NEAT - NMR Spectroscopy for the Estimation of Activity Coefficients of Target Components in Poorly Specified Mixtures

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Abstract

Mixtures of which the composition is not fully known are important in many fields of engineering and science, e.g. in biotechnology. Due to the lacking information on the composition, such mixtures cannot be described with common thermodynamic models. In the present work, a method is described with which this obstacle can be overcome for an important class of problems. The method enables the estimation of the activity coefficients of target components in poorly specified mixtures and is based on a combination of NMR spectroscopy with a thermodynamic group contribution method. It is therefore called the NEAT method (NMR spectroscopy for the Estimation of Activity coefficients of Target components in poorly specified mixtures). In NEAT, NMR spectroscopy is used to obtain information on the concentrations of chemical groups in the mixture. The elucidation of the speciation is not required, only the target component has to be known. Modified UNIFAC (Dortmund) is applied in the

present work as group contribution method, but NEAT can be extended to any other group contribution method. NEAT has been introduced recently by our group in a short communication, in which, however, only the basic ideas were presented. In the present work, NEAT is described in full detail. Different options of using NEAT are discussed and examples for the application of the method are given. They include a variety of aqueous and non-aqueous mixtures. The results show very good agreement of the activity coefficients that are predicted by NEAT with the corresponding results for the fully specified mixtures.

Introduction

In many fields of engineering, such as bioprocess engineering, polymer technology, and petrochemical engineering, mixtures of which the composition is only partially known play an important role. Such mixtures are called ‘poorly specified mixtures’ in the following. Dealing with such mixtures in process design is challenging as classical thermodynamic models of mixtures cannot be applied - they require a full specification of the composition. Approaches to circumvent this problem have been discussed mainly in the field of petrochemical engineering.¹⁻⁸ A general concept for this is introducing pseudo components. However, choosing these pseudo components and assigning thermodynamic properties to them often turns out to be difficult.

A typical task in process engineering is the separation of target components from complex liquid mixtures. Fluid separation processes are generally based on concentration differences between coexisting phases and are often described using the equilibrium stage concept. Therefore, the design of a fluid separation process to capture and purify a target component from a mixture usually requires the knowledge of the thermodynamic activity of the target component in the mixture from which it is to be separated. Rather than referring to the activity, we will refer to the activity coefficient in the following. With thermodynamic models, such as NRTL,⁹ UNIQUAC,^{10,11} UNIFAC,¹²⁻¹⁵ or COSMO-RS,^{16,17} the activity coefficients

of target components in mixtures of known composition can be calculated, but these methods cannot be applied to mixtures for which the composition is not completely known, i.e. to poorly specified mixtures.

In a previous work of our group, a new method to estimate the activity coefficient of a target component in a poorly specified mixture was presented and its applicability was demonstrated using some examples.¹⁸ The new method is called NEAT (NMR spectroscopy for the Estimation of Activity coefficients of Target components in poorly specified mixtures). It is based on a simple idea: even for mixtures for which it is hard or impossible to obtain information on the speciation (i.e. the nature and concentration of the components), it is in most cases simple to obtain or at least estimate the corresponding information on the chemical groups in the mixture. A suitable method for obtaining this information on the chemical groups is NMR spectroscopy. It is used in the present study, but also other group-sensitive analytical methods like IR spectroscopy could be applied. The results on the nature and concentration of the chemical groups in the mixture can be used directly in thermodynamic group contribution methods. Several group contribution methods for estimating activity coefficients have been described in the literature, of which the most highly developed and widely used is the UNIFAC method.¹² UNIFAC is used in the present study in the version modified UNIFAC (Dortmund).^{14,15} Alternatively, other group contribution methods for activity coefficients, such as a group contribution method version of COSMO-RS¹⁹ could be used. Furthermore, the idea of NEAT is not only applicable to activity coefficients. It could be applied also to any other thermodynamic property for which group contribution methods are available.

Even if only a combination of one-dimensional NMR spectroscopy with UNIFAC is considered, there are many different ways to put the idea of NEAT into practice. But all of them are based on the same fundamental ideas. In the present work, we described these fundamental ideas and put them into a mathematical form. Furthermore, different ways of applying NEAT are described. The examples include aqueous and non-aqueous mixtures. Also the

application of NEAT to reactive mixtures is discussed. In all cases, the predictions of the activity coefficients of the target components in the poorly specified mixtures obtained from NEAT are compared to the corresponding results for the fully specified mixtures.

Fundamentals of NEAT

NEAT was developed for tackling poorly specified mixtures, i.e. mixtures of which information on the composition is only partially available. Let us consider a mixture with a known mass m consisting of $i = 1 \dots N$ components. The N components of the mixture are divided into two sets: a first set of $k = 1 \dots K$ known components and a second set of $u = 1 \dots U$ unknown components, hence:

$$N = K + U \tag{1}$$

It is assumed that for the known components $k = 1 \dots K$ the following information is available:

- M_k the molar mass of the component k
- m_k the mass of the component k in the mixture, or alternatively
- n_k the mole number of the component k in the mixture

No component-specific information is available for the components $u = 1 \dots U$. Even the number U may be unknown.

The total mass of all unknown components in the mixture $m_{\Sigma u}$ can be calculated from:

$$m_{\Sigma u} = \sum_{u=1}^U m_u = m - \sum_{k=1}^K m_k \tag{2}$$

Let $g = 1 \dots G$ be the chemical groups in the components that make up the mixture such that each component i can be built by combining groups from that set. It is assumed that the molar mass M_g of all groups g is known. The number of groups of type g in one molecule of component i is $\nu_{i,g}$. We assume that $\nu_{k,g}$ is known for all known components $k = 1 \dots K$.

Let $n_{i,g}$ and $m_{i,g}$ be the mole number and mass of group g in component i in the mixture, respectively. For the known components k , $n_{k,g}$ and $m_{k,g}$ are known:

$$n_{k,g} = \nu_{k,g} n_k \quad (3)$$

$$m_{k,g} = n_{k,g} M_g = \nu_{k,g} n_k M_g \quad (4)$$

In NEAT, spectroscopic analysis is used to obtain information on the chemical groups in the mixture. In the simplest case, each signal in the recorded spectrum of the mixture corresponds to a single group g in the mixture. Other possible, more complex, relations are described in the following chapter. We first assume that at least one signal in the spectrum can be unambiguously and exclusively assigned to one group g occurring in any known component k . Provided that the analysis is quantitative, from this signal, a proportionality factor giving the correlation between signal intensity and group mole number can be calculated. It is assumed that this proportionality factor is the same for all groups, which is usually a good assumption.²⁰⁻²² With this proportionality factor, in turn, the mole numbers n_g of all groups g in the mixture can be calculated from the spectrum, if an assignment of signals to groups g is available. The task of finding the assignment of signals to groups g is case-specific and therefore discussed in the following chapter.

From n_g , the group mole fractions $x_g^{(n)}$ of all groups g in the mixture can be calculated:

$$x_g^{(n)} = \frac{n_g}{\sum_{g=1}^G n_g} \quad (5)$$

Let $m_{\Sigma u,g}$ be the contribution of group g to the total mass of all unknown components in the mixture $m_{\Sigma u}$. The number of $m_{\Sigma u,g}$ can be calculated from:

$$m_{\Sigma u,g} = n_g M_g - \sum_{k=1}^K \nu_{k,g} n_k M_g \quad (6)$$

Hence, the previously unknown components can be summarily characterized by group mass fractions $x_{\Sigma u, g}$ regarding only the unknown components $u = 1 \dots U$ in the mixture:

$$x_{\Sigma u, g} = \frac{m_{\Sigma u, g}}{m_{\Sigma u}} \quad (7)$$

Furthermore, with the total mole number of all groups in the mixture $n_{\Sigma g}$:

$$n_{\Sigma g} = \sum_{g=1}^G n_g \quad (8)$$

and the total mole number of all groups of the known components in the mixture $n_{\Sigma k, \Sigma g}$:

$$n_{\Sigma k, \Sigma g} = \sum_{k=1}^K \sum_{g=1}^G \nu_{k, g} n_k \quad (9)$$

the group mole fractions $x_{\Sigma u, g}^{(n)}$ of all groups $g = 1 \dots G$ in the sum of the unknown components in the mixture can be calculated:

$$x_{\Sigma u, g}^{(n)} = \frac{n_{\Sigma u, g}}{n_{\Sigma u, \Sigma g}} = \frac{n_g - n_{\Sigma k, g}}{n_{\Sigma g} - n_{\Sigma k, \Sigma g}} = \frac{n_g - \sum_{k=1}^K \nu_{k, g} n_k}{\sum_{g=1}^G n_g - \sum_{k=1}^K \sum_{g=1}^G \nu_{k, g} n_k} \quad (10)$$

The inspection of $x_{\Sigma u, g}^{(n)}$ may give information on the nature of the components $u = 1 \dots U$. Should there only be one such component U , it is expected that the ratios $x_{\Sigma u, g_1}^{(n)} / x_{\Sigma u, g_2}^{(n)}$ of two arbitrary groups g_1 and g_2 are integers and the composition of that previously unknown component regarding its groups is obtained. No information is obtained, however, on its molar mass. Should there be more than one unknown component u ($U > 1$), all groups associated to the unknown components are lumped to one mean unknown component $\tilde{u}$ in NEAT. The molar mass $M_{\tilde{u}}$ of this mean unknown component $\tilde{u}$ has to be estimated. Choosing $M_{\tilde{u}}$ can be considered as choosing a ‘representative mean molar mass’ of the different unknown components. However, it is shown below, that a crude estimate of $M_{\tilde{u}}$ is sufficient in many cases. Using this estimate, the mole number $n_{\tilde{u}}$ of the mean unknown component

$\tilde{u}$ in the mixture can be calculated:

$$n_{\tilde{u}} = \frac{m_{\Sigma u}}{M_{\tilde{u}}} \quad (11)$$

Only then also the mole fractions $x_k^{(n)}$ of the known components $k = 1 \dots K$ in the mixture can be calculated:

$$x_k^{(n)} = \frac{n_k}{\sum_{k=1}^K n_k + n_{\tilde{u}}} \quad (12)$$

Also the number of groups j in one molecule of the mean unknown component $\nu_{\tilde{u},j}$ can then be calculated:

$$\nu_{\tilde{u},g} = \frac{n_g - \sum_{k=1}^K \nu_{k,g} n_k}{n_{\tilde{u}}} \quad (13)$$

NEAT also works, if one of the groups cannot be analyzed with the selected spectroscopic method. Let that group be the group G . Hence, NEAT yields only $g = 1 \dots G - 1$ group mole numbers n_g . The mass m_G of the group G can be calculated from:

$$m_G = m - \sum_{g=1}^{G-1} n_g M_g \quad (14)$$

Assuming that the molar mass M_G of the group G is known, the mole number n_G is obtained from:

$$n_G = \frac{m_G}{M_G} \quad (15)$$

NEAT can also be applied, if not a single group but one of the components as a whole is not accessible by the selected analytical method (e.g. water by ^{13}C NMR spectroscopy). Let that component be the component N . The mass m_N of the component N can be calculated from:

$$m_N = m - \sum_{g=1}^G n_g M_g \quad (16)$$

Assuming that the molar mass M_N of the component N is known, the mole number n_N is obtained from:

$$n_N = \frac{m_N}{M_N} \quad (17)$$

All other quantities can be calculated as described above. Eqs (14) - (17) can also be used for testing the internal consistency of NEAT.

Activities and activity coefficients

There are different possibilities to define activities and activity coefficients. They are based on different ways of normalization of the chemical potential. Four normalizations are considered in the following. As an example, the chemical potential μ_t of the target component t is regarded:

$$\mu_t = \mu_t^0 + RT \ln x_t^{(n)} \gamma_t, \quad \text{Raoult} \quad (18)$$

$$\mu_t = \mu_t^{0,H} + RT \ln x_t^{(n)} \gamma_t^*, \quad \text{Henry} \quad (19)$$

$$\mu_t = \mu_t^{0,c} + RT \ln \frac{c_t}{c_0} \gamma_t^{*,c}, \quad c_t = \frac{n_t}{V}, \quad c_0 = 1 \frac{\text{mol}}{\text{l}} \quad (20)$$

$$\mu_t = \mu_t^{0,b} + RT \ln \frac{b_t}{b_0} \gamma_t^{*,b}, \quad b_t = \frac{n_t}{m_1}, \quad b_0 = 1 \frac{\text{mol}}{\text{kg}} \quad (21)$$

The previously described procedure yields an estimate for the composition of a poorly specified mixture in mole fractions. Hence, Eqs. (18) and (19) can be applied. Also Eq. (20) can be applied in NEAT, if the total volume V of the poorly specified mixture is known. Eq. (21) is applicable, if not only the amount of the target component t but also that of the reference component 1 in the mixture is known or accessible. In the following, results for activity coefficients normalized according to Eq. (18) are shown.

UNIFAC method

The group contribution method UNIFAC is used in the present work to estimate the activity coefficient of a target component in a poorly specified mixture with NEAT. In UNIFAC, the activity coefficient of the target component γ_t is computed as the sum of two parts, the

combinatorial part γ_t^C and the residual part γ_t^R :

$$\ln \gamma_t = \ln \gamma_t^C + \ln \gamma_t^R \quad (22)$$

The strength of using UNIFAC in NEAT is that the calculation of the residual part γ_t^R requires only information on groups that is easily available, i.e. no information on the component speciation is required for calculating γ_t^R .

More specifically, for the calculation of γ_t^R , information on the group mole fractions $x_g^{(n)}$ of all groups g in the mixture, which are determined or estimated in NEAT from a spectroscopic analysis, and the related relative van der Waals group surfaces Q_g and binary group interaction parameters $a_{gg'}$ of the groups g in the mixture, which are reported for a large number of groups in the literature, are required. Additionally, the stoichiometry of the target component t , i.e. the coefficients $\nu_{t,g}$, and the temperature have to be known.

The calculation of the combinatorial part γ_t^C , on the other hand, requires information on the mole fractions $x_i^{(n)}$ of all components i in the mixture. Hence, only to calculate γ_t^C , the groups of the unknown components u in the mixture have to be lumped to a mean unknown component $\tilde{u}$ and the molar mass $M_{\tilde{u}}$ of $\tilde{u}$ has to be estimated. Furthermore, the calculation of γ_t^C requires information on the relative van der Waals group surfaces Q_g and the relative van der Waals group volumes R_g of all groups g in the considered mixture, which are reported in the literature. For a detailed description of the UNIFAC equations, the reader is referred to the original papers.^{12–15}

Materials and Methods

Materials

Ultra pure water was produced with an ultra-purification system of Merck Millipore (Elix Essential 5). Suppliers and purities of the other chemicals used in this work are given in

Table 1.

Table 1: Suppliers and purities of chemicals used in this work.

Chemical	Formula	Supplier	Purity ^a
acetic acid	C ₂ H ₄ O ₂	Carl Roth	≥99.90%
acetone	C ₃ H ₆ O	Fisher Chemical	≥99.98%
L-ascorbic acid	C ₆ H ₈ O ₆	Carl Roth	≥99.00%
1,4-butanediol	C ₄ H ₁₀ O ₂	Acros Organics	≥99.90%
<i>tert</i> -butylhydroquinone	C ₁₀ H ₁₀ O ₂	Merck	≥97.00%
citric acid	C ₆ H ₈ O ₇	Carl Roth	≥99.95%
cyclohexanone	C ₆ H ₁₀ O	Sigma Aldrich	≥99.80%
dimethoxymethane	C ₃ H ₈ O ₂	Sigma-Aldrich	≥99.00%
ethanol	C ₂ H ₆ O	Merck	≥99.90%
formaldehyde	CH ₂ O	Carl Roth	≥95.00%
methanol	CH ₄ O	Carl Roth	≥99.90%
methyl acetate	C ₃ H ₆ O ₂	Sigma Aldrich	≥99.80%
methyl oleate	C ₁₉ H ₃₆ O ₂	Sigma Aldrich	≥70.00%
methyl palmitate	C ₁₇ H ₃₄ O ₂	Sigma Aldrich	≥97.00%
methyl stearate	C ₁₉ H ₃₈ O ₂	Sigma Aldrich	≥96.00%
oleic acid	C ₁₈ H ₃₄ O ₂	Sigma Aldrich	≥90.00%
1-propanol	C ₃ H ₈ O	Sigma Aldrich	≥99.50%
pyridine	C ₅ H ₅ N	Fisher Chemical	≥99.50%
TMS	C ₄ H ₁₂ Si	Merck	99.70%
TMSP-d ₄	NaC ₆ H ₉ D ₄ O ₂ Si	Deutero	≥98.00%
D-xylose	C ₅ H ₁₀ O ₅	Alfa Aeser	≥98.00%

^aSupplier specification.

Methods

Sample preparation and NMR analysis

Liquid sample mixtures containing different components were prepared gravimetrically in 20 ml glass vessels using a balance of Mettler Toledo (AG204). The total mass of all samples was about 10 g. Quantitative ¹H and inverse-gated ¹³C NMR spectra of each sample were recorded. Therefore, about 1 ml of a sample was transferred to an NMR vial. A small amount

(< 10 mg) of sodium 3-(trimethylsilyl)tetra-deuteriopropionate (TMSP-d4) was added to all aqueous samples as NMR standard. To all non-aqueous samples, a small amount (< 10 mg) of tetramethylsilane (TMS) was added. ^1H NMR and ^{13}C NMR spectra were taken using a 400 MHz NMR spectrometer from Bruker (Avance) with a cryogenic probe. The acquisition parameters are summarized in Table 2.

The evaluation of the NMR spectra with the software (MestReNova) from Mestrelab Re-

Table 2: NMR acquisition parameters used in the present work.

Parameter	^1H NMR	^{13}C NMR
pulse angle / $^\circ$	10	60
acquisition time / s	2.0 - 4.0	1.5 - 2.5
spectral width / ppm	15	240
number of scans	8 - 16	64 - 128
relaxation delay / s	20	45

search included appropriate baseline and phase correction. A chemical shift of 0 ppm was assigned to the TMSP-d4 peak.

Estimation of chemical groups and prediction of activity coefficients

In the following, the procedure for the identification and quantification of the chemical groups in poorly specified mixtures is described. It is assumed that the target component t and its mass fraction x_t and molar mass M_t are known. For the given total mass m of a mixture, the mole number n_t of t in the mixture can be calculated:

$$n_t = \frac{x_t m}{M_t} \tag{23}$$

It is assumed that at least one signal p of the target component t in the NMR spectrum of the mixture is separated from all other signals. This signal p is integrated yielding the area A_p . With the known mole number n_t of t and the known number of NMR-active nuclei z_p per molecule of t that contribute to the signal p , the NMR proportionality factor P is

calculated:

$$P = \frac{A_p}{n_t z_p} \quad (24)$$

If the mass fraction of the target component is not known, an additional component can be added gravimetrically to the mixture prior to the NMR analysis and used as quantitative standard to calculate P analogously. Alternatively, also the technique of the virtual reference could be used.²³ It is assumed that P is the same for all signals in the spectrum of a mixture. For nuclei in similar chemical groups, this is usually an excellent assumption.²⁰⁻²² But also for nuclei in strongly differing groups, the differences are typically of the order of a few percent and acceptable for NEAT as an estimation method. The validity of the assumption can be checked using experiments with standards. Results from such experiments could also be used for the calibration of the proportionality constants. Since information on the target component t is available, the chemical groups of t are not included in the estimation process in NEAT and all signals of the target component are eliminated from the NMR spectrum yielding a residual spectrum containing only the signals of the unknown components in the mixture. If there are more known components than the target component, they are treated in the same way as the target component. For the elimination, the position of all signals of the considered known components in the spectrum has to be known, which can be determined from spectroscopic experiments or data bases. However, it is generally not necessary to know the exact position of the signals, they only have to be assigned correctly to spectral regions as described below. The signals of the known components then are subtracted from the sum signal of the entire spectral regions. Therefore, no problems with overlapping signals occur. The residual NMR spectrum is divided in regions of chemical shift and a chemical group is assigned to each region. Hence, all signals that appear in a specific chemical shift region are assumed to originate from the same chemical group. In this work, the chemical groups are selected from groups from the modified UNIFAC (Dortmund) parameter table. The assignment of the groups to the spectral regions is not unique and decisions have to be made. The choice depends primarily on the group contribution method that is used and

on the NMR-spectroscopic method that is applied. Also a priori information on the type of groups or components in the mixture can be taken into account. NEAT is in general not a fixed algorithm but an approach that can be adapted to specific requirements. Furthermore, it is assumed that the assignment of groups to regions does not have to be fully correct to obtain good results. For example, if an NMR signal is assigned to some polar group P, but is caused partly or entirely by some other chemically similar polar group P*, the resulting error in the prediction of the activity coefficient of the target component may not be large. In the present work, different exemplary assignments were used for ^{13}C and ^1H NMR spectra that consider groups containing carbon (C), hydrogen (H), and oxygen (O). These assignments are shown in Tables 3 and 4, respectively.

The signals of groups containing exchanging protons, such as hydroxyl, amino, or thiol groups, in ^1H NMR spectroscopy are usually broad and their position and shape may strongly depend on the composition of the mixture. However, these signals can be identified easily and an assignment based only on the position is not necessary. Should they overlap with other signals, deconvolution can be used for quantification. For simplicity, the assignment from Table 4 was used for all predictions based on ^1H NMR spectroscopy in the present work.

Table 3: Assignment of ^{13}C NMR chemical shift regions to groups from modified UNIFAC (Dortmund) used in this work for the predictions with NEAT. The mole number of water ‘H₂O’ (in aqueous mixtures) or additional primary hydroxyl groups ‘OH(P)’ (in non-aqueous mixtures) was calculated from the mass balance, cf. Eqs. (16) or (14), respectively.

^{13}C NMR chemical shift region	Group assignment	UNIFAC label
0 - 60	alkyl, carbonyl	‘ $\underline{\text{C}}\text{H}_2$ ’, ‘ $\underline{\text{C}}\text{H}_2\text{CO}$ ’
60 - 90	alcohol	‘ $\underline{\text{C}}\text{H}_2$ ’ + ‘OH(P)’
90 - 150	alkenyl	‘ $\underline{\text{C}}\text{H}=\underline{\text{C}}\text{H}$ ’
150 - 180	carboxyl	‘ $\underline{\text{C}}\text{OOH}$ ’
>180	carbonyl	‘ $\text{CH}_2\underline{\text{C}}\text{O}$ ’
n.a.	water, hydroxyl	‘H ₂ O’, ‘OH(P)’

From the integration over each region and the resulting sum signals, the mole numbers

Table 4: Assignment of ^1H NMR chemical shift regions to groups from modified UNIFAC (Dortmund) used in this work for the predictions with NEAT. The mole number of additional quaternary carbon groups was calculated from the mass balance, cf. Eq. (14).

^1H NMR chemical shift region	Group assignment	UNIFAC label
0 - 3	alkyl	‘ CH_2 ’
3 - 4.5	carboxylate	‘ CH_2COO ’
4.5 - 6	alkenyl	‘ $\text{CH}=\text{CH}$ ’
6 - 7	aryl	‘ ACH ’
>7	hydroxyl	‘ OH(P) ’
n.a.	quaternary carbon	‘C’

of the chemical groups in the mixture are determined using the proportionality factor P and the number of NMR-active nuclei in each assigned chemical group. It should be noted that the obtained mole numbers of chemical groups depend on the group assignment, in particular for groups with different numbers of NMR-active nuclei. For instance, the signals of ‘CH’, ‘CH₂’, and ‘CH₃’ groups that are not bonded to different substituents are difficult to distinguish from their position in a ^1H NMR spectrum alone. The assignment of ‘CH’ groups to all signals in a specific spectral region leads to a three times larger group mole number than the assignment of ‘CH₃’ groups to the same spectral region. This can lead to errors. However, preexisting knowledge can be used to reduce these errors.

Generally, four fundamental cases for the mapping of UNIFAC groups to spectral regions can be distinguished. For each case, an example for the mapping of groups from the UNIFAC table to ^{13}C NMR chemical shift regions as it was used in this work, cf. Table 3, is described in the following.

In the first case, the UNIFAC group contains NMR-active nuclei and all nuclei show signals in the same spectral region. The selected group is then assigned to all signals in this specific region. An example is the assignment of ‘CH=CH’ groups to all signals in the chemical shift region ranging from 90 - 150 ppm. In the second case, the UNIFAC group contains active nuclei, but they show signals in different spectral regions. An example for this case is the assignment of a ‘CH₂CO’ group. This group leads to signals in two spectral regions:

in the region >180 ppm, the signals of the ‘CO’ part are expected, and in the region 0 - 60 ppm, the signals of the ‘CH₂’ part are expected. Consequently, ‘CH₂CO’ group are only assigned, if in both regions, at >180 ppm and at 0 - 60 ppm, signals are present and ‘CH₂’ groups are only assigned to the signals in the region 0 - 60 ppm that exceed the signals in the region >180 ppm. The third case considers UNIFAC groups that do not contain NMR-active nuclei but have an evaluable influence on adjacent groups that contain NMR-active nuclei. An example for this case is the assignment of ‘CH₂’ + ‘OH(P)’ groups, which build together a primary alcohol group, to the signals in the region 60 - 90 ppm. Hence, although ‘OH(P)’ groups do not show a signal in ¹³C NMR spectroscopy, information on the number of ‘OH(P)’ groups can thereby be obtained. Finally, in the fourth case, the UNIFAC groups do not contain NMR-active nuclei and there is no evaluable influence on adjacent groups. Information on these groups can only be obtained from the mass balance as described below. An example for this case is the consideration of additional ‘OH(P)’ or ‘H₂O’ groups, if ¹³C NMR spectroscopy is applied.

With the known molar masses of the assigned chemical groups, the total mass of all groups of the unknown components and, hence, the total mass of the unknown components $m_{\Sigma u}$ can be calculated, which is, in turn, used to calculate the difference Δm :

$$\Delta m = m - m_t - m_{\Sigma u} \tag{25}$$

Δm is expected to be positive in those cases in which not all groups in the mixture yield a signal in the NMR spectrum. In the other cases, the absolute numbers for Δm are expected to be small compared to the mass m . In such cases, the relative deviations $|\Delta m|/m$ were found to be of the order of a few percent in the experiments of the present work. Information on how Δm was used in the present work are given in the following: for all aqueous mixtures, which were only studied with ¹³C NMR spectroscopy in the present work, Δm was used to determine the mass of water m_w in the mixture, cf. Table 3. If non-aqueous mixtures were

studied with ^{13}C NMR spectroscopy, Δm was used to determine the number of additional ‘OH(P)’ groups in the mixture, cf. Table 3. If non-aqueous mixtures were studied with ^1H NMR spectroscopy, Δm was used to determine the number of additional ‘C’ groups in the mixture, cf. Table 4. If Δm was negative, the mole numbers of the determined groups of the unknown components were reduced to comply with the mass balance in all cases. The ratios of the mole numbers of the groups among each other were thereby kept constant. All determined groups of the unknown components in a poorly specified mixture were lumped to one mean unknown component $\tilde{u}$ in all cases. If not stated otherwise, a molar mass of $M_{\tilde{u}} = 150 \text{ g/mol}$ was thereby assigned to $\tilde{u}$.

For the prediction of the activity coefficients of the target component t with NEAT in the present work, each studied aqueous poorly specified mixture was regarded as ternary mixture containing the target component t , one mean unknown component $\tilde{u}$, and water w . A schematic representation of the procedure of NEAT for the application to aqueous poorly specified mixtures as used in this work is given in Figure S1 in the Supporting Information. Each studied non-aqueous poorly specified mixture was either regarded as binary mixture containing the target component t and one mean unknown component $\tilde{u}$ or as ternary mixture containing, besides t and $\tilde{u}$, a solvent s . If a solvent s was considered, its nature was assumed to be known and its mole number in the mixture was calculated from the NMR spectrum using the proportionality factor P and a signal that could unambiguously be assigned to s . Hence, the chemical groups of s in the mixture were, in analogy to the groups of t , not determined by NMR spectroscopy in NEAT.

Results and Discussion

In the following, the predictions with NEAT for the poorly specified mixtures are always compared to results that were calculated using information on the full speciation of the mixtures,

which was always known from the gravimetric sample preparation but not used for the predictions. In the Supporting Information, the results for the composition of all studied poorly specified mixtures and the stoichiometry of the mean unknown components as determined from NMR spectra of the mixtures are summarized. These data were used for obtaining the predictions with NEAT. If not stated otherwise, the results for the fully specified mixtures were calculated with the same version of UNIFAC that was used for the predictions. It should be noted, that no statements on the applicability of UNIFAC for the studied system are made here. Obviously, the quality of the predictions with NEAT cannot exceed the quality of the results of the underlying thermodynamic model for the fully specified mixtures.

Aqueous mixtures

For applying NEAT to aqueous organic mixtures, ^{13}C NMR spectroscopy is a good choice as water has a very broad and shifting signal in the ^1H NMR spectrum. In the following, results for the prediction of the activity coefficient of the target component in aqueous poorly specified mixtures with NEAT based on a single ^{13}C NMR spectrum of each mixture and the group assignment from Table 3 are shown. For the predictions, only information on the target component t was used.

As first example, ternary mixtures containing one known target component t , water w , and one unknown component u are considered. In Figure 1, results for the activity coefficient of the target component ($t = \text{ascorbic acid}$) in ternary mixtures containing water (w) and the unknown component ($u = \text{cyclohexanone}$) as a function of the mass fraction of cyclohexanone are shown. The predictions with NEAT, denoted as black squares, show a very good agreement with the results obtained using information on the full speciation of the mixture calculated with UNIFAC, denoted as black line. The predictions of UNIFAC for the activity coefficients of ascorbic acid are very high. As explained above, in the present context, it does not matter whether this is realistic or not.

Figure 1 also shows results for the activity coefficient of the target component ($t = 1,4$ -

Figure 1: Activity coefficients γ_t of target component ($t = \text{ascorbic acid}$) in ternary mixtures of t with water (w) and one unknown component ($u = \text{cyclohexanone}$) and of target component ($t = 1,4\text{-butanediol}$) in five-component mixtures with water (w) and three unknown components ($u = \text{cyclohexanone, pyridine, citric acid}$; with the same mass ratio in all mixtures) at 298 K and 1 bar. The mass ratio of ($t : w$) is (0.1 : 0.9) in all mixtures. Lines: results from modified UNIFAC (Dortmund) for the fully specified mixtures. Symbols: predictions with NEAT based on ^{13}C NMR and only information on t .

butanediol) in five-component mixtures containing water (w) and three unknown components ($u = \text{cyclohexanone, pyridine, citric acid}$) as a function of the total mass fraction $x_{\Sigma u}$ of the unknown components. Again, the predictions with NEAT are compared to the results calculated with UNIFAC using information on the full speciation of the mixtures showing an excellent agreement.

As described above, for the predictions with NEAT, the chemical groups of the unknown components u in a poorly specified mixture were lumped to a mean unknown component $\tilde{u}$, to which a molar mass $M_{\tilde{u}} = 150 \text{ g/mol}$ was assigned in the present work. In Figure 2, results for the influence of the value of $M_{\tilde{u}}$ on the predictions with NEAT are shown. As an example, one mixture with the target component ($t = 1,4\text{-butanediol}$) from Figure 1 was

selected for this purpose. The results show a very small influence of $M_{\bar{u}}$ on the predictions

Figure 2: Activity coefficient γ_t of target component ($t = 1,4$ -butanediol) in a five-component mixture with water (w) and three unknown components ($u = \text{cyclohexanone, pyridine, citric acid}$; with the same mass ratio) at 298 K and 1 bar. The composition of the mixture is $x_t = 0.091$ g/g, $x_{\Sigma u} = 0.095$ g/g. Dashed line: result from modified UNIFAC (Dortmund) for the fully specified mixture. Symbols: predictions with NEAT based on ^{13}C NMR and only information on t for different values of the molar mass $M_{\bar{u}}$ of the mean unknown component.

with NEAT if no unreasonably small values ($M_{\bar{u}} < 50$ g/mol) are chosen. This was found for all studied aqueous mixtures and can be attributed to two points: first, as described above, to the fact that $M_{\bar{u}}$ does not have an influence on the predominant residual part of the UNIFAC activity coefficient of t , but only on the combinatorial part. Second, the concentration of water in the studied mixtures is high. Due to the low molar mass and the resulting high mass fraction of water, the influence of $M_{\bar{u}}$ on the mole fraction of t , which contributes to the combinatorial part of the UNIFAC activity coefficient of t , is rather small.

In Figure 3, results for the activity coefficient of the target component ($t = \text{acetic acid}$) in ternary mixtures containing water (w) and one unknown component ($u = \text{xylose}$) are given. In contrast to the previous examples, the predictions with NEAT are compared to results

calculated with an NRTL model, which was fitted to experimental data on the vapor-liquid equilibrium of the regarded system.²⁴ The temperature is therefore in this case not constant to represent the experimental data from Galeotti et al.²⁴ For the prediction of the activity coefficients with NEAT, again ¹³C NMR spectroscopy in combination with modified UNIFAC (Dortmund) was used. The predictions show an excellent agreement with the results from the NRTL model.

NEAT can also be applied to reactive mixtures. Figure 4 shows results for the activity co-

Figure 3: Activity coefficient γ_t of target component ($t = \text{acetic acid}$) in ternary mixtures with water (w) and one unknown component ($u = \text{xylose}$) at 333.7 - 335.7 K and 1 bar. $x_u = 0.099 \text{ g/g}$ in all mixtures. Line: results from an NRTL model fitted to experimental data²⁴ for the fully specified mixtures. Symbols: predictions with NEAT based on ¹³C NMR and only information on t .

efficient of the target component ($t = \text{dimethoxymethane}$) in mixtures with different overall concentrations of water (w) and the unknown component ($u = \text{formaldehyde}$). Formaldehyde is reactive in aqueous mixtures and forms polyoxymethylene glycols of different chain lengths with water.²⁵⁻²⁹ Kuhnert et al.²⁵ reported an activity-based chemical equilibrium model to describe the formation of polyoxymethylene glycols in aqueous formaldehyde-containing

Figure 4: Activity coefficient γ_t of target component ($t = \text{dimethoxymethane}$) in reactive mixtures of t with water (w) and the unknown component ($u = \text{formaldehyde}$) as a function of the overall mass fraction of formaldehyde x_u . Black squares: results from a model based on the true speciation of the mixtures, cf. Kuhnert et al.²⁵ Red circles: predictions with NEAT based on ^{13}C NMR and only information on t .

mixtures. This model is based on an extended version of original UNIFAC^{12,13}, which was adapted to mixtures of this type. In the present work, this model was used to calculate the true compositions and the activity coefficients of the components in the reactive mixtures in chemical equilibrium (for the overall and true compositions of the studied mixtures, see Supporting Information). In Figure 4, the results for the activity coefficient of t calculated with this model including the consideration of all relevant reactions are depicted as black squares. The predictions with NEAT based on a ^{13}C NMR spectrum of each mixture in chemical equilibrium are depicted as red circles. For the predictions, only information on t but no information on the chemical reactions, the reaction products, and the composition of the mixtures in chemical equilibrium was used. In this case, NEAT is based on the extended version of original UNIFAC from Kuhnert et al.²⁵ The agreement of the predictions with NEAT with the results for the fully specified mixtures is excellent, even at high overall mass

fractions of formaldehyde.

Another example for the application of NEAT to reactive aqueous mixtures is shown in Figure 5. The studied mixtures contain the target component (t = dimethoxymethane) as well

Figure 5: Activity coefficient γ_t of target component (t = dimethoxymethane) in reactive mixtures of t with water (w), and two unknown components (u_1 = formaldehyde, u_2 = methanol) as a function of the overall mass fraction of formaldehyde x_{u_1} . Black squares: results from a model based on the true speciation of the mixtures, cf. Kuhnert et al.²⁵ Red circles: predictions with NEAT based on ^{13}C NMR and only information on t .

as water (w) and the unknown components (u = formaldehyde, methanol) in different overall mass fractions. In mixtures of this type, formaldehyde forms polyoxymethylene glycols by reacting with water and polyoxymethylene hemiformals by reacting with methanol.^{25–29} Hence, to calculate the true compositions of these mixtures, again a chemical reaction scheme has to be considered. Again, the model of Kuhnert et al.²⁵ was used to calculate the true compositions as well as the activity coefficients of the target component in the studied mixtures (for the overall and true compositions of the mixtures, see Supporting Information). The results based on the full speciation of the mixtures are depicted as black squares in Figure 5. The predictions with NEAT based on a ^{13}C NMR spectrum of each mixture in

chemical equilibrium are depicted as red circles. Again, for the predictions with NEAT, only information on t but no information on the chemical reactions, the reaction products, and the composition of the mixtures in chemical equilibrium was used. As in the previous example, NEAT is thereby based on the extended version of original UNIFAC from Kuhnert et al.²⁵ Also for these complex reactive mixtures, the predictions with NEAT are in very good agreement with the results for the fully specified mixtures.

In a previous work of our group, several examples for the application of NEAT to aqueous poorly specified mixtures were presented.¹⁸ These predictions were obtained using information on the water mass fraction in the mixtures besides information on the target component. In the Supporting Information, it is shown that NEAT also gives excellent predictions for the activity coefficient of the target component in these mixtures without using information on the water mass fraction, i.e. based only on information on the target component.

Non-aqueous mixtures

For applying NEAT to non-aqueous organic mixtures, both ^{13}C NMR spectroscopy and ^1H NMR spectroscopy were used. The assignment of chemical groups to chemical shift regions used in the present work for both NMR methods are summarized in Tables 3 and 4, respectively. For each NMR method, two variants were studied in this work: predictions using only information on the target component t and predictions using information on t as well as on the nature of a single additional component, referred to as solvent s in the following. However, no information on the concentration of s was used.

In Figure 6, results for the activity coefficient of the target component ($t = \text{ethanol}$) in five-component mixtures containing different concentrations of the unknown components ($u = \text{oleic acid, } \textit{tert}\text{-butylhydroquinone, acetone, 1-propanol}$) are shown.

The black squares show the predictions with NEAT based on ^{13}C NMR if only information on t is used. The trend of the results calculated with UNIFAC for the fully specified mixtures, which are shown as line in Figure 6, is well represented by these predictions. How-

Figure 6: Activity coefficient γ_t of target component ($t = \text{ethanol}$) in five-component mixtures with four unknown components ($u_1 = \text{oleic acid}$, $u_2 = \text{tert-butylhydroquinone (TBHQ)}$, $u_3 = \text{acetone}$, $u_4 = 1\text{-propanol}$) as a function of the total mass fraction of u_2 , u_3 , and u_4 at 298 K and 1 bar. The mass ratio of ($t : u_1$) is (0.051 : 0.949), the mass ratio of ($u_2 : u_3 : u_4$) is (0.340 : 0.331 : 0.329) in all mixtures. Line: results from modified UNIFAC (Dortmund) for the fully specified mixtures. Black squares: predictions with NEAT based on ^{13}C NMR and only information on t . Red circles: predictions with NEAT based on ^{13}C NMR and information on t and the nature of u_1 , i.e. $s = u_1$. Blue triangles: predictions with NEAT based on ^1H NMR and only information on t . Green diamonds: predictions with NEAT based on ^1H NMR and information on t and the nature of u_1 , i.e. $s = u_1$.

ever, the activity coefficient of t is overestimated. The red circles show the predictions with NEAT that are also based on ^{13}C NMR but use information on t and, additionally, on oleic acid, which is considered as the known solvent s . Using additional information on s leads to a better accuracy of the predictions with ^{13}C NEAT and a very good agreement with the results for the fully specified mixtures. The predictions with NEAT based on ^1H NMR and only information on t , which are denoted as blue triangles in Figure 6, show a very good agreement with the results for the fully specified mixtures. Using additional information on the known solvent s does not lead to a significant improvement of the predictions with ^1H NEAT, as can be seen by the green diamonds in Figure 6.

In Figure 7, results for the influence of the value of the molar mass $M_{\tilde{u}}$ of the mean unknown component $\tilde{u}$ on the predictions with NEAT are shown. As an example, one mixture with the target component ($t = \text{ethanol}$) from Figure 6 was selected for this purpose. Similar to

Figure 7: Activity coefficient γ_t of target component ($t = \text{ethanol}$) in a five-component mixture with four unknown components ($u_1 = \text{oleic acid}$, $u_2 = \text{tert-butylhydroquinone}$, $u_3 = \text{acetone}$, $u_4 = \text{1-propanol}$) as a function of the molar mass $M_{\tilde{u}}$ of the mean unknown component $\tilde{u}$ at 298 K and 1 bar. The composition of the mixture is $x_t = 0.046$ g/g, $x_{u_1} = 0.855$ g/g, $x_{u_2} = 0.034$ g/g, $x_{u_3} = 0.033$ g/g. Dashed line: result from modified UNIFAC (Dortmund) for the fully specified mixture. Black squares: predictions with NEAT based on ^{13}C NMR and only information on t . Red circles: predictions with NEAT based on ^{13}C NMR and information on t and the nature of u_1 , i.e. $s = u_1$. Blue triangles: predictions with NEAT based on ^1H NMR and only information on t . Green diamonds: predictions with NEAT based on ^1H NMR and information on t and the nature of u_1 , i.e. $s = u_1$.

the results for aqueous mixtures, cf. Figure 2, a strong influence can be observed for values of $M_{\tilde{u}} < 50$ g/mol. However, in contrast to the results for aqueous mixtures, a significant influence can be observed also for larger values. For the predictions for which only information on the target component t was used, similar results were found independent on whether ^{13}C or ^1H NMR spectroscopy was used, cf. black squares and blue triangles in Figure 7, respectively. Using additional information on the nature of oleic acid, i.e. considering oleic acid as

the known solvent s , leads to a smaller influence of $M_{\bar{u}}$ on the predictions with NEAT for both NMR methods, especially at values $M_{\bar{u}} > 100$ g/mol. This is in analogy to the results found for the aqueous mixtures, in which water was considered as known solvent. Similar results were found for all studied non-aqueous mixtures. Hence, for considering non-aqueous mixtures, a reasonable estimate for $M_{\bar{u}}$ is more important than for aqueous mixtures, especially if only information on the target component t but no other component, e.g. the solvent s , is available.

Figure 8 shows results for the activity coefficient of the target component ($t = \text{ethanol}$) in five-component mixtures with four unknown components ($u = \text{methyl oleate, methyl stearate, methyl palmitate, } \textit{tert}$ -butylhydroquinone) as a function of the mass fraction of t . All predictions with NEAT represent the trend of the results for the fully specified mixtures well. However, using only information on the target component t leads to an overestimation of the activity coefficient with NEAT based on ^1H NMR, cf. blue triangles, and an underestimation with NEAT based on ^{13}C NMR, cf. black squares. The predictions obtained with ^{13}C NEAT and using additional information on the nature of the solvent ($s = \text{methyl oleate}$) show an excellent agreement with the results for the fully specified mixtures, cf. red circles. Regarding ^1H NEAT, using additional information on s does only lead to a slight improvement of the predictions, cf. green diamonds. As expected, the agreement generally gets better the higher the mass fraction of target component becomes and, thus, the more information on the mixture is available as input for NEAT.

In Figure 9, results for the activity coefficient of the target component ($t = \text{dimethoxymethane}$) in five-component mixtures with four unknown components ($u = \text{methyl oleate, } \textit{tert}$ -butylhydroquinone, methanol, acetone) are shown.

The trend of the results for the fully specified mixtures is poorly described by the predictions with NEAT based on ^{13}C NMR and only information on t , cf. black squares. By considering additional information on the nature of methyl oleate, i.e. by considering methyl oleate as the known solvent s , the predictions show a very good agreement with the results

Figure 8: Activity coefficient γ_t of target component ($t = \text{ethanol}$) in five-component mixtures with four unknown components ($u_1 = \text{methyl oleate}$, $u_2 = \text{methyl stearate}$, $u_3 = \text{methyl palmitate}$, $u_4 = \text{tert-butylhydroquinone}$) as a function of the mass fraction of t at 298 K and 1 bar. The mass ratio of ($u_1 : u_2 : u_3 : u_4$) is (0.698 : 0.145 : 0.122 : 0.035) in all mixtures. Line: results from modified UNIFAC (Dortmund) for the fully specified mixtures. Black squares: predictions with NEAT based on ^{13}C NMR and only information on t . Red circles: predictions with NEAT based on ^{13}C NMR and information on t and the nature of u_1 , i.e. $s = u_1$. Blue triangles: predictions with NEAT based on ^1H NMR and only information on t . Green diamonds: predictions with NEAT based on ^1H NMR and information on t and the nature of u_1 , i.e. $s = u_1$.

for the fully specified mixtures, cf. red circles. A similar good agreement was found for the predictions based on ^1H NMR, independent on whether only information on t or additional information on s were used, cf. blue triangles and green diamonds, respectively.

Figure 9: Activity coefficient γ_t of target component ($t = \text{dimethoxymethane}$) in five-component mixtures with four unknown components ($u_1 = \text{methyl oleate}$, $u_2 = \text{tert-butylhydroquinone}$, $u_3 = \text{methanol}$, $u_4 = \text{acetone}$) as a function of the total mass fraction of t , u_1 , and u_2 at 298 K and 1 bar. The mass ratio of ($t : u_3 : u_4$) is (0.341 : 0.337 : 0.322), the mass ratio of ($u_1 : u_2$) is (0.949 : 0.051) in all mixtures. Line: results from modified UNIFAC (Dortmund) for the fully specified mixtures. Black squares: predictions with NEAT based on ^{13}C NMR and only information on t . Red circles: predictions with NEAT based on ^{13}C NMR and information on t and the nature of u_1 , i.e. $s = u_1$. Blue triangles: predictions with NEAT based on ^1H NMR and only information on t . Green diamonds: predictions with NEAT based on ^1H NMR and information on t and the nature of u_1 , i.e. $s = u_1$.

Conclusions

Liquid mixtures that contain a known target component but are otherwise poorly specified are common in process engineering. The conceptual process design in this situation is challenging since the existing thermodynamic models cannot be applied to such mixtures. In a previous work of our group, a method to estimate the activity coefficients of target components in such poorly specified mixtures was presented. The method is called NEAT and is based on a combination of NMR spectroscopy, which yields information on chemical groups in the mixture, and a thermodynamic group contribution method to calculate activity coefficients. Although the approach of NEAT is based on groups rather than on components, it can be interpreted as a physically motivated way of specifying such pseudo components. In the present work, NEAT is described in more detail than in the previous short communication.¹⁸ In particular, also the mathematical equations are given. In the previous work, NEAT based on results from ^{13}C NMR spectroscopy was applied to some aqueous non-reacting mixtures to demonstrate the applicability of the method. That work was extended here to non-aqueous and reactive mixtures. It is furthermore shown that NEAT also works if only information on the target component is available and no information on the solvent. However, it is shown that the consideration of information on additional components, i.e. the nature of the solvent, generally improves the predictions with NEAT. Furthermore, ^1H NMR spectroscopy was used together with NEAT for the first time. Overall, the results from the present study show that NEAT is a robust method to predict the activity coefficients of target components in poorly specified mixtures with high accuracy and therefore is a valuable tool for the conceptual process design regarding such mixtures. NEAT is highly flexible and can be tailored to specific tasks and situations, e.g. by choosing the most suitable analytical method or thermodynamic model, or by considering additional available information. In future work, NEAT will be extended to other thermodynamic models, such as COSMO-RS, and other NMR-spectroscopic techniques, and to predicting phase equilibria in systems with poorly specified mixtures.

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Supporting Information Available

The following files are available free of charge:

- Flowchart of NEAT procedure
- Composition of formaldehyde-containing mixtures
- Assignment of groups to components
- Additional results for aqueous poorly specified mixtures

Nomenclature

Symbols

a	binary group interaction parameter
A_p	relative area under signal p
b	molality [mol/kg]
c	molarity [mol/l]
g	chemical group
G	total number of chemical groups
i	component
k	known component
K	total number of known components
m	mass [g]

$m_{i,g}$	mass of group g in component i [g]
$m_{k,g}$	mass of group g in known component k [g]
$m_{\Sigma u}$	total mass of all unknown components [g]
$m_{\Sigma u,g}$	contribution of group g to the total mass of all unknown components [g]
M	molar mass [g/mol]
n	mole number [mol]
$n_{i,g}$	mole number of group g in component i [mol]
$n_{\Sigma g}$	total mole number of all groups [mol]
$n_{k,g}$	mole number of group g in known component k [mol]
$n_{\Sigma k,g}$	mole number of group g in all known components [mol]
$n_{\Sigma u,g}$	mole number of group g in all unknown components [mol]
$n_{\Sigma k,\Sigma g}$	total mole number of all group in all known components [mol]
$n_{\Sigma u,\Sigma g}$	total mole number of all group in all unknown components [mol]
N	total number of components
p	signal
P	NMR proportionality factor [1/mol]
P, P*	any polar groups
Q	relative van der Waals group surface
r	region of chemical shift
R	total number of regions of chemical shift
R	relative van der Waals group volume
R	universal gas constant [J/(mol·K)]
s	solvent
t	target component
T	temperature [K]
u	unknown component
$\tilde{u}$	mean unknown component

U	total number of unknown components
V	volume [l]
x	mass fraction [g/g]
$x_{\Sigma u}$	total mass fraction of all unknown components [g/g]
$x_{\Sigma u, g}$	mass fraction of group g in all unknown components [g/g]
$x^{(n)}$	mole fraction [mol/mol]
$x_{\Sigma u, g}^{(n)}$	mole fraction of group g in all unknown components [mol/mol]
z_p	number of NMR-active nuclei per molecule and signal p

Greek letters

γ	activity coefficient
Δ	difference
μ	chemical potential [J/mol]
$\nu_{i, g}$	stoichiometric coefficient of group g in component i
$\nu_{k, g}$	stoichiometric coefficient of group g in known component k
$\nu_{t, g}$	stoichiometric coefficient of group g in target component t
$\nu_{\tilde{u}, g}$	stoichiometric coefficient of group g in mean unknown component $\tilde{u}$

Sub- and superscripts

*	normalized according to Henry's law on the mole fraction scale
*, <i>b</i>	normalized similar to Henry's law on the molality scale
*, <i>c</i>	normalized similar to Henry's law on the molarity scale
0	reference state: pure liquid component
0,H	reference state: infinite dilution on the mole fraction scale
0, <i>b</i>	reference state: infinite dilution on the molality scale
0, <i>c</i>	reference state: infinite dilution on the molarity scale
C	combinatorial part
R	residual part

Abbreviations

COSMO-RS	Conductor like Screening Model for Real Solvents
IR	Infrared
NEAT	NMR Spectroscopy for the Estimation of Activity Coefficients of Target Components in Poorly Specified Mixtures
NMR	Nuclear Magnetic Resonance
NRTL	Non-Random Two-Liquid
TMSP	Sodium 3-(trimethylsilyl)tetradeuteriopropionate
UNIFAC	Universal Quasichemical Functional Group Activity Coefficients
UNIQUAC	Universal Quasichemical
w	water

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Graphical TOC Entry