

# Solubility of Anthracene in Binary Alcohol + Acetonitrile Solvent Mixtures at 298.2 K

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Experimental solubilities are reported for anthracene dissolved in seven binary alcohol + acetonitrile solvent mixtures at 25 °C. The alcohol cosolvents studied were 1-propanol, 2-propanol, 1-butanol, 2-butanol, 2-methyl-1-propanol, 3-methyl-1-butanol, and 2-methyl-1-butanol. Results of these measurements are used to test a mathematical representation based upon the combined nearly ideal binary solvent (NIBS)/Redlich–Kister equation. For the seven systems studied, the combined NIBS/Redlich–Kister equation was found to mathematically describe the experimental data to within overall average absolute deviation of approximately  $\pm 0.5\%$ .

## Introduction

Solid–liquid equilibrium data of organic nonelectrolyte systems are becoming increasingly important in the petroleum industry, particularly in light of present trends toward heavier feedstocks and known carcinogenicity/mutagenicity of many of the larger polycyclic aromatic compounds. Solubility data for a number of polycyclic aromatic hydrocarbons (i.e., anthracene and pyrene) and heteroatom polynuclear aromatics (i.e., carbazole, dibenzothiofene, and xanthene) have been published in the recent chemical literature (for listing of references, see Acree<sup>1–3</sup>). Despite efforts by experimentalists and scientific organizations, both in terms of new experimental measurements and critically evaluated data compilations, there still exist numerous systems for which solubility data are not readily available.

To address this problem, researchers have turned to predictive methods as a means to generate desired quantities. Numerous equations have been suggested for predicting solute solubilities in binary solvent mixtures. For the most part, the predictive methods do provide fairly reasonable estimates for noncomplexing systems. There still remains, however, the need to develop better predictive expressions and mixing models to describe the more nonideal complexing systems believed to contain hydrogen bonding solvent components. Continued development of solution models for describing the thermodynamic properties of a solute in binary solvent systems requires that a large database be available for assessing the applications and limitations of derived expressions. Currently, only a limited database exists for crystalline nonelectrolyte solubility in binary solvent mixtures. For this reason, anthracene solubilities were determined in seven binary alcohol + acetonitrile solvent mixtures. This is the first time that we have used acetonitrile in binary solvent studies. Results of these measurements are used to further test the descriptive ability of the combined nearly ideal binary solvent (NIBS)/Redlich–Kister equation.

## Experimental Methods

Anthracene (Aldrich, 99%) was recrystallized three times from acetone. 1-Propanol (Aldrich, 99+ %, anhydrous), 2-propanol (Aldrich, 99+ %, anhydrous), 1-butanol (Aldrich, 99.8+ %), 2-butanol (Aldrich, 99+ %, anhydrous), 2-methyl-1-propanol (Aldrich, 99+ %, anhydrous), 3-methyl-1-butanol (Aldrich, 99+ %, anhydrous), 2-methyl-1-butanol (Aldrich, 99+ %), and acetonitrile (Aldrich, 99.8%, anhydrous) were stored over molecular sieves and distilled shortly before use. Gas chromatographic analysis showed solvent purities to be 99.7 mol % or better. Binary solvent mixtures were prepared by mass so that compositions could be calculated to 0.0001 mol fraction.

Excess solute and solvent were placed in amber glass bottles and allowed to equilibrate in a constant temperature water bath at  $(25.0 \pm 0.1)$  °C with periodic agitation for at least 3 days (often longer). Attainment of equilibrium was verified both by repetitive measurements after a minimum of three additional days and by approaching equilibrium from supersaturation by preequilibrating the solutions at a higher temperature. Aliquots of saturated anthracene solutions were transferred through a coarse filter into a tared volumetric flask to determine the amount of sample and diluted quantitatively with methanol for spectrophotometric analysis at 356 nm on a Bausch and Lomb Spectronic 2000. Concentrations of the dilute solutions were determined from a Beer–Lambert law absorbance versus concentration working curve derived from measured absorbances of standard solutions of known molar concentrations. Apparent molar absorptivities of the nine standard solutions varied systematically with molar concentration and ranged from approximately  $\epsilon/(\text{L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}) = 7450$  to  $\epsilon/(\text{L}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}) = 7150$  for anthracene concentrations ranging from  $C/(\text{mol}\cdot\text{L}^{-1}) = 6.75 \times 10^{-5}$  to  $C/(\text{mol}\cdot\text{L}^{-1}) = 2.25 \times 10^{-4}$ . Identical molar absorptivities were obtained for select anthracene standard solutions that contained up to 5 vol % of the neat alcohol and acetonitrile cosolvents. Experimental anthracene solubilities in the seven binary alcohol + acetonitrile solvent mixtures are listed in Table 1. Numerical values represent the average

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**Table 1. Experimental Mole Fraction Solubilities of Anthracene ( $x_A^{\text{sat}}$ ) in Binary Alcohol (B) + Acetonitrile (C) Solvent Mixtures at 25.0 °C**

| $x_C^{\circ}$                      | $x_A^{\text{sat}}$ | $x_C^{\circ}$ | $x_A^{\text{sat}}$ | $x_C^{\circ}$ | $x_A^{\text{sat}}$ |
|------------------------------------|--------------------|---------------|--------------------|---------------|--------------------|
| 1-Propanol + Acetonitrile          |                    |               |                    |               |                    |
| 0.0000                             | 0.000591           | 0.4747        | 0.001305           | 0.8491        | 0.001168           |
| 0.1466                             | 0.000910           | 0.5862        | 0.001318           | 0.9293        | 0.001009           |
| 0.2683                             | 0.001128           | 0.6824        | 0.001291           | 1.0000        | 0.000830           |
| 2-Propanol + Acetonitrile          |                    |               |                    |               |                    |
| 0.0000                             | 0.000411           | 0.5049        | 0.001163           | 0.8555        | 0.001036           |
| 0.1799                             | 0.000806           | 0.5969        | 0.001182           | 0.9224        | 0.000956           |
| 0.2814                             | 0.000958           | 0.6600        | 0.001162           | 1.0000        | 0.000830           |
| 1-Butanol + Acetonitrile           |                    |               |                    |               |                    |
| 0.0000                             | 0.000801           | 0.5377        | 0.001712           | 0.8729        | 0.001227           |
| 0.1850                             | 0.001339           | 0.6384        | 0.001677           | 0.9308        | 0.001064           |
| 0.3224                             | 0.001581           | 0.7171        | 0.001564           | 1.0000        | 0.000830           |
| 2-Butanol + Acetonitrile           |                    |               |                    |               |                    |
| 0.0000                             | 0.000585           | 0.5297        | 0.001593           | 0.8692        | 0.001174           |
| 0.1679                             | 0.001108           | 0.6076        | 0.001588           | 0.9359        | 0.001011           |
| 0.3044                             | 0.001409           | 0.7303        | 0.001451           | 1.0000        | 0.000830           |
| 2-Methyl-1-propanol + Acetonitrile |                    |               |                    |               |                    |
| 0.0000                             | 0.000470           | 0.5276        | 0.001440           | 0.8715        | 0.001145           |
| 0.1671                             | 0.000925           | 0.6351        | 0.001401           | 0.9339        | 0.001005           |
| 0.3175                             | 0.001223           | 0.7258        | 0.001361           | 1.0000        | 0.000830           |
| 3-Methyl-1-butanol + Acetonitrile  |                    |               |                    |               |                    |
| 0.0000                             | 0.000727           | 0.5738        | 0.001658           | 0.8884        | 0.001197           |
| 0.1843                             | 0.001186           | 0.6751        | 0.001595           | 0.9482        | 0.001006           |
| 0.3445                             | 0.001489           | 0.7384        | 0.001526           | 1.0000        | 0.000830           |
| 2-Methyl-1-butanol + Acetonitrile  |                    |               |                    |               |                    |
| 0.0000                             | 0.000786           | 0.5779        | 0.001755           | 0.8864        | 0.001232           |
| 0.1908                             | 0.001277           | 0.6724        | 0.001729           | 0.9434        | 0.001028           |
| 0.3468                             | 0.001577           | 0.7534        | 0.001597           | 1.0000        | 0.000830           |

of between four and eight independent determinations, with the measured values being reproducible to within  $\pm 1.0\%$ .

## Results and Discussion

Acree and co-workers<sup>4–6</sup> suggested the combined NIBS/Redlich–Kister model

$$\ln x_A^{\text{sat}} = x_B^{\circ} \ln(x_A^{\text{sat}})_B + x_C^{\circ} \ln(x_A^{\text{sat}})_C + x_B^{\circ} x_C^{\circ} \sum_{i=0}^N S_i (x_B^{\circ} - x_C^{\circ})^i \quad (1)$$

as a possible mathematical representation for describing how experimental isothermal solubility of a crystalline solute dissolved in a binary solvent mixture varies with binary solvent composition. In eq 1,  $x_B^{\circ}$  and  $x_C^{\circ}$  refer to the initial mole fraction composition of the binary solvent calculated as if solute (A) were not present,  $N$  is the number of curve-fit parameters used, and  $(x_A^{\text{sat}})_i$  is the saturated mole fraction solubility of the solute in pure solvent  $i$ . The various  $S_i$  “curve-fit” parameters can be evaluated via least-squares analysis.

The combined NIBS/Redlich–Kister equation has been shown to provide very accurate mathematical representations of anthracene, pyrene, and carbazole solubilities in a large number of both complexing and noncomplexing solvent mixtures.<sup>1–3</sup> Jouyban-Gharamaleki and co-workers<sup>7–10</sup> successfully used the volume fraction,  $\phi_i$ , modification of eq 1

$$\ln x_A^{\text{sat}} = \phi_B^{\circ} \ln(x_A^{\text{sat}})_B + \phi_C^{\circ} \ln(x_A^{\text{sat}})_C + \phi_B^{\circ} \phi_C^{\circ} \sum_{i=0}^N S_i (\phi_B^{\circ} - \phi_C^{\circ})^i \quad (2)$$

**Table 2. Mathematical Representation of Anthracene Solubilities in Several Binary Alcohol (B) + Acetonitrile (C) Solvent Mixtures by eq 1**

| binary solvent system<br>component (B) + component (C) | eq 1    |                     |
|--|---------|---------------------|
|  | $S_i^a$ | % dev. <sup>b</sup> |
| 1-propanol + acetonitrile                              | 2.478   | 0.7                 |
|  | 0.042   |                     |
|  | 1.200   |                     |
| 2-propanol + acetonitrile                              | 2.736   | 0.5                 |
|  | 0.827   |                     |
|  | 0.968   |                     |
| 1-butanol + acetonitrile                               | 2.986   | 0.4                 |
|  | -0.033  |                     |
|  | 0.952   |                     |
| 2-butanol + acetonitrile                               | 3.323   | 0.5                 |
|  | 0.529   |                     |
|  | 1.031   |                     |
| 2-methyl-1-propanol + acetonitrile                     | 3.256   | 0.5                 |
|  | 0.549   |                     |
|  | 1.232   |                     |
| 3-methyl-1-butanol + acetonitrile                      | 2.963   | 0.4                 |
|  | -0.365  |                     |
|  | 0.952   |                     |
| 2-methyl-1-butanol + acetonitrile                      | 3.116   | 0.6                 |
|  | -0.528  |                     |
|  | 0.687   |                     |

<sup>a</sup> Combined NIBS/Redlich–Kister curve-fit parameters are ordered as  $S_0$ ,  $S_1$ , and  $S_2$ . <sup>b</sup> Deviation (%) =  $(100/N) \sum |[(x_A^{\text{sat}})^{\text{calc}} - (x_A^{\text{sat}})^{\text{exp}}] / (x_A^{\text{sat}})^{\text{exp}}|$ .

to describe the solubility behavior of various drug molecules in binary aqueous–organic solvent mixtures. In the pharmaceutical industry, researchers often express the solvent composition in terms of volume fractions, rather than in terms of mole fractions. In the case of structurally similar drug molecules the numerical values of the  $S_i$  coefficients were found to be nearly constant in a given binary solvent mixture.<sup>10</sup> More recently, Deng et al.<sup>11–13</sup> and Pribyla et al.<sup>14–16</sup> have shown that the  $S_i$  coefficients determined by regressing experimental anthracene data in binary alkane + alkane, alkane + alcohol, alcohol + alcohol, alcohol + ether, and alkane + ether solvent mixtures allows one to predict anthracene solubilities in ternary alkane + alkane + alcohol, alkane + alcohol + alcohol, and alkane + alcohol + ether solvent mixtures. The predictive expression for the ternary solvent mixture is

$$\ln x_A^{\text{sat}} = x_B^{\circ} \ln(x_A^{\text{sat}})_B + x_C^{\circ} \ln(x_A^{\text{sat}})_C + x_D^{\circ} \ln(x_A^{\text{sat}})_D + x_B^{\circ} x_C^{\circ} \sum_{i=0}^N S_{i,BC} (x_B^{\circ} - x_C^{\circ})^i + x_B^{\circ} x_D^{\circ} \sum_{j=0}^N S_{j,BD} (x_B^{\circ} - x_D^{\circ})^j + x_C^{\circ} x_D^{\circ} \sum_{k=0}^N S_{k,CD} (x_C^{\circ} - x_D^{\circ})^k \quad (3)$$

a mole fraction average of the logarithmic solute solubilities in the three pure solvents [ $(x_A^{\text{sat}})_B$ ,  $(x_A^{\text{sat}})_C$ , and  $(x_A^{\text{sat}})_D$ ] plus a Redlich–Kister summation term for each solvent pair. The documented success<sup>11–16</sup> of eq 3 in predicting anthracene solubilities in more than 60 different ternary solvent systems illustrates the need for measured solute solubilities in binary solvent mixtures.

The ability of eq 1 to mathematically represent the experimental solubility of anthracene in the seven binary alcohol + acetonitrile mixtures is summarized in Table 2 in the form of “curve-fit” parameters and percent deviations in back-calculated solubilities. Each percent deviation is based upon the measured anthracene solubility data at the seven different binary solvent compositions. Careful examination of Table 2 reveals that eq 1 provided a fairly accurate mathematical representation for how the solubil-

ity of anthracene varies with solvent composition. Deviations between the experimental mole fraction solubilities and back-calculated values based upon eq 1 differed by an overall average absolute deviation of about  $\pm 0.5\%$ , which is less than the experimental uncertainty.

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