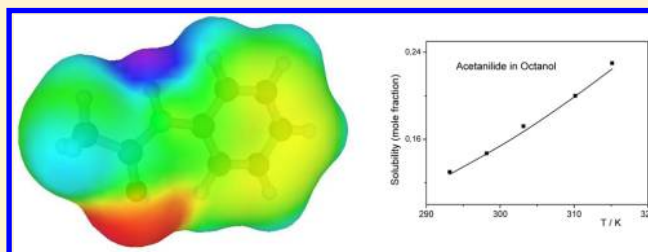


Partial Solvation Parameters and Mixture Thermodynamics

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ABSTRACT: The recently^{1,2} introduced partial solvation parameters (PSPs) are molecular descriptors that combine elements from quantum mechanics with the QSPR/LSER/solvatochromic and solubility parameter approaches. Basic regularities and universalities exhibited by PSPs are examined in this work and the concepts of homosolvation, heterosolvation and solvation energy density are quantified. A simple consistent thermodynamic framework is developed, through which the validity of the PSP approach is tested. The predictions are compared with experimental phase equilibrium data that span the full composition range from the pure fluid state to infinite dilution. They include vapor–liquid equilibria of fluids interacting with strong specific forces, dissolution of solids/liquids in various solvents and probe/oligomer or probe/polymer interactions as typically determined by inverse gas-chromatography. These applications show the potential of the PSP approach not only to reasonably predict a variety of properties of classes of complex systems but, also, to shed light to challenging aspects of intermolecular interactions. The perspectives of this unified approach to solution thermodynamics are discussed.



1. INTRODUCTION

Chemical and statistical thermodynamics were designed by their pioneers with a high sense of perfection that led to the high promise: measure a few properties of your system and thermodynamics will assist in estimating the rest of its equilibrium properties. With today's unprecedented and ever increasing speed of performing quantum mechanics calculations and molecular simulations, the above measurements do not need to be experimental and even the system compounds are not required to have been synthesized. This, in turn, changes drastically the landscape in today's design of new products and processes.

Modern quantitative structure–property relationships, or QSPR approaches, strive for the judicious selection of a minimum of molecular descriptors, which will lead to the development of reliable predictive methods for a variety of important properties in a multitude of areas of practical and academic interest.^{3–5} These descriptors may be experimentally determined properties or theoretically derived quantities.

One of the earliest but still widely used QSPR technique is the Solubility Parameter method.^{6–10} In a successful implementation,^{8–10} three molecular descriptors, known as the partial or Hansen Solubility Parameters (HSP), are used. These three HSPs, δ_d , δ_p , and δ_{hb} , reflect the dispersion, the dipolar, and the hydrogen-bonding intermolecular cohesive interactions, respectively, of each compound. The extent to which compound *i* likes or dislikes compound *j* is estimated through the radius of solubility, R_{ij} , defined as⁹

$$R_{ij}^2 = 4 \left\{ (\delta_{di} - \delta_{dj})^2 + \frac{1}{4}(\delta_{pi} - \delta_{pj})^2 + \frac{1}{4}(\delta_{hbi} - \delta_{hbj})^2 \right\} \quad (1)$$

The smaller the radius of solubility the more likely is the compound *i* to be miscible with compound *j*.

One of the most successful and widely used QSPR methods is the linear free-energy relationship (LFER) or the linear solvation-energy relationship (LSER) approach.^{11–17} The starting point in this line of developments was the solvatochromic equation of Kamlet et al.^{11–14} which correlates (initially, the solute transfer free-energy but subsequently) the general property, *Y*, of a solute in a series of solvents with the solvatochromic solvent parameters as follows:

$$Y = Y_0 + c\gamma + s\pi_1^* + a\alpha_1 + b\beta_1 + d(\text{ced}) \quad (2)$$

The independent solvatochromic solvent parameters γ , π_1^* , α_1 , β_1 , and ced stand for the polarizability correction, the polarizability/dipolarity, the hydrogen-bond acidity, the hydrogen-bond basicity, and the cohesive energy density (square of Hildebrand's solubility parameter) of the solvent, respectively. The coefficients *c*, *s*, *a*, *b*, and *d* are the corresponding properties of the solute. In the case of a series of solutes in a given solvent, the general property SP of the solute is given by the following equation:¹⁵

$$\text{SP} = \text{SP}_0 + c\gamma + s\pi^* + a\alpha + b\beta + uV \quad (3)$$

V in this equation is the solute molar volume and the solvatochromic descriptors now refer to properties of solutes. Numerous physicochemical and biochemical processes have been described by this equation. A most important evolution of eq 3 and the solvatochromic approach, free from some of its

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basic drawbacks, is Abraham's approach,^{16,17} which we will be referring to by "the LSER approach" in what follows.

In the LSER approach, five molecular descriptors, V_x , S , E , A , and B , are used for each compound and stand for the McGowan volume,¹⁶ the dipolarity/polarizability, the excess molar refraction or electron polarizability, the overall hydrogen-bond acidity, and the overall hydrogen-bond basicity, respectively, of the solute. Predictions for generalized solute properties, SP , in a given solvent are made successfully through the classical general equation:

$$SP = c + eE + sS + aA + bB + vV_x \quad (4)$$

The set of coefficients, c , e , s , a , b , and v , are the corresponding solvent properties. Abraham's approach was remarkably successful and hundreds of properties have been already predicted successfully while their list keeps getting longer.

As observed in eqs 2–4, initially, the LSER approach was coexisting with the solubility parameter approach. In fact, in the underlying scaled particle theory¹⁸ and the 3-step solvation process (cavity formation, solvent reorganization, solute insertion and solute-interaction setup) the solubility parameter was used for the estimation of the cavity term (cf., eq 2). The cavity term in eq 3 is represented by the molar volume of the solute, while in eq 4, it is represented by the McGowan volume. In contrast, in Hansen's solubility parameter approach⁹ the cohesive energy density was encompassing dipolar interactions, hydrogen-bond interactions, as well as dispersion interactions through the equation

$$ced = \delta_d^2 + \delta_p^2 + \delta_{hb}^2 \quad (5)$$

Because of this drastic conceptual difference of the two approaches, they were developed independently with, essentially, no interconnection that prevented both from a mutually beneficial cross-fertilization.

On the other hand, one of the most important recent developments in solution thermodynamics is doubtless the COSMO-RS theory.^{19–21} This is a theory of interacting molecular surface charges computed by quantum chemical methods and combines in an eloquent manner quantum mechanics with statistical thermodynamics. The quantum-mechanical basis is the conductor-like screening charge model (COSMO)²² from the class of quantum-mechanical continuum solvation models (CSM). The COSMO model is available in several quantum chemistry software suites, such as the Turbomole,²³ the DMol3,²⁴ or the GAMESS-US.²⁵ Quantum chemically optimized geometries are provided for a number of computation DFT methods/basis sets. Structural or van der Waals atom properties have currently been optimized for nine elements (H, C, N, O, F, S, Cl, Br, and I). A cavity is created around a solute molecule, which is then solvated in infinite conducting medium, producing screening surface charges and giving the *sigma* charge density distribution profiles. Once the molecular surface charge distributions (COSMO files) are available, the COSMO-RS model calculates the system free-energy of mixing and other basic thermodynamic quantities in a Quasi-Chemical surface group-contribution manner.^{26,27} As a continuous distribution, the surface charge distribution has its statistical moments, known as COSMOments. A very large number of properties in a variety of systems have already been predicted successfully by the COSMO-RS model.

In two interesting applications of the COSMO-RS theory, its COSMOments were used to correlate the LSER molecular

descriptors²⁸ and the Hansen Solubility Parameters.²⁹ It might then be considered that quantum mechanics, in general and COSMO-RS theory in particular, could act as the framework for rejoining LSER and Solubility Parameter approaches. This is what is attempted in this series papers.^{1,2}

In ref 1, we have reconsidered solubility parameter in an effort to free it from the unnecessary restrictions imposed by eq 5. The compounds have been divided into two classes, the homosolvated and the heterosolvated ones, one criterion being whether they meet eq 5 or not, respectively. This led to the introduction of four Partial Solvation Parameters (PSPs) for the dispersion, the dipolar, the hydrogen-bonding acidic, and the hydrogen-bonding basic interactions. Two COSMOments,²⁰ HB_don3 and HB_acc3 , were used for the definition of the hydrogen-bond acidity and hydrogen-bond basicity PSPs, respectively. In reference 2, three PSPs were introduced that may replace the two previous dispersion and dipolar PSPs. The new PSPs reflect the van der Waals weak nonpolar interactions, the dipolarity/polarizability, and the excess molar refraction of the compound and they can be mapped one-to-one onto the corresponding LSER molecular descriptors. Since LSER arises from free-energy related properties while solubility parameter from energy related ones, the LSER descriptors A and B were mapped onto the hydrogen-bond acidity and hydrogen-bond basicity free-energy PSPs, respectively. Basic rules governing the interrelations of PSPs have been derived.

So far, the PSP approach has been tested with criteria of the form of eq 1, which have just shown the significant improvement over the classical solubility parameter and HSP approach.^{8–10} The objective of the present work is to perform a thorough test of the PSP approach by making detailed calculations of thermodynamic properties of practical interest in a variety of systems. In order to do this, however, we require an appropriate consistent thermodynamic framework that can handle mixtures interacting with forces of varying strength, from weak to strong specific, such as the strong hydrogen bonding interactions. Thus, in what follows we will develop, first, such a thermodynamic framework and then we will test with it our PSP approach. The potential of the PSP approach that emerges from these applications will be discussed subsequently and the relevant conclusions will be drawn. In line with the previous work,^{1,2} an effort is made in the developments to preserve as much as possible the simplicity of the LSER and solubility parameter approaches.

2. PARTIAL SOLVATION PARAMETERS

In this section we will summarize the essentials of the Partial Solvation Parameter (PSP) approach and further clarify the concepts of homosolvation, heterosolvation and solvation energy density (*sed*). Details may be found in references 1 and 2 along with extensive tables with PSPs and all needed COSMO parameters. There are two schemes of PSPs, the *s*-scheme and the σ -scheme. Common to both schemes are the hydrogen bonding PSPs and the universal reference neutral compound is water. The SI units of all PSPs are MPa^{1/2}.

2.1. *s*-Scheme of PSPs. The dispersion PSP, s_d , is defined as follows: For hydrocarbons, it is identical to the dispersion component, δ_d , of Hansen's solubility parameter (HSP).⁹ For nonhydrocarbon molecules it is obtained from the corresponding dispersion HSP of their hydrocarbon homomorphs³⁰ by the following equation:

$$s_d = \delta_{d, \text{hom}} \sqrt{\frac{V_{\text{cosm, hom}}}{V_{\text{cosm}}}} \quad (6)$$

V_{cosm} is the COSMO volume of the molecule obtained from the COSMObase.²¹

The acidic and basic solvation parameters, s_a and s_b , as well as the overall hydrogen-bonding solvation parameter, s_{hb} , are obtained from the third COSMOments, HB_acc3 and HB_don3 , of charge density profiles of COSMO-RS theory^{20,21} for their hydrogen bonding acceptor and donor parts, respectively, through the following defining equations:¹

$$s_{\text{hb}}^2 = s_a^2 + s_b^2 \quad (7)$$

$$\frac{s_b^2}{s_{\text{hb}}^2} = 1 - \frac{s_a^2}{s_{\text{hb}}^2} = \frac{HB_acc3}{m\text{-SUM}} \quad (8)$$

and

$$s_{\text{hb}} = \delta_{\text{hb, water}} \sqrt{\frac{m\text{-SUM}}{m\text{-SUM}_{\text{water}}}} \sqrt{\frac{V_{\text{cosm, water}}}{V_{\text{cosm}}}} \cong 2 \sqrt{\frac{m\text{-SUM}}{V_{\text{cosm}}}} \quad (9)$$

where,

$$m\text{-SUM} = HB_acc3 + 1.492HB_don3 \quad (10)$$

The factor 1.492 in eq 10 arises from the ratio of the third HB-acceptor and HB-donor moments for water, which was selected as the reference neutral compound with equal acid and base solvation parameters.

The polar PSP may be obtained now from the cohesive energy density of the compound (cf., eq 5) through the following equation:

$$s_p^2 = \text{ced} - (s_d^2 + s_{\text{hb}}^2) \quad (11)$$

Unfortunately, eq 11 or eq 5 do not hold true for all compounds. In fact, quite often, the subtraction in eq 11 (and similarly in eq 5) leads to negative values, implying imaginary values for s_p or δ_p . Thus, we are forced to divide the compounds into two major classes. In the first class belong the compounds which meet eqs 5 or 11 and are called *homosolvated* compounds.¹ Examples are the saturated hydrocarbons, most of the nonsaturated and aromatic hydrocarbons, the self-associated alcohols, carboxylic acids, amines, etc. In the second class belong the compounds which do not meet eqs 5 or 11 and are called *heterosolvated* compounds.¹ Examples are the compounds which are proton acceptors only, such as the ketones, aldehydes, ethers, esters, tertiary amines, etc., or the compounds which are proton donors only, such as chloroform or acetylene. We will discuss heterosolvation below but we must first define the polar PSP. Since eq 11 does not hold true for these compounds we should seek alternative universalities.

One way to proceed is to use eq 11 in an alternative form. Since heterosolvated compounds are not hydrogen-bonded in their pure state or they are very weakly hydrogen-bonded, their cohesive energy is essentially reflecting their dispersion and polar character but not their hydrogen bonding capacity. For the latter, another (*heteron*) complementary compound is needed to solvate our compound and bring up its hydrogen bonding capacity, as we will see below. As a consequence, one may argue that the correct way of using eq 11 for heterosolvated compounds is

$$s_{p+}^2 = \text{ced} - s_d^2 \text{ (heterosolvated compounds)} \quad (12)$$

What we can say at this stage is that s_{p+} encompasses contributions that we would otherwise attribute to hydrogen bonding interactions, thence the subscript +. Another way to proceed is to seek a simple universal equation which would correlate s_p with a molecular parameter intimately related to its dipolarity, such as the dipole moment. Since we want this equation to be universal, it must describe properly the s_p of our reference compound, water, which is a typical homosolvated one. This condition leads to the following equation:¹

$$s_p = t \left(\frac{1.29}{\sqrt{V_{\text{cosm}}}} - 1.10 \right) \quad (13)$$

t is the dipole moment of the compound in Debyes and is also obtained from the COSMObase.²¹ The numerical factors in this equation guarantee that the result will be in units of $\text{MPa}^{1/2}$. This equation frees us from the restrictions of eq 5 which is now replaced by the equation

$$\text{sed} = s_{\text{total}}^2 = s_d^2 + s_p^2 + s_{\text{hb}}^2 \quad (14)$$

Equation 14 is, simultaneously, the definition of *solvation energy density* (sed) in direct analogy with the cohesive energy density (ced).^{6,7}

The required COSMO-RS parameters (V_{cosm} , t , HB_acc3 , and HB_don3) for calculating s_d , s_p , s_a , and s_b are already available for thousands of molecules.^{21,31} For any new compound they can be calculated rather easily via widely available quantum-chemical computation suites such as the Dmol³ DFT module²⁴ embodied in the Materials Studio suite of Accelrys or the Turbomole^{23,32} suite. The dispersion solubility parameters of the homomorph hydrocarbons may be obtained from the relevant compilations^{8–10,33} or may easily be calculated via a robust group-contribution method.³⁴

2.2. σ -Scheme of PSPs. In an effort to map LSER molecular descriptors onto partial solvation parameters and take advantage of the rich information the former contain, the alternative σ -scheme of PSPs has been proposed.² The rationale for the first σ PSP that would map McGowan volume,¹⁶ V_x , is as follows:² It should reflect cavity effects, hydrophobicity, dispersion or weak nonpolar interactions, and should be calculated by atom-specific parameters. Above all, it should be the square root of an energy density as are all PSPs, and it should lay the ground for negative PSPs (since the LSER descriptors E and S may have negative values). All these conditions are met by using the van der Waals energy (essentially, a correction energy to the energy of the reference state in solution), E_{vdW} , of COSMO-RS theory^{20,21} as our basis for the new PSP. Thus, our first descriptor, called van der Waals PSP, is defined as follows:

$$\sigma_{\text{W}} = \sqrt{\frac{E_{\text{vdW}}}{V_{\text{mol}}}} \quad (15)$$

V_{mol} is the molar volume of the compound. The van der Waals energy is already available for thousands of compounds,²¹ but it may be obtained also from alternative straightforward calculation schemes.^{35,36}

As already mentioned, the hydrogen bonding parameters are identical in the two schemes. Thus

$$\sigma_a = s_a, \sigma_b = s_b, \sigma_{\text{hb}}^2 = \sigma_a^2 + \sigma_b^2 = s_{\text{hb}}^2 \quad (16)$$

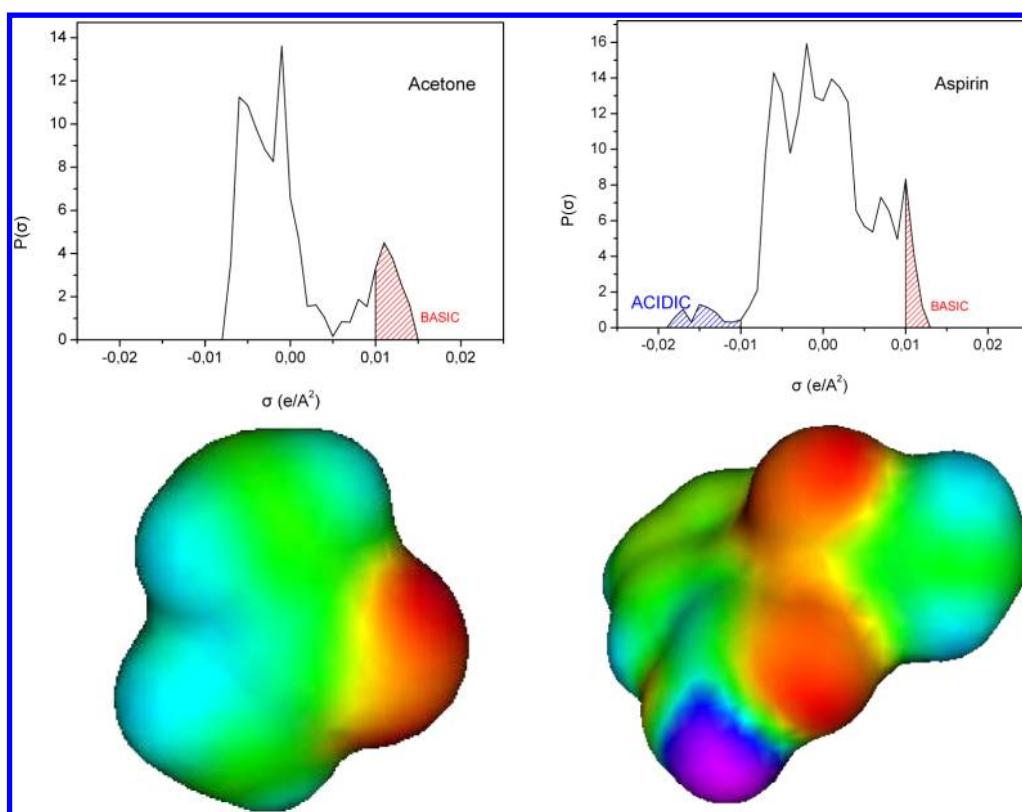


Figure 1. The surface charge density (σ) profiles of acetone and aspirin. Acetone is a typical heterosolvated compound with basic hydrogen-bonding lobe (red) only, while aspirin is a typical homosolvated compound with, both, acidic (deep blue/violet) and basic (red) hydrogen bonding lobes.

Two σ PSPs are now left to be defined, which will map the LSER descriptors E and S and for which we will use the symbols σ_E and σ_S , respectively. The detailed rationale for mapping E and S onto the electron polarizability and the polarity/polarizability PSPs, σ_E and σ_S , respectively, is exposed in ref 2. For the purposes of the present work we do not need to go into these details. All we need is the combined *polarity/refractivity* PSP which is defined as follows:

$$\sigma_{pz}^2 = \sigma_S^2 + \sigma_E^2 \quad (17)$$

For homosolvated compounds eq 11 now becomes

$$\sigma_{pz}^2 = ced - (\sigma_W^2 + \sigma_{hb}^2) \text{ (homosolvated compounds)} \quad (18)$$

and this is the way we may determine it. For heterosolvated compounds, we may, in analogy with the s-scheme, proceed in two alternative ways. In the first way and in direct analogy with eq 12, we may write

$$\sigma_{pz+}^2 = ced - \sigma_W^2 \text{ (heterosolvated compounds)} \quad (19)$$

However, whatever the scheme for the definition of PSPs, the sum of their squares should be equal to the solvation energy density, sed, of the compound or

$$\sigma_W^2 + \sigma_{pz}^2 + \sigma_{hb}^2 = \sigma_{total}^2 = s_{total}^2 = sed \quad (20)$$

In a second way, then, one may obtain the polarity/refractivity PSP from eq 20 as follows:

$$\sigma_{pz}^2 = s_{total}^2 - (\sigma_W^2 + \sigma_{hb}^2) = sed - (\sigma_W^2 + \sigma_{hb}^2) \quad (21)$$

For homosolvated compounds, sed is identical to ced and this simplifies the evaluation of σ_{pz} through eq 21. The consequence of the above is the following conditions to which PSPs are subject

$$\begin{aligned} \sigma_W^2 + \sigma_{pz}^2 &= s_d^2 + s_p^2 = sed - \sigma_{hb}^2 \\ \sigma_W^2 + \sigma_{pz+}^2 &= s_d^2 + s_p^2 = ced \end{aligned} \quad (22)$$

The above equations are most useful ones for the interconnection of the various PSPs and the exchange of information between the two sets.

As discussed in ref 2, the LSER descriptors reflect free-energy associated properties in contrast to solubility parameters and PSPs which reflect energy associated properties. By properly mapping, then, the LSER A and B descriptors into the corresponding PSPs, one may obtain a pair of free-energy PSPs, σ_{Ga} and σ_{Gb} , which reflect hydrogen bond acidity and basicity, respectively. This can be done in an entirely analogous manner to the one used for mapping the hydrogen-bonding COSMO-moments onto s_a and s_b with eqs 7–10. According to Abraham's total acidity/basicity scale, water is an almost neutral or slightly acidic compound. This neutrality is becoming perfect for water by multiplying its B by 1.0198, since $A = 1.0198B$. Thus, the m -SUM for water is now: $m\text{-SUM}_{\text{water}} = A + 1.0198B = 0.676 + 1.0198 \times 0.663 = 1.3526$. The free-energy hydrogen-bonding partial solvation parameters are then obtained as follows:²

$$\sigma_{Ga}^2 + \sigma_{Gb}^2 = \sigma_{Ghb}^2 \quad (23)$$

$$\frac{\sigma_{Gb}^2}{\sigma_{Ghb}^2} = 1 - \frac{\sigma_{Ga}^2}{\sigma_{Ghb}^2} = \frac{B}{m\text{-SUM}} \quad (24)$$

Table 1. Partial Solvation Parameters of Pure Compounds

Part A: The van der Waals and polarity/refractivity PSPs for non self-associated compounds					
homosolvated			heterosolvated		
compound	σ_W (MPa ^{1/2})	σ_{pz} (MPa ^{1/2})	compound	σ_W (MPa ^{1/2})	σ_{pz+} (MPa ^{1/2})
methane	11.60 ^a	0.00 ^a	formaldehyde	14.98	18.53
ethane	12.40 ^a	1.00 ^a	glyoxal	14.61	20.16
propane	12.95 ^a	3.00 ^a	acetaldehyde	14.33	13.82
<i>n</i> -butane	13.55 ^a	4.00 ^a	acrolein	14.49	14.05
<i>n</i> -pentane	13.65	5.00	1-propanal	14.11	13.19
<i>n</i> -hexane	13.75	6.50	<i>trans</i> -crotonaldehyde	14.48	15.22
<i>n</i> -heptane	13.75	7.00	methacrolein	14.21	12.21
<i>n</i> -octane	13.75	7.00	1-butanal	14.00	12.34
<i>n</i> -nonane	13.75	7.50	2-methylpropanal	13.74	12.31
<i>n</i> -decane	13.75	7.50	1-pentanal	13.93	12.08
<i>n</i> -undecane	13.75	7.50	1-hexanal	13.90	11.67
<i>n</i> -dodecane	13.75	8.00	benzaldehyde	14.66	15.86
<i>n</i> -tridecane	13.75	8.00	1-heptanal	13.89	11.37
<i>n</i> -tetradecane	13.75	8.00	2-methylhexanal	13.60	11.09
<i>n</i> -pentadecane	13.75	8.00	3-methylhexanal	13.64	10.61
<i>n</i> -hexadecane	13.75	8.00	terephthaldehyde	14.36	17.61
<i>n</i> -heptadecane	13.75	8.00	<i>p</i> -tolualdehyde	14.43	15.74
<i>n</i> -octadecane	13.75	8.00	2-ethylhexanal	13.61	11.10
<i>n</i> -nonadecane	13.75	8.00	1-octanal	13.86	11.35
<i>n</i> -eicosane	13.75	8.50	1-nonanal	13.87	11.09
<i>n</i> -heneicosane	13.75	8.50	1-decanal	13.82	11.07
<i>n</i> -docosane	13.75	8.50	1-undecanal	13.81	10.97
<i>n</i> -tricosane	13.75	8.50	1-dodecanal	13.81	10.97
<i>n</i> -tetracosane	13.75	8.50	1-tridecanal	13.80	10.87
<i>n</i> -pentacosane	13.75	8.50	acetone	14.10	13.80
<i>n</i> -hexacosane	13.75	8.50	methyl ethyl ketone	13.98	12.68
<i>n</i> -octacosane	13.75	8.50	2-pentanone	13.91	11.89
<i>n</i> -dotriacontane	13.75	8.50	3-pentanone	13.97	11.99
isobutane	13.17	2.90	2-hexanone	13.86	11.70
isopentane	13.37	3.65	3-hexanone	13.88	11.30
2-methylpentane	13.48	5.10	2-heptanone	13.84	11.32
3-methylpentane	13.48	5.80	3-heptanone	13.85	11.66
2,3-dimethylpentane	13.37	6.40	4-heptanone	13.87	10.23
2,3,4-trimethylpentane	13.22	6.95	acetophenone	14.46	15.13
2,2,3,3-tetramethylpentane	13.04	7.65	2-octanone	13.83	11.21
cyclopentane	14.10	8.05	2-nonanone	13.80	10.90
cyclohexane	13.85	8.35	5-nonanone	13.78	10.53
cycloheptane	13.85	8.56	camphor	12.26	8.22
1-pentene	13.81	4.36	benzophenone	14.30	13.50
1-hexene	13.87	5.73	anthraquinone	13.19	11.92
<i>cis</i> -3-hexene	13.87	6.30	methyl formate	14.23	14.75
<i>trans</i> -3-hexene	13.91	6.36	ethyl formate	13.97	12.98
cyclopentene	14.39	8.82	<i>n</i> -propyl formate	13.90	12.17
cyclohexene	14.20	10.07	<i>n</i> -butyl formate	13.81	11.89
dimethylacetylene	15.02	8.93	methyl acetate	14.04	13.32
benzene	14.84	11.43	ethyl acetate	13.85	12.03
toluene	14.59	11.09	<i>n</i> -propyl acetate	13.80	11.38
ethylbenzene	14.41	10.77	<i>n</i> -butyl acetate	13.78	10.93
<i>n</i> -propylbenzene	14.30	10.36	methyl propionate	13.93	12.36
<i>n</i> -butylbenzene	14.24	10.17	ethyl propionate	13.79	11.15
<i>n</i> -pentylbenzene	14.17	10.22	methyl methacrylate	14.09	12.04
<i>n</i> -hexylbenzene	14.13	10.20	dimethyl ether	13.81	6.16
<i>m</i> -xylene	14.40	10.89	methyl ethyl ether	13.79	6.78
<i>o</i> -xylene	14.40	11.45	diethyl ether	13.75	6.98
<i>p</i> -xylene	14.38	10.67	methyl isopropyl ether	13.59	7.07
<i>p</i> -ethyltoluene	14.24	10.66	methyl- <i>n</i> -propyl ether	13.86	7.28
mesitylene	14.30	10.87	ethyl isopropyl ether	13.52	6.40
<i>m</i> -cymene	14.07	9.77	ethyl propyl ether	13.71	7.04

Table 1. continued

Part A: The van der Waals and polarity/refractivity PSPs for non self-associated compounds						
homosolvated			heterosolvated			
compound	σ_W (MPa ^{1/2})	σ_{pz} (MPa ^{1/2})	compound	σ_W (MPa ^{1/2})	σ_{pz+} (MPa ^{1/2})	
<i>o</i> -cymene	13.95	10.37	methyl- <i>n</i> -butyl ether	13.80	7.77	
<i>p</i> -cymene	14.03	10.10	methyl <i>sec</i> -butyl ether	13.50	7.50	
<i>m</i> -diethylbenzene	14.13	10.26	methyl <i>tert</i> -butyl ether	13.32	7.05	
<i>o</i> -diethylbenzene	14.14	10.26	di- <i>n</i> -propyl ether	13.76	7.26	
<i>p</i> -diethylbenzene	14.14	10.37	di- <i>n</i> -butyl ether	13.74	7.70	
2-ethyl- <i>m</i> -xylene	14.07	11.45	di- <i>n</i> -pentyl ether	13.76	7.10	
2-ethyl- <i>p</i> -xylene	14.14	10.49	di- <i>n</i> -hexyl ether	13.75	9.06	
styrene	14.70	12.06	di- <i>n</i> -octyl ether	13.74	9.14	
naphthalene	14.43	13.04	tetrahydrofuran	14.29	12.48	
anthracene	13.82	11.13	1,3-dioxane	14.10	15.12	
phenanthrene	14.38	14.00	1,4-dioxane	14.17	14.87	
biphenyl	14.46	12.72	chloroform	17.25	6.20	
D-limonene	13.79	9.54	dichloromethane	17.33	10.72	
α -terpinene	13.68	9.85	acetonitrile	14.60	19.11	
indene	14.81	13.91	acrylonitrile	14.48	15.97	
carbon tetrachloride	16.97	6.06	<i>N,N</i> -dimethylformamide	14.74	18.88	
methyl chloride	16.92	10.14	<i>N,N</i> -dimethylacetamide	14.46	17.04	
monochlorobenzene	15.51	11.57	dimethyl sulfoxide	15.46	21.83	
benzyl chloride	15.45	12.89	<i>N</i> -methyl-2-pyrrolidone	14.50	18.06	
carbon disulfide	18.42	8.77	trimethylamine	13.80	6.33	
carbon dioxide	14.20	7.79	triethylamine	13.46	6.99	
Part B: The partial solvation parameters for hydrogen- bonded compounds (MPa ^{1/2})						
homosolvated						
compound	σ_W	σ_{pz}	σ_b	σ_a	σ_{Gb}	σ_{Ga}
methanol	15.18	10.62	18.72	15.4	18.34	15.01
ethanol	14.65	10.92	15.04	11.4	15.12	11.28
1-propanol	14.45	10.96	12.91	10.1	13.17	9.87
1-butanol	14.30	11.33	11.49	8.98	11.91	8.74
1-pentanol	14.23	10.46	10.84	8.96	11.19	8.59
1-hexanol	14.16	9.79	10.08	8.33	10.51	7.96
1-heptanol	14.10	10.42	9.42	7.79	9.95	7.41
1-octanol	14.07	10.23	8.88	7.35	9.49	6.96
1-nonanol	14.03	10.96	8.43	6.98	9.10	6.58
1-decanol	13.98	10.82	8.11	6.66	8.83	6.27
1-undecanol	13.99	10.93	7.71	6.37	8.51	5.97
1-dodecanol	13.96	11.09	7.47	6.14	8.30	5.73
1-tridecanol	13.93	10.51	7.14	5.91	8.04	5.49
1-tetradecanol	13.85	10.27	6.91	5.71	7.85	5.28
1-pentadecanol	13.83	9.84	6.69	5.53	7.68	5.10
1-hexadecanol	13.77	9.79	6.49	5.37	7.52	4.92
1-heptadecanol	13.76	8.95	6.31	5.22	7.38	4.77
1-octadecanol	13.68	9.02	6.19	5.09	7.28	4.63
1-nonadecanol	13.70	8.79	5.99	4.95	7.14	4.49
1-eicosanol	13.66	9.05	5.85	4.83	7.03	4.36
isopropanol	14.23	10.03	13.31	9.61	13.39	9.57
2-butanol	14.23	9.24	11.13	8.58	11.39	8.43
2-methyl-1-propanol	14.11	7.76	10.90	9.66	11.21	9.24
2-methyl-2-propanol	13.87	8.81	11.51	7.65	11.82	7.75
2,2-dimethyl-1-propanol	13.00	8.98	9.60	7.37	10.19	7.22
2-pentanol	14.07	10.29	10.24	7.91	10.61	7.73
3-pentanol	14.07	10.30	9.74	6.86	10.27	6.83
2-ethyl-1-butanol	13.95	10.10	8.85	7.85	9.38	7.48
2-hexanol	14.04	10.34	9.53	7.16	9.98	7.01
2-heptanol	13.98	7.93	8.77	6.15	9.44	6.05
2-octanol	13.96	9.87	8.40	6.45	9.03	6.22
cyclohexanol	14.10	14.04	10.58	7.49	10.91	7.42
phenol	14.95	13.93	4.79	13.4	8.35	11.89

Table 1. continued

Part B: The partial solvation parameters for hydrogen- bonded compounds (MPa ^{1/2})						
homosolvated						
compound	σ_W	σ_{pz}	σ_b	σ_a	σ_{Gb}	σ_{Ga}
benzyl alcohol	14.84	15.44	8.89	8.53	10.63	8.07
<i>m</i> -cresol	14.73	13.63	4.61	12.1	8.07	10.73
<i>o</i> -cresol	14.76	12.21	3.86	12.03	7.71	10.62
<i>p</i> -cresol	14.67	14.18	4.82	12.07	8.09	10.70
4-hydroxystyrene	14.03	11.57	3.65	12.07	7.69	10.67
<i>p</i> -ethylphenol	14.44	11.88	4.40	11.23	7.64	9.92
2,3-xyleneol	13.95	11.28	3.44	10.95	7.33	9.63
2,4-xyleneol	14.64	11.83	3.87	10.99	7.45	9.68
ethylene glycol	15.16	20.36	16.55	14.75	17.51	13.94
1,2-propylene glycol	14.67	17.76	14.14	11.85	15.19	11.30
1,3-propylene glycol	14.65	18.61	15.50	12.10	16.02	11.62
glycerol	14.56	24.13	15.16	11.84	16.59	11.38
1,2-butanediol	14.38	16.05	12.77	10.74	13.85	10.20
1,3-butanediol	14.36	15.08	14.12	11.01	14.65	10.54
1,4-butanediol	14.31	17.69	14.08	10.80	14.50	10.37
2,3-butanediol	14.13	14.55	13.17	9.40	14.20	9.18
diethylene glycol	14.54	17.36	14.28	7.38	15.56	7.73
triethylene glycol	14.46	13.57	13.78	6.36	15.28	6.70
sorbitol	13.54	29.80	12.02	13.01	14.36	11.82
tetraethylene glycol	14.37	11.67	13.69	5.61	15.24	6.05
formic acid	15.06	8.78	9.59	22.96	13.90	20.34
acetic acid	14.27	9.01	10.28	17.49	13.84	15.55
propionic acid	14.03	8.38	8.99	15.21	12.19	13.48
<i>n</i> -butyric acid	13.90	9.41	7.99	13.68	11.07	12.09
<i>n</i> -pentanoic acid	13.86	7.95	7.30	12.54	10.30	11.05
<i>n</i> -hexanoic acid	13.81	9.85	6.77	11.66	9.69	10.25
<i>n</i> -heptanoic acid	13.82	12.07	6.37	10.94	9.22	9.59
<i>n</i> -octanoic acid	13.78	12.02	6.00	10.33	8.82	9.04
<i>n</i> -nonanoic acid	13.81	12.12	5.75	9.80	8.50	8.56
<i>n</i> -decanoic acid	13.72	11.64	5.49	9.36	8.21	8.16
<i>n</i> -undecanoic acid	13.77	11.70	5.27	8.97	7.97	7.80
<i>n</i> -dodecanoic acid	13.65	12.27	5.08	8.63	7.76	7.49
<i>n</i> -tridecanoic acid	13.68	11.95	4.90	8.32	7.57	7.20
<i>n</i> -tetradecanoic acid	13.60	11.62	4.74	8.05	7.40	6.95
pentadecanoic acid	13.62	11.49	4.58	7.80	7.24	6.72
<i>n</i> -hexadecanoic acid	13.54	11.12	4.46	7.57	7.11	6.51
adipic acid	13.25	14.45	8.90	15.86	12.81	13.86
benzoic acid	14.01	14.42	6.09	12.78	9.39	11.31
methylamine	15.01	4.33	20.91	2.33	20.55	8.85 ^a
ethylamine	14.24	8.32	17.30	1.59	17.20	5.70
<i>n</i> -propylamine	14.07	9.17	15.12	1.44	15.15	4.35
<i>n</i> -butylamine	14.05	9.54	13.63	1.28	13.75	4.00
<i>n</i> -pentylamine	13.95	8.57	12.51	1.18	12.15	3.95
<i>n</i> -hexylamine	13.90	8.36	11.64	1.09	11.95	3.00
dimethylamine	14.41	7.48	15.38	2.19	16.50 ^a	5.50
diethylamine	14.02	6.45	11.52	0.75	12.55	3.05
di- <i>n</i> -propylamine	13.93	6.99	9.77	0.68	10.05	2.75
di- <i>n</i> -butylamine	13.86	8.27	8.70	0.62	9.15	2.60
2-ethoxyethanol	14.41	9.42	11.92	5.06	13.20	5.65
acetylsalicylic acid	13.65	12.95	5.90	10.98	21.15	6.00
acetanilide	14.27	18.28	8.73	8.82	10.80	8.00
acetaminophen	12.02	14.18	9.86	13.69	11.90	8.75
<i>p</i> -chlorophenol	15.64	13.35	3.70	12.89	6.90	11.50
water	16.26	15.40	29.91	29.91	28.28	28.28
hydrogen peroxide	15.80	24.62	13.95	32.41	17.25	28.70

Table 1. continued

compound	heterosolvated					
	sed/ced	σ_{pz}	σ_b	σ_a	σ_{Gb}	σ_{Ga}
acetone	1.05	10.05 ^b	11.35	0.00	10.25 ^a	0.00
methyl ethyl ketone	1.04	8.65	10.15	0.00	8.65 ^a	0.00
2-pentanone	1.03	8.90	9.17	0.00	7.95 ^a	0.00
acetaldehyde	1.04	10.25	10.75	0.00	12.00 ^a	0.00
1-propanal	1.02	10.10	9.34	0.00	12.50 ^a	0.00
1-butanal	1.01	9.60	8.23	0.00	11.00 ^a	0.00
1-pentanal	1.00	9.65	7.29	0.00	8.90 ^a	0.00
ethyl acetate	1.02	8.20	8.82	0.00	8.15 ^a	0.00
<i>n</i> -propyl acetate	1.02	8.05	8.03	0.00	8.00 ^a	0.00
<i>n</i> -butyl acetate	1.01	8.45	7.47	0.00	8.05 ^a	0.00
methyl propionate	1.01	9.25	8.21	0.00	8.10 ^a	0.00
dimethyl ether	1.22	2.10	12.11	0.00	9.80 ^a	0.00
diethyl ether	1.11	3.80	9.58	0.00	8.70 ^a	0.00
di- <i>n</i> -propyl ether	1.07	4.50	8.22	0.00	6.70 ^a	0.00
di- <i>n</i> -butyl ether	1.04	5.25	7.33	0.00	7.35 ^a	0.00
di- <i>n</i> -octyl ether	1.00	7.40	5.31	0.00	4.60 ^a	0.00
tetrahydrofuran	1.16	8.50	11.88	0.00	10.25 ^a	0.00
chloroform	1.05	3.20	0.00	8.80	0.00	7.90 ^a
trimethylamine	1.19	2.75	11.35	0.00	11.20	0.00
triethylamine	1.09	4.15	8.54	0.00	9.25	0.00

^aValues obtained from VLE data.⁴⁶ ^bValues in column are obtained from $\sigma_{pz+} - \sigma_{hb}/3$ and are valid for nonaqueous systems

and

$$\sigma_{Ghb} = \sigma_{Ghb,water} \sqrt{\frac{m-SUM}{m-SUM_{water}}} \sqrt{\frac{V_{cosm,water}}{V_{cosm}}} = 5.5 \sqrt{\frac{m-SUM}{V_{cosm}}} \quad (25)$$

where

$$m-SUM = A + 1.0198B \quad (26)$$

Having energy (from COSMOments) and free-energy (from LSER) hydrogen-bonding PSPs, one may calculate energies, entropies, and free-energies of hydrogen bond formation of type $\alpha\beta$ between molecules of type i and j , respectively, by the following equation:

$$E_{\alpha\beta,ij}^H = -h\sigma_{a,i}^{\alpha}\sigma_{b,j}^{\beta}\sqrt{V_{mol,i}V_{mol,j}} \quad (27)$$

$$G_{\alpha\beta,ij}^H = -f\sigma_{Ga,i}^{\alpha}\sigma_{Gb,j}^{\beta}\sqrt{V_{mol,i}V_{mol,j}} + g \quad (28)$$

and

$$S_{\alpha\beta,ij}^H = (E_{\alpha\beta,ij}^H - G_{\alpha\beta,ij}^H)/T \quad (29)$$

The proposed² values for the universal coefficients h , f , and g are $h = 1.86$, $f = 1.70$, and $g = 2.50$ kJ/mol.

2.3. Remarks on Homosolvation and Heterosolvation.

From the above, it is clear that the distinction of homosolvation from heterosolvation is a crucial issue in the PSP approach. We may further amplify on this issue, in a simplified manner, from another point of view through COSMO-RS theory.^{19–21}

In Figure 1 are shown the (screening) charge density or sigma profiles^{19–21} of acetone and aspirin. In the COSMO-RS approach,^{19–21} hydrogen bonding is operational with the portions or lobes of the sigma profiles beyond values of $|\sigma| \geq 0.01$ e/Å² (hatched areas in Figure 1). For hydrogen bonding to occur, such portions from, both proton acceptor (basic) and proton donor (acidic) sides are required. When this occurs, the

hydrogen bonding contribution of two surface pieces with complementary charge densities σ and σ' to the potential energy of the system is calculated through the functional:^{19–21}

$$E_{HB}(\sigma, \sigma') = a_{eff}c_{HB} \min(0; \min(0; \sigma_{donor} + 0.01) \max(0; \sigma_{acceptor} - 0.01)) \quad (30)$$

a_{eff} and c_{HB} are universal adjustable parameters. If the above condition is not satisfied, these surface pieces are just interacting pairwise in a Quasi-Chemical manner^{26,27} with all other surface pieces but not with the specific functional form of eq 30. Aspirin has both types of portions and, thus, hydrogen bonding is operational, not only in solution, but also in its pure state. This is a typical *homosolvated* compound. In contrast, acetone possesses basic lobe only and, thus, it hydrogen bonds only when it is solvated by another (*heteron* in Greek) compound which possesses acidic lobe. This is a typical *heterosolvated* compound. In the pure state of acetone, the surface charges of its basic lobe just participate in the above pairwise interactions as strong (polar) surface charge densities. In other words, acetone in its pure state or in mixtures with inert solvents does not exhibit any hydrogen bonding character as quantified by eq 30. In the solubility parameter or PSP terminology, the above are translated as follows: The cohesive energy of acetone arises from dispersion and (di)polar interactions only. This is why its cohesive energy density does not satisfy the above eqs 5 or 11 or 18. In contrast, the cohesive energy of aspirin arises from dispersion, (di)polar, as well as hydrogen bonding interactions and, thus, the use of eqs 5, 11, or 18 is legitimate in this case. On the other hand, when a surface piece is involved in a hydrogen-bonding interaction of longer lifetime, it appears not available for a weaker pairwise interaction of shorter lifetime to the extent other surface pieces appear available. As a consequence, the values of s_{p+} and σ_{pz+} obtained from cohesive energy density, are expected to be higher than the corresponding values of s_p or σ_{pz} obtained from solvation energy density through eqs 22.

Extensive tables with PSP values are reported in refs 1 and 2, except for s_{p+} and σ_{pz+} PSPs. For the purposes of this work, values of σ PSPs are collected in Table 1 for a number of common compounds, including σ_{pz+} values and the ratio of sed over ced for some heterosolvated compounds. This Table will be discussed in a later section. Once the PSPs are available, we may proceed to the development of a coherent thermodynamic framework for their critical testing.

3. MIXTURE THERMODYNAMICS FRAMEWORK

In this section, we will use PSPs and will develop a simple model for the thermodynamics of binary liquid mixtures, which can be extended to multicomponent mixtures in a straightforward manner. The σ PSPs will be used here but the model can be easily adapted to s PSPs. Traditionally, the solubility parameter and the LSER approaches find their main uses in infinite dilution systems. Their use in concentrated solutions is often not encouraging. In this work, we will apply the PSP approach to both concentrated solutions and systems at infinite dilution. For clarity, we will divide the presentation into two subsections, one for concentrated solutions and a second for infinite dilution systems.

3.1. Concentrated Solutions. Let us consider a mixture of N_1 moles of component 1 with N_2 moles of component 2 at an external temperature T and at a relatively low pressure p . Each molecule of type 1 consists of r_1 identical segments and each molecule of type 2 consists of r_2 identical segments. Since our molecules are polymeric in nature and will include high polymers, we will adopt the simple lattice picture^{37–39} for their arrangement in the volume of our system. The numbers of external contacts per molecule are zq_1 and zq_2 for components 1 and 2, respectively, z being the lattice coordination number. Besides mole fraction, $x_i = N_i/N$, the composition of the mixture may be expressed by the following alternative fractions:

$$\varphi_i = \frac{r_i N_i}{r_1 N_1 + r_2 N_2} = \frac{r_i N_i}{rN}, i = 1, 2 \text{ (volume fraction)} \quad (31a)$$

$$\theta_i = \frac{q_i N_i}{q_1 N_1 + q_2 N_2} = \frac{q_i N_i}{qN}, i = 1, 2 \text{ (surface area fraction)} \quad (31b)$$

The key quantity of our interest is the excess Gibbs free energy, G_m^E , from which we may derive expressions for the chemical potential or the activity coefficients. G_m^E may be considered to be subdivided into a combinatorial (superscript c) and a residual part (superscript r) as follows:

$$\frac{G_m^E}{RT} = \frac{\Delta G_m^c + \Delta G_m^r}{RT} \quad (32)$$

In terms of activity coefficients, eq 32 implies the following relation:

$$\ln \gamma_i = \ln \gamma_i^c + \ln \gamma_i^r \quad (32a)$$

PSPs will let us determine this residual contribution to the excess free energy or the activity coefficient. For the combinatorial part, the widely used Guggenheim–Staverman⁴⁰ expression will be adopted or

$$\begin{aligned} \frac{\Delta G_m^c}{RT} = & x_1 \left[\ln \left(\frac{\varphi_1}{x_1} \right) + \frac{z}{2} q_1 \ln \left(\frac{\theta_1}{\varphi_1} \right) \right] \\ & + x_2 \left[\ln \left(\frac{\varphi_2}{x_2} \right) + \frac{z}{2} q_2 \ln \left(\frac{\theta_2}{\varphi_2} \right) \right] \end{aligned} \quad (33)$$

which, for the activity coefficient, implies

$$\ln \gamma_i^c = \ln \left(\frac{\varphi_i}{x_i} \right) + \frac{z}{2} q_i \ln \left(\frac{\theta_i}{\varphi_i} \right) + \frac{\varphi_j}{r_j} (l_{rj} - l_{rj}) \quad (33a)$$

where

$$l_i = \frac{z}{2} (r_i - q_i) - (r_i - 1) \quad (34)$$

The residual part encompasses contributions from the weak van der Waals (superscript W), dipolar/induced dipolar (superscript pz), and hydrogen bonding (superscript hb) interactions and may be considered, in turn, to be subdivided into the corresponding free energy of mixing terms or

$$\frac{\Delta G_m^r}{RT} = \frac{\Delta G_m^W + \Delta G_m^{pz} + \Delta G_m^{hb}}{RT} \quad (35)$$

and similarly for the activity coefficients or the chemical potentials. At low pressures we may further assume that

$$\Delta G_m^W \cong \Delta H_m^W \cong \Delta E_m^W \text{ and } \Delta G_m^{pz} \cong \Delta H_m^{pz} \cong \Delta E_m^{pz} \quad (36)$$

To calculate the above two mixing energies, we will adopt the simple picture of mean-field pairwise interactions of first neighbors in the lattice.^{37–39} We will consider, first, the weak van der Waals interactions and will assume that each segment site of type i interacts with a neighbor segment site of type j with an interaction energy ε_{ij} and the following equations apply:

$$\begin{aligned} \frac{z}{2} \varepsilon_{11} = \varepsilon_1^*, \frac{z}{2} \varepsilon_{22} = \varepsilon_2^*, \frac{z}{2} \varepsilon_{12} = \frac{z}{2} \sqrt{\varepsilon_{11} \varepsilon_{22}} = \varepsilon_{12}^* \\ = \sqrt{\varepsilon_1^* \varepsilon_2^*} \end{aligned} \quad (37)$$

The potential energy of pure component i , due to these van der Waals interactions, is simply

$$-E_i^W = N_i q_i \frac{z}{2} \varepsilon_{ii} = N_i q_i \varepsilon_i^*, i = 1, 2 \quad (38)$$

If N_{ij} is the total number of interactions between sites of types i and j , the corresponding potential energy of the mixture is

$$-E_m^W = N_{11} \varepsilon_{11} + N_{12} \varepsilon_{12} + N_{22} \varepsilon_{22} \quad (39)$$

In the random mixing approximation^{37–39} the following equations apply:

$$\begin{aligned} N_{ii} = N_i q_i \frac{z}{2} \theta_i, i = 1, 2 \\ N_{ij} = N_i q_i z \theta_j = N_j q_j z \theta_i, i \neq j \end{aligned} \quad (40)$$

For the mixing energy, then, we have

$$\begin{aligned} \Delta E_m^W = E_m^W - E_1^W - E_2^W = -qN(\theta_1^2 \varepsilon_1^* + \theta_2^2 \varepsilon_2^* \\ + 2\theta_1 \theta_2 \varepsilon_{12}^* - \theta_1 \varepsilon_1^* - \theta_2 \varepsilon_2^*) = -qN\theta_1 \theta_2 \\ \times (2\varepsilon_{12}^* - \varepsilon_1^* - \varepsilon_2^*) = -qN\theta_1 \theta_2 \Delta \varepsilon_{12}^* \end{aligned} \quad (41)$$

On the other hand, from its very definition, the van der Waals PSP is given by

$$\sigma_{W_i}^2 = \frac{-E_i^W/N_i}{V_{mol,i}} = \frac{q_i \varepsilon_i^*}{V_{mol,i}}, i = 1, 2 \quad (42)$$

Equation 41 may, then, be expressed as follows:

$$\begin{aligned} \Delta E_m^W &= -qN\theta_1\theta_2(2\varepsilon_{12}^* - \varepsilon_1^* - \varepsilon_2^*) \\ &= qN\theta_1\theta_2(\sqrt{\varepsilon_1^*} - \sqrt{\varepsilon_2^*})^2 \\ &= qN\theta_1\theta_2 \frac{V_{mol,1}}{q_1} \left(\sigma_{W1} - \sigma_{W2} \sqrt{\frac{V_{mol,2}}{V_{mol,1}}} \frac{q_1}{q_2} \right)^2 \\ &\cong x_1\varphi_2 V_{mol,1} \frac{r}{q} \left(\sqrt{\frac{q_2}{r_2}} \sigma_{W1} - \sqrt{\frac{q_1}{r_1}} \sigma_{W2} \right)^2 \\ &\cong x_1\varphi_2 V_{mol,1} (\sigma_{W1} - \sigma_{W2})^2 \end{aligned} \quad (43)$$

The contributions to mixing energy from electron polarizability and polarity/polarizability interactions could be treated similarly, though the quadratic mixing rule of eq 37 may not apply, especially, in the case of strong dipolar interactions. Quite generally we may, then, write:

$$\begin{aligned} \Delta E_m^{pz} &\cong x_1\varphi_2 V_{mol,1} \{f_E(\sigma_{E1} - \sigma_{E2})^2 + 2\xi'_{12}\sigma_{E1}\sigma_{E2} \\ &\quad + f_S(\sigma_{S1} - \sigma_{S2})^2 + 2\xi_{12}\sigma_{S1}\sigma_{S2}\} \cong \beta_{12}x_1\varphi_2 \\ &\quad V_{mol,1}[(\sigma_{pz1} - \sigma_{pz2})^2 + 2\xi_{12}\sigma_{pz1}\sigma_{pz2}] \end{aligned} \quad (44)$$

The coefficients in this equation may be functions of polarizability, dipole moment, temperature, etc.

For the hydrogen-bonding contribution to the excess free energy, we will use our previous approach,^{41,42} which has been applied to numerous systems so far in the literature. The essentials of this approach, which is based on Veytsman statistics,⁴³ are summarized in the Appendix. In this approach and in the general case of a system with m types of donors and n types of acceptors, we may write for the contribution of hydrogen-bonding to the heat of mixing

$$\begin{aligned} \Delta H^H &= \left\{ \sum_{\alpha} \sum_{\beta} N_{\alpha\beta}^H E_{\alpha\beta}^H \right\}_m - \left\{ \sum_{\alpha} \sum_{\beta} N_{\alpha\beta}^{H,0} E_{\alpha\beta}^H \right\}_1 \\ &\quad - \left\{ \sum_{\alpha} \sum_{\beta} N_{\alpha\beta}^{H,0} E_{\alpha\beta}^H \right\}_2 \end{aligned} \quad (45)$$

In this equation, the summations of the products of numbers of hydrogen bonds of type $\alpha\beta$ with the corresponding hydrogen-bonding energy extend over all α - β donor-acceptor combinations in mixture (subscript m) and in pure components (subscripts 1 and 2). We may also write

$$\nu_H = \sum_{\alpha} \sum_{\beta} \nu_{\alpha\beta} = \sum_{\alpha} \sum_{\beta} \frac{N_{\alpha\beta}^H}{rN} \quad (46)$$

where ν_H is the average per segment number of hydrogen bonds in the system. If d_i^k is the number of hydrogen bond donors of type i ($i = 1, m$) in each molecule of type k ($k = 1, 2$) and a_j^k the number of hydrogen-bond acceptors of type j ($j = 1, n$) in each molecule of type k , the hydrogen bonding contribution to the chemical potential of component i in the mixture is given by (cf. Appendix):

$$\frac{\mu_{i,H}}{RT} = r_i \nu_H - \sum_{\alpha=1}^m d_{\alpha}^i \ln \frac{\nu_{\alpha}^{\alpha}}{\nu_{\alpha 0}} - \sum_{\beta=1}^n a_{\beta}^i \ln \frac{\nu_{\alpha}^{\beta}}{\nu_{0\beta}} \quad (47)$$

where

$$\nu_{\alpha}^{\alpha} = \frac{N_{\alpha}^{\alpha}}{rN} = \frac{\sum_{k=1}^m d_{\alpha}^k N_k}{rN} \quad (48)$$

and

$$\nu_{\alpha}^{\beta} = \frac{N_{\alpha}^{\beta}}{rN} = \frac{\sum_{k=1}^n a_{\beta}^k N_k}{rN} \quad (49)$$

while

$$\nu_{\alpha 0} = \nu_{\alpha}^{\alpha} - \sum_{\beta=1}^n \nu_{\alpha\beta} \quad (50)$$

and similarly

$$\nu_{0\beta} = \nu_{\alpha}^{\beta} - \sum_{\alpha=1}^m \nu_{\alpha\beta} \quad (51)$$

The $\nu_{\alpha\beta}$ values satisfy the minimization conditions

$$\frac{\nu_{\alpha\beta}}{\nu_{\alpha 0} \nu_{0\beta}} = \exp \left(-\frac{G_{\alpha\beta}^H}{RT} \right) \text{ for all } (\alpha, \beta) \quad (52)$$

Equations 52 are a set of $(m \times n)$ quadratic equations that must be solved simultaneously to obtain the number of each type of hydrogen bonds.

In eq 52, $G_{\alpha\beta}^H$ is the free enthalpy of formation of the hydrogen bond of type α - β and is given in terms of the energy (E), and entropy (S) of hydrogen bond formation (assuming negligible volume change) by the equation

$$G_{\alpha\beta}^H = E_{\alpha\beta}^H - TS_{\alpha\beta}^H \quad (53)$$

Hydrogen bonding PSPs will provide us with values for the free-energy, energy (or enthalpy), and entropy change upon formation of the hydrogen bond through eqs 27–29.

With the above equations we may write for the overall heat of mixing of our system the following equation:

$$\begin{aligned} H^E &= x_1\varphi_2 V_{mol,1} [(\sigma_{W1} - \sigma_{W2})^2 + \beta(\sigma_{pz1} - \sigma_{pz2})^2 \\ &\quad + 2\xi_{12}\sigma_{pz1}\sigma_{pz2}] + \left\{ \sum_{\alpha} \sum_{\beta} N_{\alpha\beta}^H E_{\alpha\beta}^H \right\}_m \\ &\quad - \left\{ \sum_{\alpha} \sum_{\beta} N_{\alpha\beta}^{H,0} E_{\alpha\beta}^H \right\}_1 - \left\{ \sum_{\alpha} \sum_{\beta} N_{\alpha\beta}^{H,0} E_{\alpha\beta}^H \right\}_2 \end{aligned} \quad (54)$$

where superscript 0 indicates pure-component state. The first terms in this equation are also the contributions of weak van der Waals and polarity/refractivity interactions to the residual excess free energy, or

$$\begin{aligned} \frac{\Delta G_m^W + \Delta G_m^{pz}}{RT} &= \frac{x_1\varphi_2 V_{mol,1} [(\sigma_{W1} - \sigma_{W2})^2 + \beta_{12}(\sigma_{pz1} - \sigma_{pz2})^2 + 2\xi_{12}\sigma_{pz1}\sigma_{pz2}]}{RT} \\ &= \frac{x_1\varphi_2 V_{mol,1} \Delta\sigma}{RT} \end{aligned} \quad (55)$$

From this equation, we obtain for the contribution to the chemical potential of component 1 the following equation:

$$\frac{\mu_{1,\sigma}}{RT} = \frac{\varphi_2 V_{\text{mol},1}}{RT} \Delta\sigma - \frac{\varphi_1 \varphi_2 V_{\text{mol},1}}{RT} \Delta\sigma = \varphi_2^2 V_{\text{mol},1} \frac{\Delta\sigma}{RT} \quad (56)$$

and similarly for component 2. Thus, the overall equation for the residual part of the chemical potential (or the activity coefficient) is

$$\ln \gamma_1^r = \frac{\mu_1^r}{RT} = \frac{\mu_{1,\sigma}}{RT} + \frac{\mu_{1,H}}{RT} = \varphi_2^2 V_{\text{mol},1} \frac{\Delta\sigma}{RT} + r_1 \nu_H - \sum_i^m d_i^1 \ln \frac{\nu_d^i}{\nu_{i0}} - \sum_j^n a_j^1 \ln \frac{\nu_a^j}{\nu_{0j}} \quad (57)$$

To see how these equations may be used, let us examine the simple case of alkanol–alkane mixtures. In the case of pure alkanols or polymers with –OH hydrogen bonding groups only (1–1 type interaction only, $a_1 = d_1 = x_1$ groups), the equation for the number of hydrogen bonds (cf., eq A18 in Appendix) reduces to the simple equation

$$r\nu_H = \frac{A_{11} + 2x_1 - \sqrt{A_{11}(A_{11} + 4x_1)}}{2} \quad (58)$$

where

$$A_{11} = r \exp(G_{11}^H/RT) = r/K_{11} \quad (59)$$

In this case, eq 47 reduces to the following equation

$$\frac{\mu_{1,H}}{RT} = r_1 \nu_H - 2 \ln \frac{x_1}{x_1 - r\nu_H} \quad (60)$$

and for component 2 (inert solvent) to the simple equation

$$\frac{\mu_{2,H}}{RT} = r_2 \nu_H \quad (61)$$

Thus, the full expression for the chemical potential or the activity coefficient of component 1 (and similarly for component 2) is

$$\begin{aligned} \frac{\mu_1 - \mu_1^0}{RT} &= \ln \gamma_1 x_1 = \ln x_1 + \ln \left(\frac{\varphi_1}{x_1} \right) + \frac{z}{2} \ln \left(\frac{\theta_1}{\varphi_1} \right) \\ &+ \frac{\varphi_2}{r_2} (l_1 r_2 - l_2 r_1) + \varphi_2^2 V_{\text{mol},1} \frac{\Delta\sigma}{RT} + r_1 \nu_H - 2 \\ &\ln \frac{x_1}{x_1 - r\nu_H} - \left(r_1 \nu_{H,0} - 2 \ln \frac{1}{1 - r_1 \nu_{H,0}} \right) \end{aligned} \quad (62)$$

where, the subscript H,0 means hydrogen bonding in pure-liquid state. The fraction of hydrogen bonds in the pure state is given by the equation (cf., eq 58)

$$\begin{aligned} r_1 \nu_{H,0} &= r_1 \nu_{11,0} = \frac{A_{11} + 2 - \sqrt{A_{11}(A_{11} + 4)}}{2} \\ &= \frac{r_1 + 2K_{11} - \sqrt{r_1(r_1 + 4K_{11})}}{2K_{11}} \end{aligned} \quad (63)$$

and

$$A_{11} = r_1/K_{11} \quad (64)$$

3.2. Systems at Infinite Dilution. The above formalism simplifies significantly in the case of infinite dilution. In this case our key equation for the activity coefficient of component i (the solute) at infinite dilution in component j (the solvent)

may be divided into its combinatorial and residual components as follows:

$$\ln \gamma_{i/j}^\infty = \ln \gamma_{i/j}^{c,\infty} + \ln \gamma_{i/j}^{r,\infty} \quad (65)$$

For the combinatorial contribution, we will use again the Guggenheim–Staverman⁴⁰ equation which, in the limit of infinite dilution, becomes

$$\begin{aligned} \ln \gamma_{i/j}^{c,\infty} &= \ln \frac{r_i}{r_j} + \frac{z}{2} q_i \ln \frac{q_i r_j}{q_j r_i} + \frac{z}{2r_j} (q_j r_i - q_i r_j) \\ &+ \left(1 - \frac{r_i}{r_j} \right) \end{aligned} \quad (66)$$

As seen in the previous subsection on concentrated solutions, there are two major contributions to the residual term of the activity coefficient at infinite dilution. One is from the weak van der Waals and polarity/refractivity interactions and the other from hydrogen bonding interactions. For the former, we obtain from eq 56 in the limit at infinite dilution ($\varphi_2 \approx 1$) the following equation:

$$\ln \gamma_{1/2}^{\sigma,\infty} = \ln \gamma_1^{\sigma,\infty} = V_{\text{mol},1} \frac{\Delta\sigma}{RT} \quad (67)$$

The hydrogen-bonding contribution to $\ln \gamma_{1/2}^{r,\infty}$, for the general case, is given in the Appendix (cf. eq 21A). This contribution takes simple forms in three cases of much practical interest.

In the simple case of a self-associated solute (1) at infinite dilution in an inert solvent (2), the residual activity coefficient of the solute is given by (cf., eq 62–63)

$$\ln \gamma_1^{r,\infty} = V_{\text{mol},1} \frac{\Delta\sigma}{RT} - (r_1 \nu_{H,0} + 2 \ln(1 - r_1 \nu_{H,0})) \quad (68)$$

In the case of a solute 1 with one donor site at infinite dilution in solvent 2 with a acceptor sites per molecule, none of which self-associate but they cross-associate, the residual activity coefficient at infinite dilution is given by the equation:

$$\ln \gamma_1^{r,\infty} = V_{\text{mol},1} \frac{\Delta\sigma}{RT} - \ln \left(1 + \frac{a}{r_2} K_{12} \right) \quad (69)$$

In a (co)polymeric solvent, the ratio a/r_2 is the number of acceptor sites per polymer or copolymer segment.

In the case of a self-associated solvent 1 with one donor and one acceptor sites at infinite dilution in a polymeric solvent 2 possessing a acceptor sites per polymer chain, the residual activity coefficient at infinite dilution is given by the equation

$$\begin{aligned} \ln \gamma_1^{r,\infty} &= V_{\text{mol},1} \frac{\Delta\sigma}{RT} - \ln \left(1 + \frac{a}{r_2} K_{12} \right) \\ &- (r_1 \nu_{H,0} + 2 \ln(1 - r_1 \nu_{H,0})) \end{aligned} \quad (70)$$

Equation 70 is a very useful one in a variety of applications, especially, in the characterization of polymers by inverse gas-chromatography and in surface characterization, when self-associated probes are used.

With the above formalism, we have a coherent thermodynamic framework for testing our PSP approach. We will test, in particular, the predictive capacity of our approach in a variety of systems. This is done in the next section. The required PSPs are reported in Table 1. Regarding parameters r and q , there are no unanimously accepted values in the literature but the most widely used are, probably, the so-called UNIQUAC param-

ters,^{44,45} which will be used here as well, with one exception: For water, we will use the parameters $r = 1.03$ and $q = 1.0$, considering it a near-spherical molecule.

4. APPLICATIONS

In line with the presentation of the thermodynamic model in the previous section, the section on Applications will be divided also into two subsections, one for concentrated solutions and a second for systems at infinite dilution. Each case has its own challenges and both deserve appropriate consideration. Common to both, however, will be a simplification of eq 55. Because of the lack of detailed information on coefficients β_{12} and ξ_{12} , and in analogy with eq 1 and our previous work,² we will adopt here the following most simple form:

$$\Delta\sigma = (\sigma_{w1} - \sigma_{w2})^2 + \frac{1}{3}(\sigma_{pz1} - \sigma_{pz2})^2 \quad (71)$$

The factor 1/3 has been preferred over the traditional factor 1/4 because in eq 71 there is no longer any contribution from hydrogen bonding terms, since hydrogen bonding contributions have been treated separately in the previous section. In any case, the testing of the PSP approach will also test the universality of this 1/3 factor.

4.1. Concentrated Solutions. Our first test will concern the very definition of σ_{pz+} PSP. As mentioned in section 2.2, this is a convenient PSP for heterosolvated compounds since it is obtained directly from the cohesive energy density of the compound and does not require any knowledge of its hydrogen bonding PSP. The basic hypothesis behind it is that hydrogen bonding is not operational in the pure state of heterosolvated compounds and the corresponding portion of the sigma profile^{19–21} is contributing as plain dipolar interactions. If this is the case, then one should be able to predict the phase behavior of its mixtures with inert solvents. This is indeed the case. A number of tests have been made with various heterosolvated compounds and the results do corroborate this hypothesis. One representative example is shown in figure 2 for the system acetone (heterosolvated)–benzene (inert). As shown, the predicted vapor–liquid equilibrium lines are in rather good agreement with experiment.⁴⁶

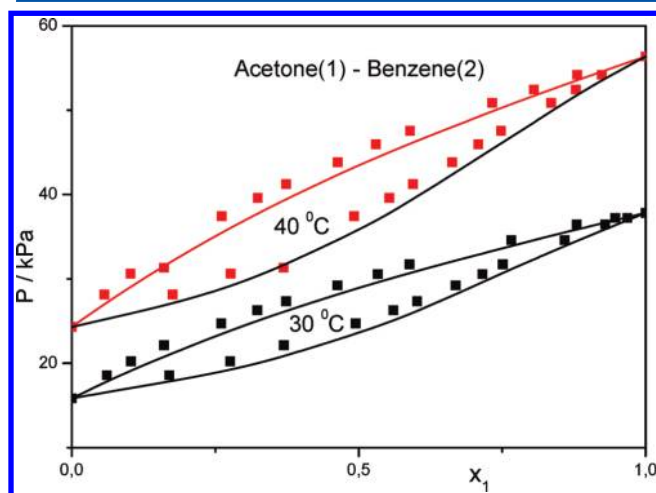


Figure 2. Experimental⁴⁶ (symbols) and predicted (lines) vapor–liquid equilibria for the system acetone (1)–benzene (2) at 30 and 40 °C.

One may argue that the above system is not deviating very much from regularity and, as a consequence, the test is not a stringent one for the predictive capacity of the PSP approach. Thus, the remaining tests will concern highly nonideal hydrogen-bonded systems. The only systems that did not involve hydrogen bonding were the binary mixtures of lower hydrocarbons with higher ones for rectifying the σ_w values of the former (obtained from the van der Waals energy of COSMO-RS^{19–21}), since they were leading to negative σ_{pz} values² when subtracted from ced. This is marked in Table 1.

The next class of tested systems is self-associated + inert mixtures. The relevant equations for this case are eqs 58–64 of the previous section. One typical example from this class of systems is ethanol – n-hexane. Both components are homosolvated ones and there is no ambiguity in their PSPs. In Figure 3 are compared the predictions of the PSP approach

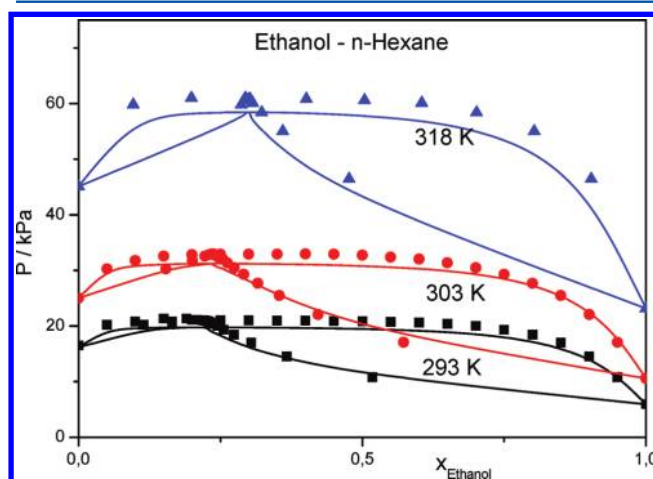


Figure 3. Experimental⁴⁶ (symbols) and predicted vapor–liquid equilibria for the system ethanol–hexane at three temperatures.

with the experimental VLE data.⁴⁶ As observed, the agreement is rather good, especially if one takes into consideration the fact that this mixture forms an azeotrope over the studied temperature range. Similar performance was observed with other mixtures from the same class.

In the third class of tested systems, the involved hydrogen bonding is rather complex as both components self-associate and cross-associate. One typical example from this class of systems is the mixture ethanol + water. Ethanol has one donor and one acceptor site, while water has two donors and two acceptor sites per molecule. This means that the hydrogen bonding PSPs for water should be divided by 2 to obtain the PSP per hydrogen bonding site. In this case one has to use the simple algorithm of the Appendix to obtain the numerical solution for the numbers of hydrogen bonds. In Figure 4, the predictions of the PSP approach are compared with the experimental VLE data⁴⁶ for this mixture. As observed, the PSP model performs quite satisfactorily with this rather complex system as well.

Before we proceed, one crucial point should be clarified. In the PSP tables of references 1 and 2 we have reported the PSP values as obtained from the corresponding equations without any correction or refinement. We have, as an example, reported the calculated van der Waals PSPs for the lower hydrocarbons, although they were leading to negative PSPs. As mentioned before, the VLE data with higher alkanes seem to be a reliable

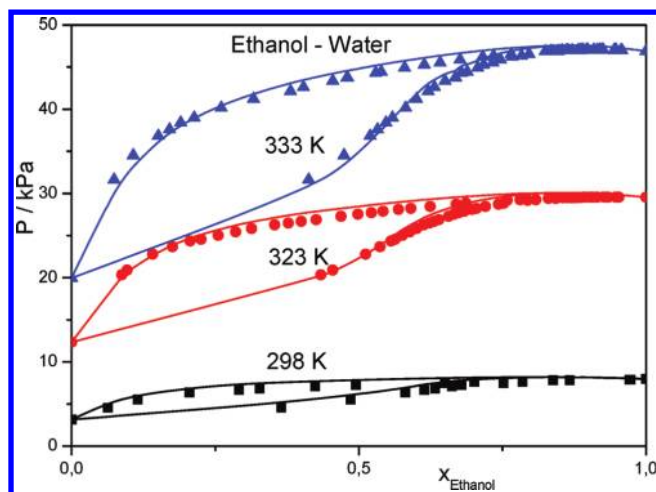


Figure 4. Experimental⁴⁶ (symbols) and predicted (lines) vapor–liquid equilibria for the system ethanol–water at three temperatures.

source of information for correcting the PSPs for these light compounds. Another ambiguity concerns the free-energy hydrogen-bonding PSPs of some compounds, especially the heterosolvated ones. These PSPs were obtained by mapping the A (acidity) and B (basicity) LSER molecular descriptors^{16,17} as given by COSMObase.²¹ In the COSMObase data there are often obvious corrections that should be made, as in the case of esters or ethers where it gives nonzero A values. In some other cases, however, as in amines, the corrections to be made are not obvious. In view of this, a different strategy has been adopted: Being convinced about the capacity of the PSP approach to predict phase equilibria of hydrogen bonded systems of known PSPs, we may also use it in the inverse way, to verify the PSPs, especially in cases of ambiguous values. In other words, the phase equilibrium data of mixtures with compounds of known PSPs may be used as a reliable source of information for correcting these ambiguous PSPs. Once these PSPs are known, they may be used for the prediction of phase behavior with other compounds.

Work along the lines of the above strategy is ongoing in our laboratory and has been applied, already, to many systems with satisfactory results. As an example, VLE data⁴⁶ of methylamine (2 donors, one acceptor) with *n*-butane have been correlated and its correct σ_{Ga} value was found equal to 8.85 MPa^{1/2}. This value was then used for the prediction of vapor–liquid equilibrium with other compounds with satisfactory results. An example is given in Figure 5 for the mixture of methylamine with *n*-hexane. These corrected PSPs are reported in Table 1.

Application of the above strategy to heterosolvated compounds is more challenging since, in this class of compounds, there is ambiguity not only in σ_{Ga} or σ_{Gb} PSPs but also in σ_{pz} values. These PSPs must be obtained simultaneously from hydrogen bonded systems. Fortunately, the phase equilibrium results are more sensitive to the hydrogen bonding PSPs and, thus, one may proceed to their determination with reasonable guesses for σ_{pz} values, in a first iteration, which may be refined in a second iteration. As already mentioned, the σ_{pz} values are expected to be smaller than the corresponding $\sigma_{\text{pz}+}$ values. In fact, one good initial guess is $\sigma_{\text{pz}} = \sigma_{\text{pz}+} - 1/3\sigma_{\text{hb}}$.

Once, however, these PSPs are determined, they may be used for the prediction of the phase behavior with other compounds. As an example, the above initial guess for acetone gives: $\sigma_{\text{pz}} =$

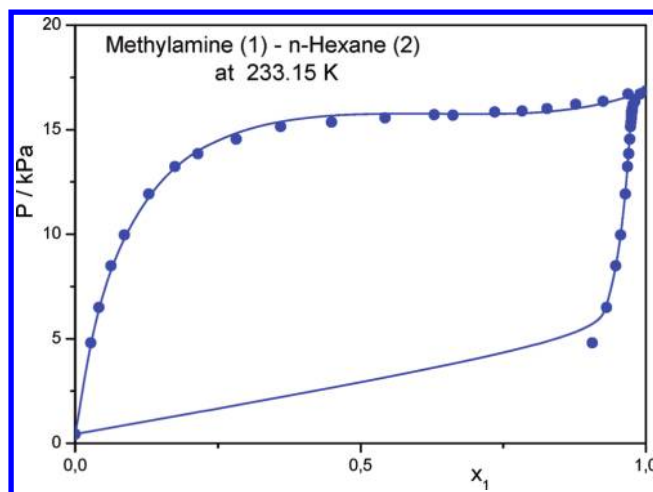


Figure 5. Experimental⁴⁶ (symbols) and predicted (lines) vapor–liquid equilibria for the mixture Methylamine (1)–*n*-Hexane (2) at 233.15 K.

10.05 MPa^{1/2}. With this value for σ_{pz} we obtain from its mixture with methanol (and verify by its mixture with ethanol) that $\sigma_{\text{Gb}} = 10.25 \text{ MPa}^{1/2}$.

For chloroform, the above initial guess is $\sigma_{\text{pz}} = 3.2 \text{ MPa}^{1/2}$. With this value for σ_{pz} , we obtain from its mixture with ethanol that $\sigma_{\text{Ga}} = 7.9 \text{ MPa}^{1/2}$. Having all PSPs for acetone and chloroform, we may predict their phase behavior, as shown in figure 6. This is how the reported PSP values in Table 1 were obtained for the heterosolvated compounds.

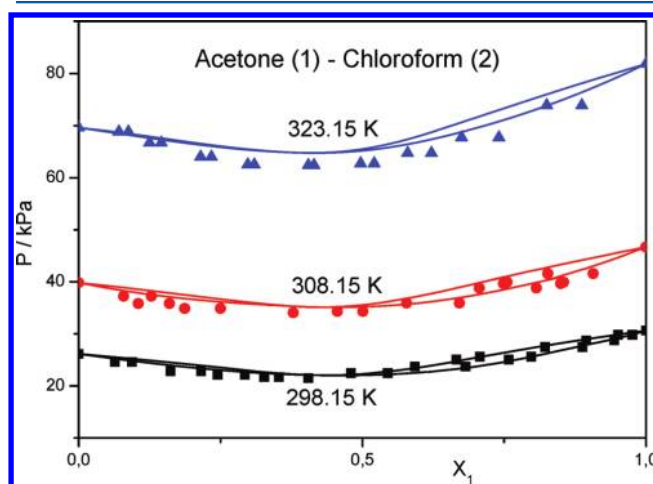


Figure 6. Experimental⁴⁶ (symbols) and predicted (lines) vapor–liquid equilibria for the mixture acetone (1)–CHCl₃ (2) at 3 temperatures.

The above picture breaks down in the case of mixtures of these heterosolvated compounds with water. If we want to retain the above values for all PSPs, our approach fails to properly predict the phase behavior of their mixture with water. If, however, we let the σ_{pz} PSP of heterosolvated compounds get low values, reminiscent of the corresponding values of lower hydrocarbons, then, the model is able to reasonably describe their phase behavior. One representative example is shown in figure 7 for the mixture of butanone (methyl ethyl ketone) with water. This is a challenging system approaching vapor – liquid – liquid phase separation. The calculations shown in figure 7 were

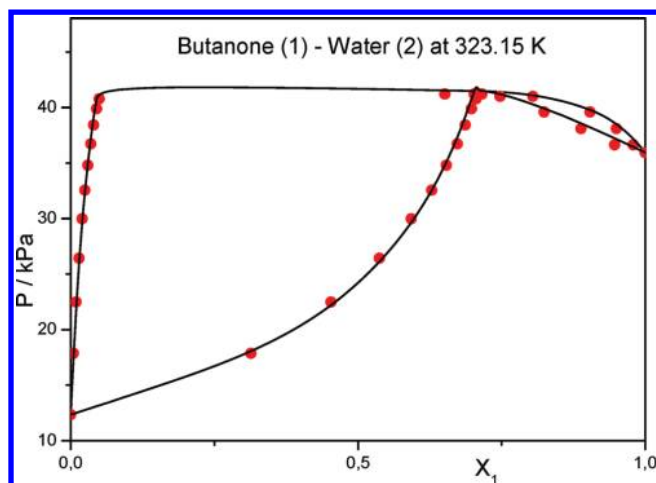


Figure 7. Experimental⁴⁶ (symbols) and calculated (lines) vapor–liquid equilibria for the mixture butanone (1)–water (2) at 323.15 K. Calculations were made with $\sigma_{pz} = 4.3$ for butanone.

made by reducing the σ_{pz} PSP of butanone to 4.3 MPa^{1/2}. It appears that these heterosolvated compounds, when in mixtures with water, exhibit a “hydrophobic” character to a much greater extent than their σ_{pz+} or their ordinary σ_{pz} PSP (reported in Table 1) imply. We will come back to this chameleonic behavior of these compounds, to Table 1, and to heterosolvation after we apply the PSP approach to infinitely dilute systems.

4.2. Systems at Infinite Dilution. The solubility parameter approach^{6–10} and the LSER approach^{11–17} are intimately related to studies of systems at infinite dilution with very important applications. In this section we will examine the capacity of the PSP approach to describe or even predict the related thermodynamic phenomena in some of these applications.

Our first application concerns solubility of solids in a variety of solvents. In this area falls the very important case of solubility of solid drugs. For the solubility (mole fraction) of solid 1 in solvent 2 we will adopt here the simple approach of Kramer and Thodos,⁴⁷ or

$$\gamma_1 = \frac{1}{\gamma_{1/2}^\infty} \left(\frac{f_1^{OS}}{f_1^{OL}} \right) \quad (72)$$

The term in parentheses is the ratio of the fugacity coefficients of component 1 in the pure solid and the pure liquid state, respectively, and it can be approximated by the following equation:

$$\ln \left(\frac{f_1^{OS}}{f_1^{OL}} \right) = \frac{\Delta H_1^m}{RT} \left(\frac{T}{T_1^m} - 1 \right) \quad (73)$$

and thus

$$\gamma_1 = \frac{1}{\gamma_{1/2}^\infty} \exp \left\{ \frac{\Delta H_1^m}{RT} \left(\frac{T}{T_1^m} - 1 \right) \right\} \quad (74)$$

where, ΔH_1^m is the enthalpy of fusion of solid 1 and T_1^m its melting point. Thus, for the calculation of solid solubility, the required quantity is the activity coefficient of the solid at infinite dilution in the solvent. Expressions for this quantity have been given in section 3.2. If heats of fusion are not available, one may

use Yalkowsky's⁴⁸ approximation and replace the term in the bracket in eq 74 by the term

$$A = -0.002278(T_1^m - 298.15)$$

Equation 74 has been applied to the solubility of acetanilide and paracetamol whose melting points are⁴⁹ 386.65 and 440.65 K, respectively, while their heats of fusion are⁴⁹ 21.2 and 27.1 kJ/mol, respectively. Acetanilide has one donor site and two acceptor sites, while paracetamol has one donor site and three acceptor sites. For simplicity, the acceptor sites in each of these molecules are considered equivalent. We may, then, use eq A21 of the Appendix for the hydrogen-bonding contribution to the activity coefficient at infinite dilution. In Figure 8 are compared

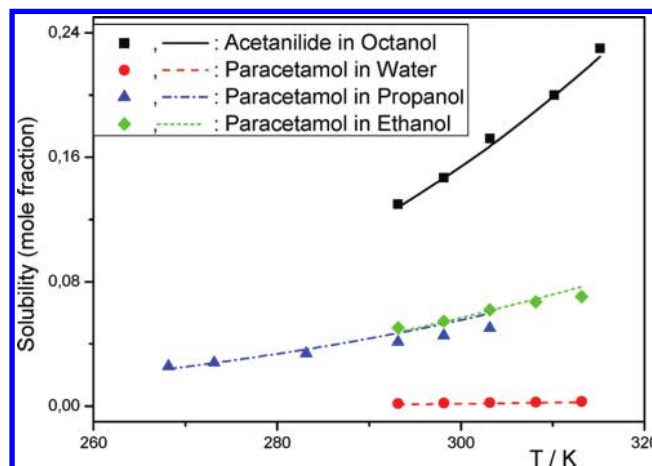


Figure 8. Experimental⁵⁰ (symbols) and predicted (lines) solubilities of solid drugs in hydrogen-bonded solvents as a function of temperature.

the experimental⁵⁰ solubilities of acetanilide and paracetamol in various solvents with the predicted ones by the PSP approach. In view of the complexity of these systems, the results shown in Figure 8 are rather satisfactory.

Another very important application is the characterization of heavy compounds by inverse gas chromatography (IGC). Of particular interest are the experimental data reported by Martire and Priedl⁵¹ for the characterization of *n*-heptadecane and di-*n*-octyl ether by IGC. For *n*-heptadecane we already have the values of its PSPs reported in Table 1. Thus, we may compare the experimental⁵¹ activity coefficients at infinite dilution in heptadecane with the predictions of the PSP approach. This is done in figure 9 for nonpolar (*n*-heptane), as well as for hydrogen-bonded (ethanol, 1-butanol, *t*-butanol) solutes (1) at infinite dilution in the solvent *n*-heptadecane at various temperatures. As shown in this figure, the predictions are in rather satisfactory agreement with the experimental data.

The other heavy solvent, di-*n*-octyl ether, poses some more challenges since, from the PSP perspective, it is a heterosolvated compound. From Table 1, its σ_{pz+} PSP is equal to 9.14 MPa^{1/2}, and the initial guess for its σ_{pz} is 7.4 MPa^{1/2}. Its σ_{Gb} may be determined by fitting the PSP calculations to experimental data for one solute – probe. By using the experimental data⁵¹ of 2-propanol for this purpose, we obtain $\sigma_{Gb} = 4.6$ MPa^{1/2}. Having all PSPs, we may predict the activity coefficients at infinite dilution for the other probes-solutes. The results are compared with experimental data in figure 10. As shown, the agreement is rather satisfactory, though there is some noticeable discrepancy for *t*-butanol at lower temper-

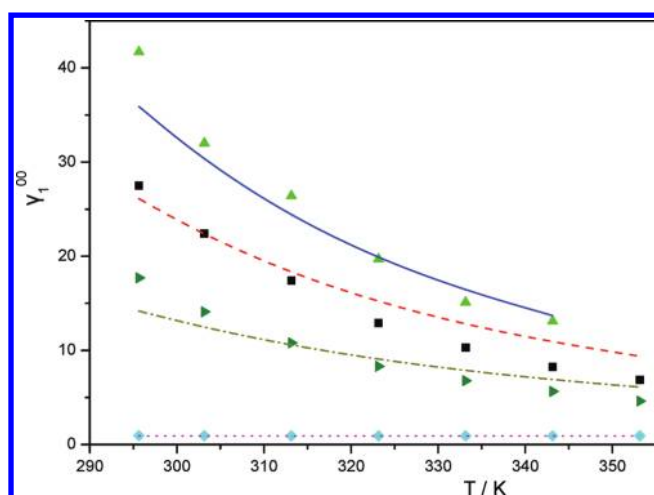


Figure 9. Experimental⁵¹ (symbols) and predicted activity coefficients at infinite dilution in *n*-heptadecane. Solid line: Ethanol. Dashed line: 1-Butanol. Dashed-dotted line: *t*-Butanol. Dotted line: *n*-Heptane.

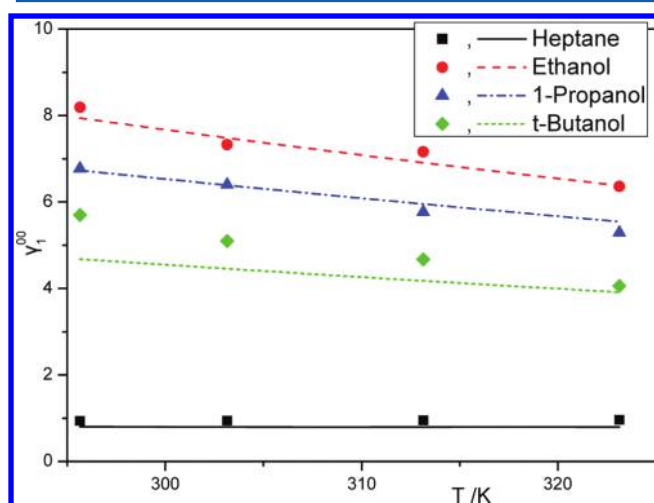


Figure 10. Experimental⁵¹ (symbols) and predicted (lines) activity coefficients at infinite dilution in di-*n*-octyl ether. The value of $\sigma_{\text{Gb}} = 4.6 \text{ MPa}^{1/2}$ for the ether was obtained from fitting the experimental data⁵¹ for 2-propanol.

atures. Martire and Priedl⁵¹ have also estimated the hydrogen bonding enthalpies and entropies for these systems with their hydrogen-bonding model. In Table 2 are compared the PSP predictions (eqs 27 and 29) with their calculations for these hydrogen-bonding quantities. As observed, the agreement in enthalpies is rather reasonable, in view of the fact that the

Table 2. Comparison of Hydrogen-Bonding Enthalpies and Entropies in Solute–Di-*n*-octyl-ether Systems

solute	enthalpy change (J mol^{-1})		entropy change ($\text{J K}^{-1} \text{mol}^{-1}$)	
	experimental ⁵¹	predicted	experimental ⁵¹	predicted
methanol	-19388 ± 2067	−16859	−60.4	−17.94
ethanol	-15668 ± 660	−15020	−51.7	−19.65
1-propanol	-14552 ± 413	−15021	−37.4	−19.70
2-propanol	-15585 ± 413	−14465	−53.7	−18.47
1-butanol	-17404 ± 1323	−14782	−57.9	−18.09
2-butanol	-16867 ± 910	−14126	−56.2	−18.91
<i>t</i> -butanol	-16445 ± 620	−14782	−59.1	−19.59

“experimental”⁵¹ data do involve a hydrogen-bonding model as well. The discrepancy in entropies is noticeable. The predicted entropy change upon formation of these hydrogen bonds ($\text{OH}\cdots\text{O}-$) is near constant and equal to $-18.8 \pm 0.8 \text{ J K}^{-1} \text{mol}^{-1}$, within the range of expected values for this type of hydrogen bond. The “experimental”⁵¹ ones vary from about -37 to $-60 \text{ J K}^{-1} \text{mol}^{-1}$. Again, these are not absolute values but model-dependent.

Inverse gas chromatography is widely used for polymer characterization.^{52,53} Typically, the reported parameter in these studies is the Flory–Huggins χ interaction parameter.³⁸ This parameter is related to the activity coefficient of solute i at infinite dilution in a polymeric solvent j with r segments per chain, in the frame of Flory–Huggins theory,³⁸ through the equation

$$\ln \gamma_{i,\text{FH}}^\infty = \ln\left(\frac{1}{r}\right) + \left(1 - \frac{1}{r}\right) + \chi_{ij} = \ln \gamma_{i,\text{FH}}^{\infty} + \chi_{ij} \quad (75)$$

A comparison of eqs 65, 66, and 75 leads to the following equation for the Flory–Huggins interaction parameter:

$$\chi_{ij} = \frac{z}{2} q_i \ln\left(\frac{q_i r_j}{r_i q_j}\right) + \frac{z}{2} r_i \left(\frac{q_j}{r_j} - \frac{q_i}{r_i}\right) + \ln \gamma_i^{r,\infty} \quad (76)$$

For non hydrogen-bonded systems, the working equation is (cf., eq 67)

$$\chi_{ij} = \frac{z}{2} q_i \ln\left(\frac{q_i r_j}{r_i q_j}\right) + \frac{z}{2} r_i \left(\frac{q_j}{r_j} - \frac{q_i}{r_i}\right) + V_{\text{mol},i} \frac{\Delta\sigma}{RT} \quad (77)$$

For hydrogen-bonded systems, the relevant terms from section 3.2 should be added to eq 77. As an example, in the case of a 1–1 cross association but no self-association, the equation becomes (cf. eq 69):

$$\chi_{ij} = \frac{z}{2} q_i \ln\left(\frac{q_i r_j}{r_i q_j}\right) + \frac{z}{2} r_i \left(\frac{q_j}{r_j} - \frac{q_i}{r_i}\right) + V_{\text{mol},i} \frac{\Delta\sigma}{RT} - \ln\left(1 + \frac{a}{r_2} K_{12}\right) \quad (78)$$

Sometimes, it is more practical to use the activity coefficient based on the weight fraction rather than the mole fraction. Their relation at infinite dilution is

$$\Omega_{1/2}^\infty = \gamma_{1/2}^\infty \left(\frac{r_2 \rho_2}{r_1 \rho_1}\right) \quad (79)$$

ρ_i being the density of component i .

The characterization of polymeric materials poses additional challenges to the PSP approach. Although, one may use COSMO-RS theory and have an approximate estimation of its PSPs, in practice, this is not helping very much. This is why IGC is a most useful method in this respect. One has to make a judicious choice of solvents and obtain PSPs from the measured χ values through eq 76. The subject of polymer characterization is a large one and deserves a separate publication. Here we will confine ourselves to two examples of applications of the PSP approach.

As a first example, the experimental data of Tian and Munk⁵² will be used for the characterization of poly(dimethyl siloxane) (PDMS). From the PSP point of view, because of the presence

of $-O-$ along the polymer chain, this macromolecule is a heterosolvated compound. We may obtain its van der Waals and polarity/refractivity PSPs by probing it with inert probes—solutes, such as octane, cyclohexane, or benzene. With such inert probes we have obtained for PDMS: $\sigma_W = 14.5$, $\sigma_{pz} = 3.7$ MPa $^{1/2}$. The hydrogen bonding PSPs may be obtained by probing it with hydrogen-bonding probes, such as the alkanols. By using 1-propanol and 1-butanol as probes, we have obtained for the hydrogen bonding PSPs of PDMS the following values (the acidic PSPs are zero in this case): $\sigma_b = 3.0$ and $\sigma_{Gb} = 5.2$ MPa $^{1/2}$. The kind of agreement between experimental and calculated χ_{12} parameters is shown in Figure 11.

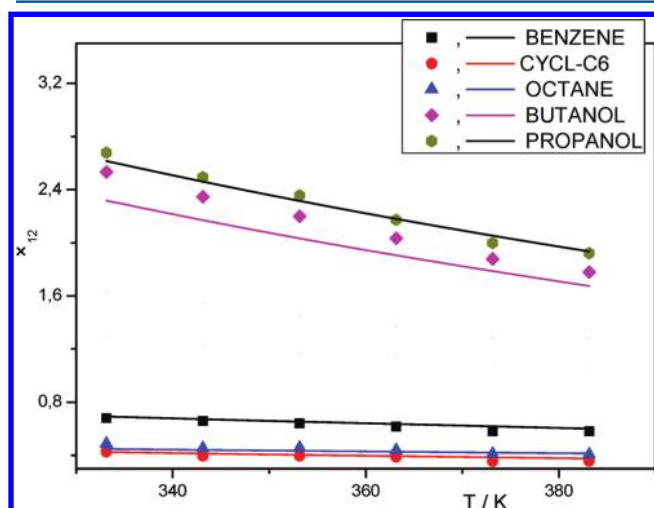


Figure 11. Experimental⁵² (symbols) and calculated (lines) Flory-Huggins χ_{12} interaction parameters for solute-poly(dimethyl siloxane) (PDMS) mixtures. The calculations have been made with the following PSPs for PDMS: $\sigma_W = 14.5$, $\sigma_{pz} = 3.7$, $\sigma_a = 0$, $\sigma_b = 3.0$, $\sigma_{Ga} = 0$, $\sigma_{Gb} = 5.2$ all in MPa $^{1/2}$.

Basic heterosolvated compounds do not seem to be appropriate probes for this polymer characterization. Relatively high or very low values of their σ_{pz} PSPs are required to correlate the experimental data.

As a last example, we show in Figure 12 some calculations with poly(ϵ -caprolactone) (PCL). This is also a basic heterosolvated polymer, as are many polar polymers. Of particular interest are the calculations with chloroform, an acidic probe. As shown, the PSP approach can easily account for negative χ parameters, which is not possible with the plain solubility parameter approach.^{6–10} In this case, the equation that has been used for χ is eq 78, while the PSPs for chloroform were those reported in Table 1. This implies that this heterosolvated probe did not exhibit any chameleonic character with PCL, and the prevailing orientation was the one dictated by its hydrogen bond. Of interest is the positive slope of the χ line with temperature for this probe/polymer pair. Corresponding slopes for alkanols in PDMS are negative. In the case of chloroform/PCL pair, the increase in temperature disrupts hydrogen bonds, thus making chloroform less favorable for PCL. In contrast, the destruction of hydrogen bonds of alkanols interacting with PDMS concerns, primarily, the self-association ones (cf., eq 68 and 70). Thus, as the temperature rises, alkanols are becoming less favorable for themselves and, as a consequence, more favorable for the polymer (lower χ).

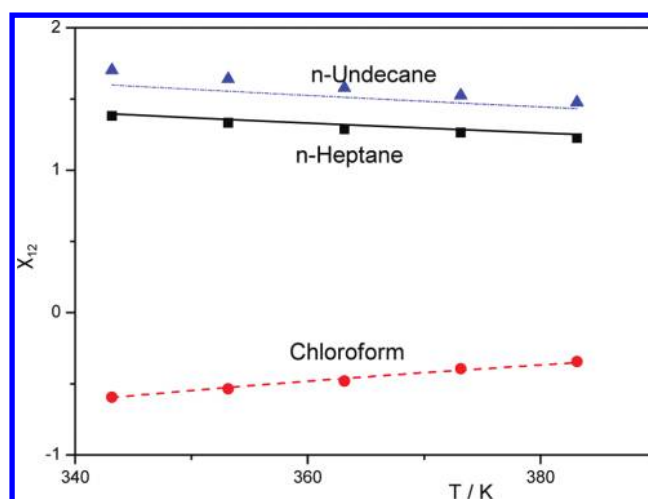


Figure 12. Experimental⁵² (symbols) and calculated (lines) Flory-Huggins χ_{12} interaction parameters for solute-poly(ϵ -caprolactone) (PCL) mixtures. The calculations have been made with the following PSPs for PCL: $\sigma_W = 18.5$, $\sigma_{pz} = 9.7$, $\sigma_a = 0$, $\sigma_b = 7.3$, $\sigma_{Ga} = 0$, $\sigma_{Gb} = 8.2$ all in MPa $^{1/2}$.

5. DISCUSSION

The solubility parameter approach,^{6–10} the solvatochromic/LSER approach,^{11–17} and the COSMO-RS theory of solutions^{19–21} are remarkable and inspiring efforts that marked the recent developments in various branches of physical chemistry. The task undertaken in this series of papers,^{1,2} amounts to infiltrating and distilling the essentials of these three approaches and give them a coherent form, understandable and usable by a broad scientific community. The results of the previous section are much encouraging. The PSP approach seems to cover satisfactorily, not only the traditional infinite dilution range but rather the full composition range. The systems that have been treated in the previous section are challenging hydrogen-bonded ones and the capacity of the PSP approach to satisfactorily predict their phase behavior indicates that hydrogen bonding is handled efficiently by this approach. This, in turn, indicates that the mapping of hydrogen-bonding COSMOs^{19–21} onto hydrogen-bonding energy PSPs and of hydrogen-bonding LSER descriptors^{16,17} onto hydrogen-bonding free-energy PSPs was a key step of primordial importance in the development of the PSP approach. Doubtless, the capacity of the PSP approach to account satisfactorily for the effect of temperature on the phase behavior and related properties is primarily due to this proper account of hydrogen-bonding.

The other two PSPs, namely, the van der Waals and the polarity/refractivity PSP, are also of vital importance. The former seems to cover efficiently what was initially attributed to the total solubility parameter by the “cavity term”.^{11,12} The latter PSP is then left to express all the remaining interaction features of the compound. For the purposes of the present work it was not deemed necessary to break it down into its components, σ_E and σ_S , the electron polarizability and the polarity/polarizability, respectively. It seems, however, that this will not be avoided and in a later stage we must resort to these specific features of each compound, especially, of the heterosolvated ones.

As we have seen in the previous section, heterosolvated compounds have one value of their polarity/refractivity PSP for their pure state or for their mixtures with inert solvents (the

σ_{pz+}), another value for their interaction with hydrogen-bonding solvents (the σ_{pz} reported in part B of Table 1), and another lower value for their interaction with water. In fact, they appear to exhibit still another value when probing polymers and surfaces, indicating, probably, a preferential orientation over them. These imply that heterosolvated compounds exhibit a varying character depending on the compound they interact with. Until we understand the regularities (if any) in this behavior of heterosolvated compounds, it is rather premature to use them as probes in IGC and other related techniques for the characterization of polymers and other surfaces. These peculiarities, however, pose a crucial question: Are they just handicaps of the PSP approach or they are reflecting something more fundamental or intrinsic features of the compounds? A definite answer may be given after an extensive and systematic study of carefully chosen compounds and systems. In the event they are proved fundamental or intrinsic features, the PSP approach seems sufficiently sensitive to capture and probe them.

Heterosolvation was introduced as a concept¹ to describe the very fact that the cohesive interactions may be different from the solvation ones. By design, COSMO-RS theory^{19–21} does take into consideration heterosolvation in an elegant manner through the functional of eq 30. This does not mean, however, that COSMO-RS can handle all the above-mentioned peculiarities of heterosolvated compounds. At present, the way COSMO-RS handles the free energy of hydrogen bonding or the preferential orientation over surfaces is still rather empirical. Advances in COSMO-RS, in this respect, will have a direct beneficial impact on the PSP approach.

The performance of the PSP approach is heavily based on the reliability of Table 1. Because of this, we are striving in this series of works^{1,2} to set forth strict rules for the determination of PSPs. As we often need to resort to mixture properties, it is crucial to have a coherent and consistent thermodynamic framework for extracting the PSPs out of these properties. The results of the previous section indicate that the thermodynamic framework of the present work has a sound basis and the qualifications for this purpose. Doubtless, there is much room for fine-tuning its details, such as the universal coefficients in eqs 27, 28, or 71, but already the selected ones seem to satisfactorily pick up the essential features of the compounds. This fine-tuning may lead to various iterations of Table 1 until it will be finalized.

The final form of Table 1 requires a concerted effort with other related approaches, as well. As an example, the mapping of A and B LSER descriptors onto the corresponding PSPs has no meaning if these A and B values are wrong or spurious. A change in the parametrization of COSMO-RS theory^{19–21} may affect PSPs significantly. Even the UNIQUAC r and q parameters may need reconsideration. These parameters have been modified for some compounds in the frame of UNIQUAC in order to cope with their strong specific interactions. But this has been done for a specific model that handles hydrogen bonding in a specific way. The way PSP approach handles hydrogen bonding is drastically different from UNIQUAC's. So far we were forced to change the r and q parameters for water only. The new parameters ($r = 1.03$, $q = 1.0$) appear much more appropriate for the molecular structure of water and the way PSP is handling hydrogen bonding. An analogous change may be needed for other strongly hydrogen bonded compounds.

As already mentioned, much care has been exercised to keep the formalism as simple as possible. Whenever permissible, rigor was sacrificed in favor of simplicity. In most cases the involved equations are analytical. Exceptions may occur for highly complex hydrogen-bonded systems. The cases examined in section 4.2, although cases with multiple hydrogen bonds, are still relatively simple ones and can be handled with simple equations for the activity coefficients at infinite dilution. As long as we can make the assumption that all donors or acceptors of our compound are identical, the general analytical eq A21 of the Appendix is sufficient even for complex molecules of any number of donors and/or acceptors. Thus, the PSP approach remains simple in its practical use, even in very complex systems.

Regarding hydrogen-bonding treatment, it may be used to evaluate the related assumptions in other approaches in the literature. As an example, in the Hansen Solubility Parameter approach^{9,10} the hydrogen bonding contribution to the activity coefficient at infinite dilution is assumed to be given by the third term in eq 1. If the two compounds cross-associate only, this term should be compared with the last term in eq 69. Of course

$$(\delta_{hb1} - \delta_{hb2})^2 \neq -\ln\left(1 + \frac{a}{r_2}K_{12}\right)$$

since the first term is always positive while the second is always negative. Various empirical modifications of the first term, in order to become negative, exist in the literature.^{10,34,54,55} The developments in the present work and in reference 1 may lead to a modified solubility parameter approach, where eq 1 could be replaced by an equation of the form

$$R_{ij}^2 = 4\left\{(\delta_{di} - \delta_{dj})^2 + \frac{1}{4}(\delta_{pi} - \delta_{pj})^2 - \frac{RT}{4V_{mol,i}}\ln\left(1 + \frac{a}{r_j}K_{ij}\right)\right\} \quad (1a)$$

out of which we could get useful information on the hydrogen-bonding equilibrium constant, K_{ij} . Analogous conclusions can be drawn for systems with more involved hydrogen bonding.

The present work does not complete by any means the work that should be done on the PSP approach. Much work is needed to extent Table 1 and to add verified PSPs in it. Such an extensive table of verified PSPs will facilitate significantly the further development of the PSP approach. Currently, there is an ongoing work in our laboratory to extent Table 1 and include new compounds, especially, heterosolvated ones. The *cosmo* files of a series of pharmaceuticals are produced with quantum chemical computation methods^{23,24,32} and their PSPs are determined. This, in turn, will facilitate the thorough study of (solid) drug solubility and related issues. Particular attention deserves the characterization of (co)polymers, polymer blends, ionic liquids, nanostructures, and solid surfaces, a much challenging field.

6. CONCLUSIONS

In this work, a simple, coherent and consistent thermodynamic framework has been developed for testing PSPs and the PSP approach to solution thermodynamics. The performed tests included concentrated mixtures as well as systems at infinite

dilution. In their majority, the tested systems were highly nonideal with strong hydrogen bonding interactions. These applications indicated that the PSP approach has a significant predictive capacity for major classes of compounds over the full composition range and over an extended temperature range. The condition for this performance is the availability of reliable PSP values for pure components. The concept of heterosolvation has been further clarified and the peculiarities of heterosolvated compounds have been discussed in an effort to draw particular attention to these compounds, especially, when used as probes for the characterization of other compounds. Advances in the PSP approach may involve a concerted effort in experiment as well as in related approaches to solution thermodynamics. This effort may lead to an integral predictive approach with the capacity to sense properly the strength of intermolecular interactions, the hydrophobicity, or the preferential molecular orientations.

APPENDIX

Hydrogen-Bonding Contributions

This Appendix summarizes the essentials of the approach to multi-donor/multi-acceptor hydrogen bonding in a binary mixture of polymeric components. A simple and robust algorithm for obtaining the number of hydrogen bonds is also given. Details of the approach may be found in the relevant literature.^{41–43,56,57}

Let us consider a system consisting of N_1 molecules of type 1 and N_2 molecules of type 2 at temperature T . Let us assume that there are m different kinds of hydrogen-bonding donors and n kinds of hydrogen-bonding acceptors. Let d_i^k be the number of hydrogen bond donors of type i ($i = 1, m$) in each molecule of type k ($k = 1, 2$) and a_j^k the number of hydrogen-bond acceptors of type j ($j = 1, n$) in each molecule of type k . The total number N_d^i of hydrogen-bond donors i in the system is

$$N_d^i = d_1^i N_1 + d_2^i N_2 \quad (\text{A1})$$

and the total number N_a^j of hydrogen-bond acceptors j in the system is

$$N_a^j = a_1^j N_1 + a_2^j N_2 \quad (\text{A2})$$

The total energy E_H of the system due to hydrogen bonding is given by

$$E_H = \sum_i^m \sum_j^n N_{ij} E_{ij}^0 \quad (\text{A3})$$

where N_{ij} is the number of hydrogen bonds between hydrogen bond donors of type i and hydrogen bond acceptors of type j , and N_{ij}^0 the corresponding hydrogen bonding energy of the i – j interaction. The total number of hydrogen bonds in the system is

$$N_H = \sum_i^m \sum_j^n N_{ij} \quad (\text{A4})$$

To find the different number of isoenergetic configurations of our system (the different ways of forming or distributing the hydrogen bonds in the system), we have to do the following:

- Find the number of different ways of selecting the associated donor sites out of the donor population.

- Find the number of different ways of selecting the associated acceptor sites out of the acceptor population.
- Find the number of different ways of making hydrogen bonds between the selected donor and acceptor sites.

The number of configurations of the system is the product of these three terms (a through c) and is given by the following general equation:^{41–43}

$$\begin{aligned} \Omega &= \prod_i^m \frac{N_d^i!}{N_{i0}! N_{i1}! \dots N_{im}!} \prod_j^n \frac{N_a^j!}{N_{0j}! N_{1j}! \dots N_{mj}!} \prod_i^m \prod_j^n N_{ij}! \\ &= \prod_i^m \frac{N_d^i!}{N_{i0}!} \prod_j^n \frac{N_a^j!}{N_{0j}!} \prod_i^m \prod_j^n \frac{1}{N_{ij}!} \end{aligned} \quad (\text{A5})$$

where N_{i0} is the number of free (non-hydrogen bonded) donor groups of type i and N_{i0} the respective number of free acceptor groups of type j

$$N_{i0} = N_d^i - \sum_j^n N_{ij} \quad (\text{A6})$$

$$N_{0j} = N_a^j - \sum_i^m N_{ij} \quad (\text{A7})$$

However, to form a hydrogen bond, the two interacting groups must be proximate. In our framework, the probability for a donor i –acceptor j pair to be proximate is approximated by the equation:⁴¹

$$P_{ij} = \frac{e^{S_{ij}^0/R}}{rN} \quad (\text{A8})$$

where S_{ij}^0 is the entropy loss (intrinsically negative) associated with hydrogen bond formation of an (i, j) pair.

With these definitions we may now write for the canonical partition function for hydrogen bonding the following equation:

$$\begin{aligned} Q_H(T, N_1, N_2, \{N_{ij}\}) &= \left(\frac{1}{rN} \right)^{N_H} \prod_i^m \frac{N_d^i!}{N_{i0}!} \prod_j^n \frac{N_a^j!}{N_{0j}!} \prod_i^m \prod_j^n \frac{\exp(-N_{ij} G_{ij}^0/RT)}{N_{ij}!} \end{aligned} \quad (\text{A9})$$

where the free-energy change upon formation of a hydrogen bond of type i – j is given by the equation

$$G_{ij}^0 = E_{ij}^0 - TS_{ij}^0 \quad (\text{A10})$$

Applying statistical thermodynamics, we may obtain the numbers N_{ij} of hydrogen bonds by requiring that they minimize the system free energy at equilibrium. The hydrogen bonding contribution to the free energy of the system, obtained from eq A9, is given by

$$\begin{aligned} \frac{G_H}{kT} &= rN \left\{ \sum_i^m \sum_j^n \nu_{ij} \left[1 + \frac{G_{ij}^0}{RT} + \ln \left(\frac{\nu_{ij}}{\nu_{i0} \nu_{0j}} \right) \right] \right. \\ &\quad \left. + \sum_i^m \nu_d^i \ln \frac{\nu_{i0}}{\nu_d^i} + \sum_j^n \nu_a^j \ln \frac{\nu_{0j}}{\nu_a^j} \right\} \end{aligned} \quad (\text{A11})$$

where the hydrogen-bond fractions are defined as

$$\nu_{ij} \equiv \frac{N_{ij}}{rN} \quad \nu_{i0} \equiv \frac{N_{i0}}{rN} \quad \nu_d^i \equiv \frac{N_d^i}{rN}, \text{ etc} \quad (\text{A12})$$

The free-energy minimization conditions

$$\left(\frac{\partial G_H}{\partial N_{ij}} \right)_{T,P,N_1,N_2,\{N_s\}} = 0 \quad (\text{A13})$$

when applied to eq A11, lead to the following equations:

$$\frac{\nu_{ij}}{\nu_{i0}\nu_{0j}} = \exp\left(-\frac{G_{ij}^0}{RT}\right) \text{ for all } i, j \quad (\text{A14})$$

or

$$\nu_{ij} = [\nu_d^i - \sum_k \nu_{ik}] [\nu_a^j - \sum_k \nu_{kj}] \exp\left(-\frac{G_{ij}^0}{RT}\right) \quad (\text{A15})$$

which is a system of $(m \times n)$ quadratic equations for ν_{ij} . ν_{ij} in these equations are again fractions of hydrogen bonds, or $\nu_{ij} = N_{ij}/rN$, $\nu_H = N_H/rN$, and similarly for ν_{i0} and ν_{0j} .

The hydrogen bonding contribution to the chemical potential of component k ($k = 1, 2$) is obtained as

$$\mu_{k,H} = \left(\frac{\partial G_H}{\partial N_k} \right)_{T,V,N_j,\{N_j\}} \quad (\text{A16})$$

which, combined with eq A11, gives

$$\frac{\mu_{k,H}}{RT} = r_k \nu_H - \sum_i d_i^k \ln \frac{\nu_d^i}{\nu_{i0}} - \sum_j a_j^k \ln \frac{\nu_a^j}{\nu_{0j}} \quad (\text{A17})$$

This formalism is applicable to a variety of systems of practical interest varying in complexity from simple self-associated systems, such as the alkanols, up to highly complex systems forming three-dimensional interpenetrating hydrogen-bonding networks, such as the multicomponent hydrogels and the self- and cross-associating polymer blends.

The hydrogen-bond fractions $r\nu_{ij}$ can be calculated from the following $(m \times n)$ equations:

$$r\nu_{ij} = \frac{1}{2} \{P_{ij} - \sqrt{(P_{ij}^2 - 4Q_{ij})}\} \text{ for all } i, j \text{ pairs} \quad (\text{A18})$$

where

$$P_{ij} = A_{ij} + (d_i^1 x_1 + d_i^2 x_2) + (a_j^1 x_1 + a_j^2 x_2) - \sum_{m \neq j} r\nu_{im} - \sum_{n \neq i} r\nu_{nj} \quad (\text{A19})$$

and

$$Q_{ij} = (d_i^1 x_1 + d_i^2 x_2 - \sum_{m \neq j} r\nu_{im})(a_j^1 x_1 + a_j^2 x_2 - \sum_{n \neq i} r\nu_{nj}) \quad (\text{A20})$$

x_i in these equations is the mole fraction of component i in the mixture

The numerical procedure for solving these equations, in the general case, is as following: We assume some initial values (usually smaller than 1) for the ν_{ij} s and calculate the P_{ij} s and Q_{ij} s. By using eq A18, we do the first calculation of the ν_{ij} s. This set of ν_{ij} s is used for calculating the second set of P_{ij} s and Q_{ij} s, which in turn is used for the second calculation of the ν_{ij} s. This

procedure is repeated until two consecutive calculations of the ν_{ij} s differ by less than a preset tolerance. This is a fast, efficient and robust algorithm.

At infinite dilution, the above implicit equations become analytical. In the general case of component 1 (the solute) with d_1 donors and a_1 acceptors and component 2 (the solvent) with d_2 donors and a_2 acceptors per molecule, the contribution of hydrogen bonding to the activity coefficient at infinite dilution is given by the following equation:

$$\begin{aligned} \ln \gamma_1^{H,\infty} &= r_1(\nu_{22,0} - \nu_{11,0}) - d_1 \\ &\ln \left\{ \left(1 + \frac{a_2}{r_2} K_{12} - \nu_{22,0} K_{12} \right) \left(1 - \frac{r_1}{d_1} \nu_{11,0} \right) \right\} - a_1 \\ &\ln \left\{ \left(1 + \frac{d_2}{r_2} K_{21} - \nu_{22,0} K_{21} \right) \left(1 - \frac{r_1}{a_1} \nu_{11,0} \right) \right\} \end{aligned} \quad (\text{A21})$$

where

$$r_1 \nu_{11,0} = \frac{1}{2} \{A_{11} + a_1 + d_1 - \sqrt{(A_{11} + a_1 + d_1)^2 - 4a_1 d_1}\} \quad (\text{A22})$$

and

$$\begin{aligned} r_2 \nu_{22,0} &= \frac{1}{2} \{A_{22} + a_2 + d_2 \\ &- \sqrt{(A_{22} + a_2 + d_2)^2 - 4a_2 d_2}\} \end{aligned} \quad (\text{A23})$$

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Notes

The authors declare no competing financial interest.

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