	11
Adsorption from flowing nitrogen	25-60	1	10	62	5
Packed bed breakthrough curves	22	4	105	226	16,20
Packed bed breakthrough times	23	1	5	54	1
Column elution chromatography	200	1	1	15	18

residuals for each section were totaled as b was varied until this total was minimized. The value of b that gave the best fit of all the data to eqn (5) was

$$b = 3.56 \times 10^{-5} \text{ mol}^2 \text{ cal}^{-2} \text{ cm}_o^{-3} (\text{cm}_L^3 / \text{mol})^{1.8} \quad (6)$$

where the subscripts o and L refer to micropore and adsorbate liquid volumes, respectively. The standard deviation of all W_g data from the best fit eqn (5) with 1334 degrees of freedom was 0.029 g/g. Figure 4 shows a comparison of values estimated from the fit with experimental isotherm data. Only eight experimental isotherm data differed from the estimates by more than 0.1 g/g. Individual values of W_o obtained for the carbons are listed in Table 3.

6. APPLICATIONS

Assuming a similar activated carbon, eqns (5) and (6) can be used to estimate equilibrium capacities and adsorption isotherms, using only handbook data. For example, assuming a micropore volume of 0.45 cm³, the capacity for carbon tetrachloride at 840 ppm in air and 30° C ($C_{\text{sat}} = 187000$ ppm for $P_{\text{sat}} = 142$ torr) is estimated to be

$$W_g = (0.45)(1.594) \times \exp[-(3.56 \times 10^{-5})(0.45)(26.453)^{-1.8}] \times (1.987)^2(303)^2\{\ln(840/187000)\}^2 = 0.45 \text{ g/g.}$$

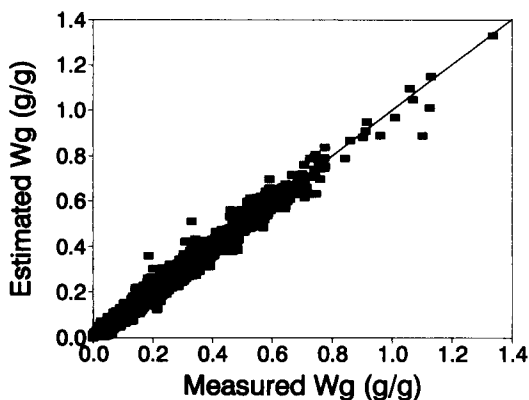


Fig. 4. Comparison of gravimetric capacities estimated by the correlation with experimental capacities.

If the micropore volume can be measured, rather than assumed, and/or if one or more isotherm data can be measured to give a specific b , this estimate can be improved.

7. CONCLUSIONS

Very good adsorption isotherm data correlations were obtained with the D/R equation using only molar polarizations to merge the isotherms for widely different compounds from many different experimental sources. The two most difficult parameters to obtain in the D/R isotherm equation, affinity coefficient and carbon structural constant, have been replaced with molar polarization and a "universal" constant, b . Reference compounds, particularly of differing polarities, were not needed.

Capacities of carbons characterized or qualified with one test vapor can be estimated for other organic vapors using only molar polarizations, liquid densities, and saturation vapor pressures (or concentrations).

Table 3. Micropore volumes of carbons from data fitting

Carbon Type ^a	Reference	Micropore volume, W_o (cm ³ /g)	
		All compounds	Range ^b
BPL	3	0.425	0.30-0.51
BPL	13	0.423	0.41-0.45
BAC	5	0.474	0.46-0.49
Unknown	1	0.408	0.38-0.57
MSA	16	0.719	0.56-0.85
AO	16	0.559	0.52-0.61
G212	20	0.697	
G215	20	0.696	
JXC	4	0.431	0.40-0.41
PCC	15	0.438	0.38-0.46
AC	15	0.413	0.39-0.42
WVB	15	0.557	0.49-0.56
B	11	0.532	0.52
E	11	0.507	0.50
A1	18	0.540	0.45

^aSee references for details.

^bRange of values from individual isotherms.

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