

Thermodynamic analysis of an asymmetric system: Aqueous sodium dehydrocholate- hexadecyltrimethylammonium bromide mixed micelles

Romina B. Pereyra^a, Erica P. Schulz^{a,*}, Guillermo A. Durand^b, Hernán Ritacco^c, Pablo C. Schulz^a

^a Departamento de Química – INQUISUR (Universidad Nacional del Sur-CONICET), Bahía Blanca, Argentina

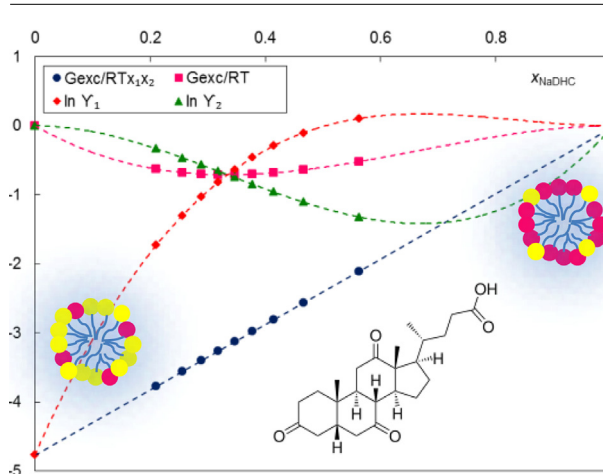
^b Departamento de Ingeniería Química – PLAPIQUI (Universidad Nacional del Sur – CONICET), Bahía Blanca, Argentina

^c Departamento de Física – IFISUR (Universidad Nacional del Sur – CONICET), Bahía Blanca, Argentina

HIGHLIGHTS

- System sodium dehydrocholate – hexadecyltrimethylammonium bromide in aqueous medium.
- Nonideal and asymmetric behavior result from very different surfactant structures.
- Affinity of DHC[−] for HTAB micelles is stronger than that of HTA⁺ for NaDHC ones.
- Mixture composition with minimum total free energy has minimal ionization degree.
- EOMMM asymmetric for realistic analysis when surfactant structure is very different.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 21 June 2016

Received in revised form 9 August 2016

Accepted 11 August 2016

Available online 14 September 2016

Keywords:

Catanionic

Mixed micelles

Bile salt

Surfactant

Micellization

Asymmetric thermodynamic behavior

ABSTRACT

Presuming that the thermodynamic behavior of a system is symmetric, as in the Regular Solution Theory (RST or Rubingh's method), may mask relevant characteristics and lead to erroneous conclusions derived from inexact computed properties (micelle composition, intramicellar interaction energy, activity coefficients and excess free energy of mixed micellization). This work addresses a system which seems *prima facie* strongly non-ideal and asymmetric due to the very different structures of the surfactants: the aqueous solutions of the catanionic system sodium dehydrocholate (NaDHC) and hexadecyltrimethylammonium bromide (HTAB). It has been analyzed with two procedures: the RST and the EOMMM (Equation Oriented Mixed Micellization Modeling). The latter finds the Margules parameters and the micelle compositions that globally minimize the total free energy of micellization. It does not assume symmetry and assures the fulfillment of the Gibbs-Duhem relation.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Surfactant mixtures are not only of theoretical but also of practical interest due to their numerous applications, which often take

* Corresponding author.

E-mail addresses: erica.schulz@uns.edu.ar, erica.patricia.schulz@gmail.com (E.P. Schulz).
<http://dx.doi.org/10.1016/j.colsurfa.2016.08.092>
 0927-7757/© 2016 Elsevier B.V. All rights reserved.

advantage of enhanced properties when compared to the sum of the pure components properties (synergism). Not only the properties of the components are combined when surfactants are mixed, but in many cases new properties arise, such as in cationic-anionic surfactant mixtures [1–7]. From a commercial and industrial point of view, surfactant mixtures have a prominent role in several applications: for instance in detergents, tertiary oil recovery, drug carrier systems and flotation. In spite of their widespread use, many issues of surfactant mixtures remain uncomprehended at a fundamental level. Therefore, surfactant mixtures for specific applications are often chosen based on experience, empirical evidence, or trial and error search. The understanding of the interplaying forces that govern the phase behavior is essential for the rational design of surfactant mixtures. Most of the effort in this sense has been devoted to electrostatic interactions, while scarce attention has been put on the steric ones, mainly on the hydrophobic group geometry.

To rationally apply surfactant mixtures, it is primordial to count with a good description and characterization and, if possible, a predicting technique for the behavior of the micellar systems. Therefore, a proper thermodynamic panorama is a valuable tool for the surfactant technologist, especially when looking for customized mixtures with unique and desirable properties such as the very attractive interactions that can result in critical micelle concentration of the mixture substantially lower than those of the pure surfactants.

The most widely used theory dealing with mixed micellization, the Regular Solution Theory (RST) or Rubingh's Model [8] (see Theory below) assumes that the system is symmetric. Procedures that do not suppose symmetry are mathematically more difficult to solve. Besides, the original RST is usually solved iteratively for each mixture composition and consequently the optimum values of the Margules parameters may not probably be obtained. Moreover, different values are usually achieved for each mixture composition and thus, the Gibbs-Duhem equation is not fulfilled. A question naturally arises when using a procedure that assumes symmetry: how much this assumption affect the results in an asymmetric system? In the present work, a system that seems *prima facie* strongly non-ideal and asymmetric due to the very different structures of the surfactants has been analyzed with the RST and the recently developed Equation Oriented Mixed Micellization Model [9] (EOMMM, see Theory below) using asymmetric Margules formulations for the excess free energy and activity coefficients. The Equation Oriented Optimization approach simultaneously solves the equation system in order to find the minimum/maximum of an objective function subject to a set of constraints. The EOMMM finds the Margules parameters and the micelle compositions that globally minimize the total free energy of micellization.

Instead of a small hydrophilic head group and flexible, liquid-like hydrophobic tails as conventional surfactants, bile salts have a rigid cholesteric backbone, almost flat, with very weakly separated hydrophobic and hydrophilic sides. This results in very distinct aggregates structure and properties. Some of them resemble those of classical amphiphile micelles, while others are very different [10]. Bile salts micelles have low aggregation numbers ($n \approx 4-11$) [11,12], with low solubilization capacity and quite a variety of structures, depending on the number and localization of the secondary hydrophilic groups such as hydroxyl and carbonyl ones [10]. These facts suggest that, from an energetic point of view, the inclusion of a classic surfactant into a bile salt micelle must be very different than the inclusion of a bile salt molecule into a classic surfactant micelle, i.e., the system thermodynamics must be asymmetric.

The studies on mixed micelles of bile salts and other surfactants are mainly with phospholipids. There are scarce studies with single tail surfactants, although bile salt mixed micelles are extensively studied as novel drug delivery systems [13]. A glance on some of these works indicates that the studied systems have proba-

bly asymmetric behavior. Hexadecyltrimethylammonium bromide (HTAB) – sodium deoxycholate (NaDOC) mixed micelles showed different micellar morphology in the HTAB –rich side (small globular micelles, at $\alpha_{\text{NaDOC}} \leq 0.2$; α_{NaDOC} being the mole fraction of NaDOC in the overall surfactant mixture without considering the solvent) than in the NaDOC –rich side of the composition range (cylindrical threadlike micelles) [14]. The aqueous mixed systems sodium cholate (NaC) or NaDOC with hexadecylpyridinium chloride (HDPC) have been studied with the Rubingh's model, showing repulsion between the components in the HDPC-rich side (for $\alpha_{\text{NaC}} < 0.5$ and for $\alpha_{\text{NaDOC}} < 0.3$) and attractive interaction in the bile salt-rich side of the composition range [15]. A glance on the evolution of the free energy of micellisation as a function of α_{NaDOC} in the same article, also indicates that the mixed systems must be thermodynamically asymmetric. Moreover, the authors noticed that some experimental results could not be included in the RST. This is a consequence of the fact that these systems are not thermodynamically symmetric and thus the Rubingh's treatment does not apply.

Suzuki et al. [16] studied mixed micelles of sodium taurocholate (NaTC) and sodium taurodeoxycholate (NaTDOC) with octaethylene glycol monododecylether (C_{10}E_8). They found that the evolution of the aggregation number of mixed micelles as a function of the mixture composition is different for $\alpha_{\text{bilesalt}} \leq 0.3$ than above this composition, thus suggesting asymmetry of these systems. The same conclusion may be obtained by the dependence of the RST intramicellar interaction parameter β_{M} in the mixed system NaDOC- decanoyl-*N*-methylglucamide (MEGA-10) [17]: β_{M} is much higher in the NaDOC –rich side of the composition range than in the MEGA-10 side.

The observations in the above systems lead us to study the system NaDHC – HTAB which we presumed to be strongly asymmetric due to the very different structural nature of the components. Moreover, NaDHC has carbonyl instead of hydroxyl groups in the steroidal backbone and thus they do not form intramicellar hydrogen bonds that considerably influence the bile salts micelle formation [10]. This system would allow us to compare both models, RST and EOMMM and determine which results are disguised when the symmetric restriction is imposed in the model.

Micelles intervene in several biomedical processes such as the solubilization and transport of cholesterol in the gastrointestinal tract by means of bile salt-lecithin mixed micelles [18]. This is why most of the studies on bile salts mixed micelles are with phospholipids. The dehydrocholic acid is a synthetic bile salt manufactured by the oxidation of cholic acid and acts as hydrocholeretic, increasing the bile salt output to clear increased bile acid load. Due to this characteristic, this choleric drug is used in gallbladder diseases: following cholecystectomy in some instances, symptoms develop which are referable to partial obstruction of the common duct, either by a calculus overlooked at the time of operation or by a mucous plug, blood clot or inspissated bile. The foreign body may escape from the duct when employing hydrocholic acid to exert pressure more or less continuously over a given period, without resorting to a surgical treatment [19]. The micellar-forming incapability of dehydrocholic acid has been analyzed on the basis of its effect on organic acid secretion [20] and it has been associated to the insolubility of phospholipids and cholesterol [21] and to the choleric effect: bile acids which do not form micelles cause bile flow (choleresis) at the canalicular level presumably because micelles are larger and thus less osmotically potent than are ionized bile acid themselves [22]. Further insight into the micellar interactions of dehydrocholic acid and their salts will not only allow a better understanding of the biomedical processes where they are involved, but a rational design of drug carriers for these substances.

In the present work, the nature of the molecular interactions between sodium dehydrocholate (NaDHC) and hexadecyltrimethylammonium bromide (HTAB) has been addressed. The whole

composition range of the aqueous mixtures has been studied in order to elucidate the effect of including a rigid cholesteric backbone in a catanionic micelle. To determine how the symmetry assumption can mislead to erroneous conclusions, the thermodynamic behavior analysis has been performed with RST (which assumes symmetry) and the EOMMM with asymmetric Margules formulations (which contemplates both symmetric and asymmetric cases).

2. Theory

There are two types of thermodynamic methods for modeling micelle formation in surfactant solutions: (i) phenomenological models such as the pseudo-phase separation model and the mass-action model and (ii) molecular thermodynamic methods (see Supplementary information (SI) for the sections on Phenomenological Models and Molecular Thermodynamic Methods). These two types of methods are generally considered in literature as parallel treatments for micelle formation. The phenomenological methods mainly aim to the estimation of the mixed micelle compositions while the molecular thermodynamic theories are generally used to predict critical micelle concentrations and other properties. In the present work, two procedures based on phenomenological models were employed in order to analyze the micellization thermodynamics: the Regular Solution Theory (RST) or Rubingh's procedure and the recently published method, Equation Oriented Mixed Micellization Model (EOMMM). Both methods consider the micelles as a separation of a charged pseudo microphase (pseudo-phase separation model). The first treats the non-idealities via the regular solution approximation and is based on symmetric Margules formulations [23–25] (see the SI for RST). The EOMMM is a new approach based on Equation Oriented Optimization and Margules asymmetric formulations which is not restricted to the number of components and guarantees the applicability of the Gibbs-Duhem relation [9] (see SI for EOMMM).

The critical micelle concentration (CMC) has been determined from conductivity data employing the excess specific conductivity ($\Delta\kappa = \kappa - \kappa_{\text{extrap}}$ where κ_{extrap} is the specific conductivity extrapolated from the pre-CMC straight line). $\Delta\kappa$ has been plotted against the total concentration, as proposed Miura and Kodama [26] to magnify the conductivity changes at the CMC.

The differential conductivity ($\Lambda_{\text{dif}} = \partial\kappa/\partial C$) can be also calculated using the conductivity and plotted as a function of the average concentration C_{av} [27]. $\partial\kappa/\partial C$ has been computed as an average of the first derivative of the κ vs. C curve, obtained by six different numerical methods (see S.I. for Numerical Differentiation with Finite-Divided-Difference Formulas) and C_{av} is $(C_1 + C_2)/2$, where C_1 and C_2 are the interval limits in where each derivative is computed.

To compute the micellar ionization degree (α) the equation proposed by Evans [28] has been employed:

$$1000 \left(\frac{d\kappa}{dC} \right)_2 = \frac{(n-m)^2}{n^{4/3}} \left[1000 \left(\frac{d\kappa}{dC} \right)_1 - \Lambda_x \right] + \alpha \Lambda_x \quad (1)$$

where $(d\kappa/dC)_1$ and $(d\kappa/dC)_2$ are the slopes of the specific conductivity curves before and after the CMC, n is the aggregation number, m the number of counterions attached to the micelle, and Λ_x is the equivalent conductivity of the counterion. Eq. (1) is a quadratic function of α , because $(n-m) = n\alpha$. It is also dependent on n . However, this dependence is weak and any reasonable value of n gives a good estimation of α [28]. We employed $n = 100$, which is a common value for n in spherical micelles of surfactants having a C_{16} single chain [29,30]. Filipovic-Vincekovic [31] found that non-equimolecular micelles in catanionic systems are significantly smaller than the equimolecular ones. Since all the micelles studied

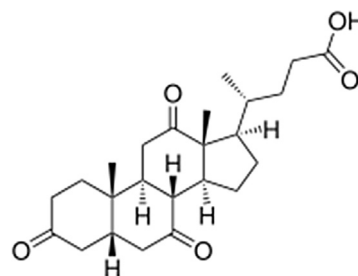


Fig. 1. Dehydrocholic acid (3,7,12 trioxo-5 β cholane-24-oic acid) structure.

here are not equimolecular (even if $\alpha_{\text{NaDHC}} = 0.5$, vide infra), using a constant value of n does not significantly affect the estimated value of α .

In the estimation of α for surfactant mixtures, we employed the average counterion conductivity:

$$\Lambda_x = \alpha_{\text{NaDHC}} \lambda_{\text{Na}^+} + (1 - \alpha_{\text{NaDHC}}) \lambda_{\text{Br}^-} \quad (2)$$

with $\lambda_{\text{Br}^-} = 77.4$ and $\lambda_{\text{Na}^+} = 50.9 \text{ S cm}^2 \text{ mol}^{-1}$ [32].

3. Experimental

Hexadecyltrimethylammonium bromide (HTAB, 99%) was from Fluka. Dehydrocholic acid (HDHC) was from Dr. Theodor Schuchardt GMBH & Co. (München) and of analytical grade. Fig. 1 shows the HDHC structure. Both surfactants were used as purchased. A concentrated sodium dehydrocholate (NaDHC) aqueous solution was prepared dissolving a determined quantity of HDHC in an appropriate amount of concentrated NaOH solution. Then, this concentrated NaDHC solution was mixed with a concentrated HTAB solution in appropriate proportions to obtain concentrated solutions with the following molar fractions of NaDHC on a surfactant-only basis $\alpha_{\text{NaDHC}} = 0$ (pure HTAB); 0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9 and 1 (pure NaDHC) (i.e. without considering the water; $\alpha_{\text{HTAB}} + \alpha_{\text{NaDHC}} = 1$). Only three fold-distilled water (specific conductivity $3 \mu\text{S cm}^{-1}$) was used.

Conductivity was measured after adding measured volumes of concentrated solution of each surfactant mixture to water using an automatic Instrumentalia Antares II conductimeter. The conductimeter was calibrated with KCl aqueous solutions, as usual.

Surface tension of the different dilutions of the NaDHC-HTAB system was measured with a semiautomatic ring tensiometer (Krüss).

Dye solubilization experiments were performed in two sets of tubes containing the solutions with the different concentrations of the NaDHC-HTAB system: small Sudan III crystals were added in one of the series and small Sudan Black B crystals into the other. The tubes were sealed, left for a week and periodically stirred. Then the tubes were centrifuged and the supernatant absorbance was measured with a Spectronic-20 UV-vis spectrophotometer at $\lambda = 600 \text{ nm}$ (Sudan III) and $\lambda = 490 \text{ nm}$ (Sudan Black B).

pH determinations of the dilutions of the surfactant mixtures were made with a millivoltmeter and pH-meter CRIBABB and a Broade and James glass electrode.

Br^- determinations were made with an Orion Br^- ion-selective electrode and Na^+ determinations were made using a Na^+ ion-selective electrode Orion 8411 Ross both with the same millivoltmeter and vs. a saturated calomel electrode (SCE).

The DHC^- ion-selective electrode was made gluing at one extreme of a PVC tube a membrane made with 300 mg of PVC dissolved in 50 mL of tetrahydrofuran (THF), 0.2 mL dibutylphthalate (plasticiser) and 0.167 g of $\text{Pd}(\text{DHC})_2$. This salt was made by mixing the appropriate amounts of PdCl_2 and an aqueous solution of NaDHC. The insoluble $\text{Pd}(\text{DHC})_2$ salt was filtered and washed sev-

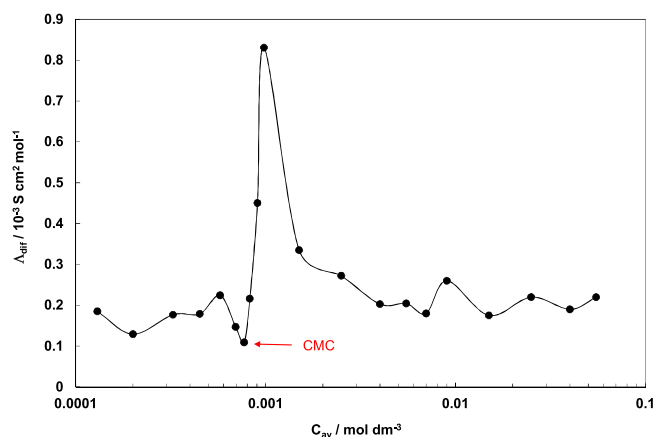


Fig. 2. Differential conductivity of the mixture with $\alpha_{\text{NaDHC}} = 0.7$.

eral times with three-fold distilled water and then left to dry. The crystals were powdered and suspended in the above PVC solution. Then the suspension was left in a Petri dish to let the THF evaporate and the resulting membrane was cut and glued to the tube. The tube was filled with an aqueous solution 0.01 mol dm^{-3} of NaDHC and 0.1 mol dm^{-3} of KCl with a small amount of solid AgCl. An Ag/AgCl electrode made with a silver wire was placed inside the tube and connected to the millivoltmeter by a copper wire passing through a rubber plug.

The HTA⁺ ion-selective electrode was prepared as the preceding one, using as carrier a HTA-dodecylsulphate complex suspended in the PVC solution. The internal electrode was an Ag/AgBr and the internal solution was 0.01 mol dm^{-3} HTAB and 0.1 mol dm^{-3} NaCl with some crystals of AgBr.

All the ion-selective electrodes potentials were measured against a SCE and all determinations were made at 25.0°C .

Mean values and variances were computed by the minimum variance linear unbiased method [33] and the Student *t* function was employed to compute the error intervals with a confidence level of 0.90. Errors of the derived data were computed with the error expansion method.

4. Results

Since the HTAB hydrolysis is very weak and its detection is extremely difficult [34], we did not measure the pH of pure HTAB solutions. The pH vs. log C of solutions containing NaDHC showed the typical shape of hydrolysable surfactants (see Fig. 1 in SI) [35,36].

Fig. 2 in SI shows the specific conductivity (κ) vs. the total concentration, C. Fig. 3 in SI is the plot of $\Delta\kappa$ ($=\kappa - \kappa_{\text{extrap}}$) vs. C, where κ_{extrap} is the specific conductivity extrapolated to growing concentrations from the pre-CMC region for the system with $\alpha_{\text{NaDHC}} = 0.7$. When comparing these two figures, it is evident that this latter representation allows a better determination of the CMC.

Fig. 2 shows the differential conductivity Λ_{dif} for the mixture with $\alpha_{\text{NaDHC}} = 0.7$. Similar plots can be seen in Fig. 4 in the SI for the systems with $\alpha_{\text{NaDHC}} = 0$ (pure HTAB); 0.2; 0.4; 0.6; 0.8; 1 (pure NaDHC).

It can be observed in all these mixtures that immediately above the CMC there is an increase of Λ_{dif} , indicating that the micelles formed at the CMC are very conductive because they are highly charged [37]. At higher concentrations, counterions are incorporated into the micelle Stern layer and the differential conductivity decreases. This phenomenon has been observed in cationic surfactant micellization studied with ion-selective electrodes: the surfactant ion initially aggregates without counterions but they

are included in the Stern layer at a higher concentration [38,39]. In some cases there is a slight increase of the differential conductivity with the total concentration due to a structural change of the micelles and/or a change in the intermicellar interactions.

Fig. 5 in the SI shows the response of the surfactant ion-selective electrodes for the system with $\alpha_{\text{NaDHC}} = 0.7$, as well as the concentration of free (non-micellised) DHC⁻ and HTA⁺ ions as a function of the total concentration of the mixture. The concentration of *i* in the mixture is obtained as $[i]_{\text{total}} = C \cdot \alpha_i$, which is plotted as a function of the potential E. The curve of $[i]_{\text{total}}$ vs. E follows a straight line below the CMC whose extrapolation allows the calculation of the concentration of the free ion *i*, $[i]_{\text{free}}$, for the corresponding E values above the CMC. Therefore, the amount of *i* in micelles may be computed as $[i]_{\text{M}} = [i]_{\text{total}} - [i]_{\text{free}}$.

The DHC⁻ ion-selective electrode was insensitive to the concentration of HTA⁺. The HTA⁺ ion-selective electrode is sensitive to both surfactant ions. However as its response to each of the amphiphilic ions is different, the determination of the composition of the monomeric solution above the CMC with this electrode is not straightforward. Therefore, the ion-selective electrode measurements were useful for the determination of the CMC but not reliable

Fig. 6 in SI shows the determinations by dye solubilization for the system with $\alpha_{\text{NaDHC}} = 0.5$, showing the existence of a possible pre-micellar aggregation and a change in the micelles structure (occurring at the so called second CMC), may be to rod-like or disk-like micelles, which strongly increases the solubilization capacity of micelles [40]. As an example, the second CMC of pure dodecyltrimethylammonium bromide, DTAB, is 32 mM [41]. The increase of the solubilization capacity is due to the reduction of the Laplace pressure in the micellar hydrocarbon core (one of the curvature radiuses tends to infinity) [42–44].

Fig. 7 in SI shows the surface tension vs. concentration plots for the mixtures with $\alpha_{\text{NaDHC}} = 0.2$; 0.5 and 0.9. For $\alpha_{\text{NaDHC}} = 0.2$ and 0.9 the plots are similar to those of other surfactants, i.e. the mixture acts as a pure surfactant. In the case of $\alpha_{\text{NaDHC}} = 0.5$ there is a minimum, which appears when a more surface-active component in the adsorbed monolayer at the air/solution interface is solubilized by previously formed micelles, then causing a sudden desorption and increase in the surface tension. This has been observed in surfactants with a surface active impurity, such as dodecanol in sodium dodecyl sulfate. Minima in the surface tension vs concentration plots were observed in the systems sodium cholate (NaC) – hexadecylpyridinium chloride (HDPC) with $\alpha_{\text{NaC}} = 0.25$ and sodium deoxycholate (NaDOC) – HDPC with $\alpha_{\text{NaDOC}} = 0.20$, whereas for the other α_{bilesalt} values the plots were more conventional [15]. Therefore, this mixture does not act as a pure surfactant, and at least one part of one of the components acts as a surface-active impurity.

Fig. 3 summarizes the critical micelle concentration, the second CMC and the ideal CMC (i.e. obtained with Clint's relation, see Eq. (32) in S.I.) of the catanionic mixtures as a function of the mole fraction of NaDHC in the overall surfactant mixture, while Fig. 4 shows the micelle ionization degree in the mixed system as a function of α_{NaDHC} .

Fig. 5 shows the excess free energy of micellization (G^{exc}) and the activity coefficients (γ) as a function of the micelles composition obtained with the EOMMM using asymmetric Margules formulations with a margin of 0.3. This margin is the maximum deviation allowed for the CMCs determined by the EOMMM from the experimentally determined ones (see Fig. 8 in the S.I. for the experimental, ideal and obtained by the EOMMM CMCs as a function of the mixtures compositions). The analogous plot but employing symmetric Margules formulations is given in Fig. 9 in the SI. The GAMS input file and the corresponding input data to solve the EOMMM have been included in the S.I. The high slope of $\Delta G^{\text{exc}}/RTx_1 \times 2$ vs. x_{DHC}

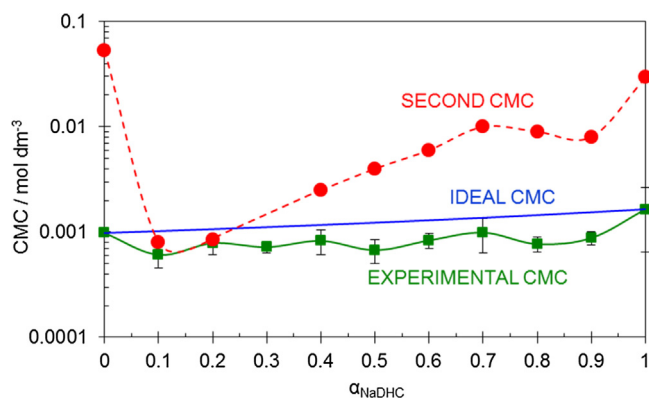


Fig. 3. Ideal and experimental CMC and second CMC as a function of the composition of the surfactant mixture α_{NaDHC} . Squares: CMC, circles: second CMC.

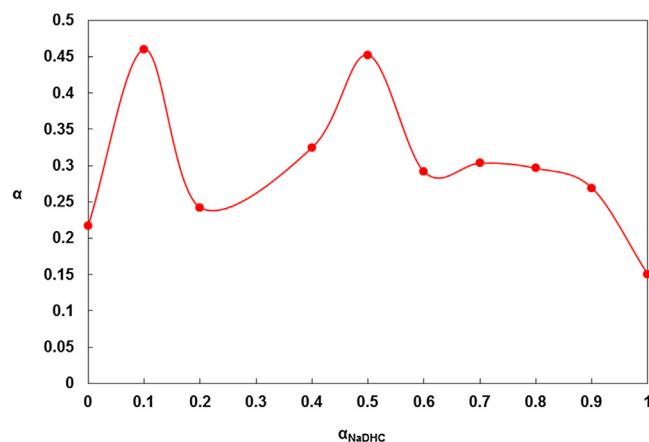


Fig. 4. The micelle ionization degree as a function of the surfactant mixture composition.

in Fig. 5 evidences that the system is very asymmetric. In symmetric systems this straight line is horizontal (see Fig. 9 in the SI).

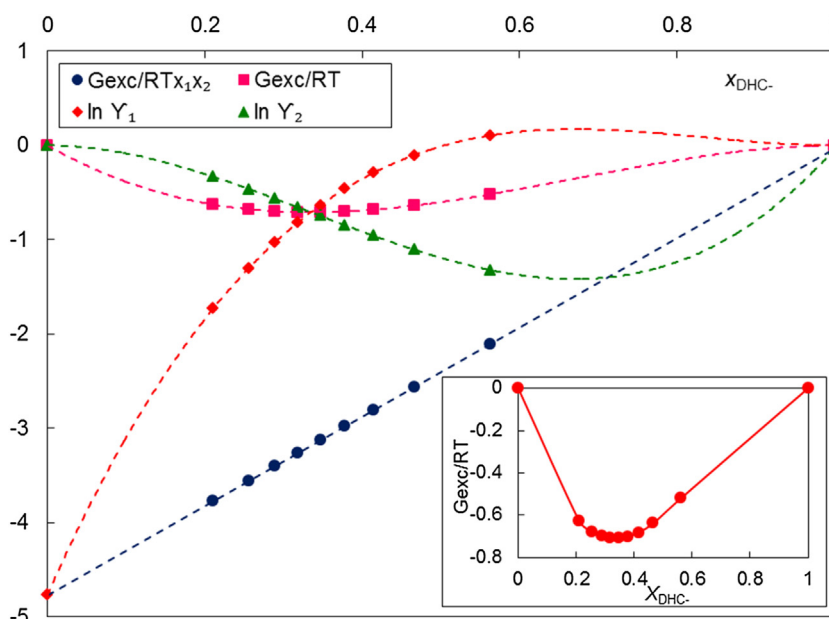


Fig. 5. Excess free energy of micellization (G^{exc}) and activity coefficients dependence with the molar fraction of NaDHC in the micelles (X_{DHC}) obtained with the EOMMM using asymmetric Margules formulations with a margin of 0.3 (subscripts 1 and 2 refer to NaDHC and HTAB, respectively).

5. Discussion

Sudan III has a phenolic hydroxyl group and thus it may have a low solubility in alkaline solutions, such as those having NaDHC. This may be the reason for the small increase of absorbance below the CMC. Therefore, we also used Sudan Black B (which does not have acidic groups) to confirm the formation of small premicelles at very low concentrations, as it can be seen in Fig. 6 in the SI. Fig. 10 in the SI shows the concentrations at which the premicelles were detected. Since these values are very small, their uncertainty is high and they must be taken with care. In mixed micelles with $0.3 < \alpha_{\text{NaDHC}} \leq 0.9$ the premicelles are formed at smaller concentrations than the pure components, i.e., including a second component favors the formation of premicelles. The premicelles are probably a sort of DHC-HTA complex similar to ion pairs.

Premicellar aggregates have been found in other bile salts, such as sodium taurocholate [45,46], sodium deoxycholate [47] and sodium taurodeoxycholate [46].

As expected, it can be observed in Fig. 3 that the experimental CMC is lower than the ideal ones and that the addition of small quantities of NaDHC strongly reduces the second CMC, as previously observed in HTAB solutions when some hydrotropes such as sodium salicylate are added [45,46], even in very low concentrations of the order of $1 \times 10^{-3} \text{ mol dm}^{-3}$ [47].

The origin of the non-ideal intramicellar interactions is the coulombic attraction between the anionic and cationic polar head-groups and the great difference between the hydrophobic groups of both surfactants. Therefore, the neighborhood of the species in the mixed micelles is very different to that in pure micelles. In particular, the structure of the dehydrocholate hydrocarbon backbone may allow a larger water-hydrocarbon contact, as it can be deduced from the different structures proposed for bile salts micelles [10].

According to the RST applied to each mixture composition independently, the intramicellar interaction parameter β_{M} is almost constant, with an average value of -2.29 ± 0.03 in $k_{\text{B}}T$ units (k_{B} is the Boltzmann constant and T is the absolute temperature). When calculated with the EOMMM assuming symmetric interactions (SYM), $W/RT (= \beta_{\text{M}})$ is -2.75 . These values are less negative than the typical values for common catanionic mixtures: -13.2 for sodium decylsulfate- (SDeS) decyltrimethylammonium bromide (DeTAB)

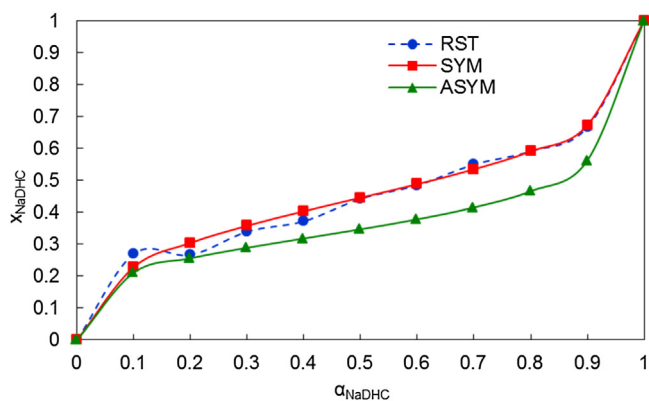


Fig. 6. Molar fraction of NaDHC in the mixed micelles (x_{NaDHC}) as a function of the total system molar fraction of NaDHC (α_{NaDHC}) calculated according to RST and EOMMM considering symmetric (SYM) and asymmetric (ASYM) Margules formulations.

[24] or -27.8 [7]; -14.2 for sodium octylsulfate – oyltrimethylammonium bromide [7] and -13.2 for SDeS – DeTAB [48]. Higher β_M values have been found for some particular anionic – cationic surfactant aqueous mixtures, such as HTAB–NaDOC ($\beta_M = -2.7$ [49]), HTAB – NaC ($\beta_M = -4.0$ [49]) and dodecyltrimethylammonium bromide – disodium dodecanephosphonate ($\beta_M = -1.66$ [50]). All of these systems have some structural characteristics that are different to the most commonly studied catanionic mixtures.

Interesting conclusions can be derived from the results of the EOMMM considering asymmetric Margules formulations. When the component i is infinitely diluted (x_i tends to zero), the natural logarithm of the activity coefficient of that component tend to the Margules parameter divided RT , which is analogous to the intramicellar interaction parameter (β_M) obtained by the RST. Thus, when $x_i \rightarrow 0$, $\ln \gamma_i \rightarrow \ln \gamma_i^\infty = W_{ij}/RT = \beta_{M,ij}$ (i.e. when $x_{\text{NaDHC}} \rightarrow 0$) DHC^- ions infinitely diluted in mixed micelles of almost pure HTAB micelles, $\ln \gamma_{\text{DHC}^-} = W_{\text{DHC}^- \text{HTA}^+}/RT$, that is analogous to the $\beta_{M, \text{DHC}^- \text{HTA}^+}$ obtained by the RST). The intramicellar interaction parameters obtained ($W_{\text{DHC}^- \text{HTA}^+}/RT = -4.77$ and $W_{\text{HTA}^+ \text{DHC}^-}/RT = -0.0419$) evidence an attractive interaction in the mixed micelles. Notice that the average value of both W_{ij}/RT is -2.41 , which is very close the β_M obtained from the RST. Moreover, the affinity of DHC^- ions for HTAB micelles ($W_{\text{DHC}^- \text{HTA}^+}/RT = -4.77$) is stronger than that of HTA^+ ions for NaDHC ones ($W_{\text{HTA}^+ \text{DHC}^-}/RT = -0.0419$), reflecting the different structures of the pure micelles: micelles of HTAB have an hydrocarbon core with scarce water inclusion, while NaDHC micelles have a hydrocarbon structure which allows the contact between water and the hydrocarbon tail of HTA^+ when it enters into the NaDHC micelles.

Fig. 6 shows the molar fraction of DHC^- in the mixed micelles (x_{DHC^-}) as a function of the total system molar fraction of NaDHC (α_{NaDHC}) according to the three procedures: RST (calculated for each mixture independently according to the common procedure) and the EOMMM considering symmetric (SYM) and asymmetric (ASYM) Margules formulations. The x_{DHC^-} obtained with ASYM are lower than those given by the RST and SYM procedures. Thus, estimating the mixed micelle compositions of asymmetric systems with a model that imposes symmetry may lead to a significant difference with those estimated with the EOMMM employing asymmetric formulations. In the present system, the difference is about 25%. The thermodynamic treatment of the EOMMM is more rigorous than that of the RST. In a previous work [9] we have validated the EOMMM with mixed surfactant systems taken from literature whose micellar composition had been experimentally determined and we have shown that the compositions obtained with EOMMM are more accurate than those obtained with the RST.

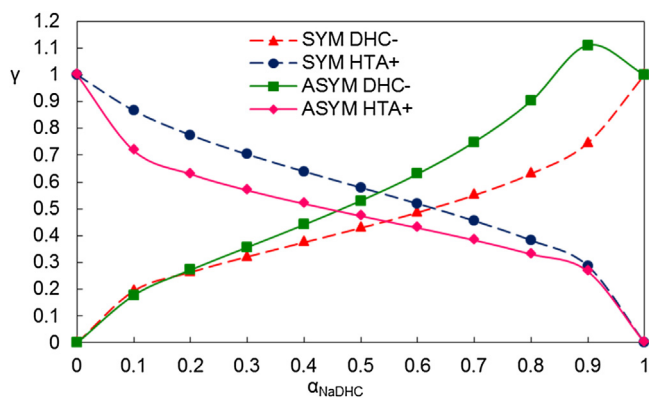


Fig. 7. Activity coefficients of DHC^- and HTA^+ ions in the mixed micelles obtained with EOMMM using symmetric (SYM) and asymmetric (ASYM) Margules formulations as a function of the overall surfactant mixture composition (α_{NaDHC}).

Fig. 7 shows the intramicellar activity coefficients obtained with EOMMM using symmetric (SYM) and asymmetric (ASYM) Margules formulations as a function of α_{NaDHC} . The activity coefficients obtained with EOMMM-ASYM present a maximum for DHC^- ($\gamma_{\text{DHC}^-} = 1.11$) in $\alpha_{\text{NaDHC}} = 0.9$, which corresponds to $x_{\text{DHC}^-} = 0.56$ (see **Fig. 6**) which corresponds to the less negative value of G^{exc}/RT (-0.52 J/mol) in **Fig. 5**. Since $G^{\text{exc}}_{\text{DHC}^-}/RT = \ln \gamma_{\text{DHC}^-}$, this means that the inclusion of DHC^- ions into the mixed micelle having $x_{\text{NaDHC}} = 0.56$ is less favorable than its inclusion in pure NaDHC micelles (Pure component micelles is the standard state in the pseudophase separation model for micellization). The activity coefficient for HTA^+ ($\gamma_{\text{HTA}^+} = 0.3$) in the same aggregate indicates that the inclusion in mixed micelles of this component is more favorable than in pure HTAB micelles. The excess Gibbs free energy of micellization remains negative because it is a weighted average of the components' contributions ($G^{\text{exc}}/RT = x_{\text{DHC}^-} \ln \gamma_{\text{DHC}^-} + x_{\text{HTA}^+} \ln \gamma_{\text{HTA}^+}$). The interpretation of the individual components must be related to the mixed micelle structure. The inclusion of DHC^- ions in the mixed micelle for $x_{\text{DHC}^-} > 0.56$ must produce a more open micelle hydrocarbon core increasing the hydrocarbon-water contact and thus increasing the Gibbs free energy of the system. On the other hand, an extra HTA^+ ion inclusion must reduce this contact (see insert in **Fig. 5**). This situation occurs because of the asymmetric nature of this mixed surfactant system.

This situation has been also observed in other bile salts mixed micelles. In the system NaC–HDPC with $\alpha_{\text{NaC}} = 0.5$, $\gamma_{\text{C}^-} = 1.01$, and in the NaDOC–HDPC with $\alpha_{\text{NaDOC}} = 0.33$, $\gamma_{\text{DOC}^-} = 1.14$ [15]. In the system NaDOC–sodium oleate (NaO) at 20°C , $\gamma_{\text{NaDOC}} = 1.07$ and $\gamma_{\text{NaOC}} = 1.01$, and at 30°C , $\gamma_{\text{NaDOC}} = 1.21$ and $\gamma_{\text{NaO}} = 1.01$. At both temperatures, this situation led to repulsive intramicellar interactions, i.e., $\beta_M > 0$ [51]. The authors of both mentioned articles did not give any interpretation of these results.

By this time it is not necessary to emphasize that the system thermodynamics cannot be symmetric since the strongly different structures of the surfactants produce very different micellar interactions in the extreme compositions. The minimum excess free energy obtained with EOMMM-ASYM is when x_{DHC^-} is 0.34 (see inset in **Fig. 5**) which corresponds to $\alpha_{\text{NaDHC}} = 0.5$ (see **Fig. 6**). If the system were symmetric, the minimum excess free energy would have been at $x_{\text{DHC}^-} = 0.5$ (see **Fig. 9** in S.I.). This behavior indicates that the microenvironment of each surfactant in the mixed micelles is strongly different from that in its pure micelles.

The excess free energy of micellization for the three procedures (RST; EOMMM-SYM and EOMMM-ASYM) is presented in **Fig. 11** in the S.I. As expected, the $\Delta G_{\text{mix}}^{\text{excess}}$ obtained with RST has a non-smooth dependence because, as they have been calculated for each mixture independently and thus they do not fulfill the Gibbs-

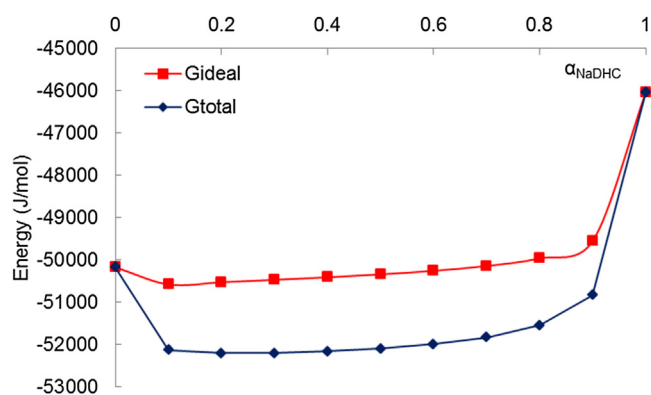


Fig. 8. Total and ideal free energy as a function of the overall surfactant mixture composition (α_{NaDHC}) obtained with EOMMM with asymmetric Margules formulations.

Duhem equation. On the other hand, the EOMMM solves all the mixture compositions simultaneously minimizing the free energy of micellisation while satisfying the Gibbs-Duhem equation and thus the $\Delta G_{\text{mix}}^{\text{excess}}$ dependence with the surfactant mixture composition is smooth and continuous. Thus, using the complete set of data reduces the possibility of scattering of the results and underdetermination of the mathematical problem, which may give several solutions for the same system as observed when applying the RST [52]. As expected, the EOMMM-ASYM procedure gave the minimal $\Delta G_{\text{mix}}^{\text{excess}}$ values since the symmetric Margules formulations are a particular case of the asymmetric ones.

The mixture with composition $\alpha_{\text{NaDHC}} = 0.2$ ($x_{\text{DHC}^-} = 0.25$) has the minimum total free energy (see Fig. 8). As a result of considering asymmetric interactions, $x_{\text{DHC}^-} = 0.25$ is the thermodynamically more favorable micelle composition (Fig. 6), instead of the intuitive value of 0.5. This is a consequence of the equilibrium between the electrostatic interaction of oppositely charged headgroups and the disruption of the tight structure of the hydrocarbon core of the micelles of HTAB by the inclusion of the cholesteric backbone increasing the hydrocarbon-water contact in the mixed micelles. Interestingly, there is a minimum in α in $\alpha_{\text{NaDHC}} = 0.2$ ($x_{\text{DHC}^-} = 0.25$) (see Fig. 4), which is the composition having the minimum of free energy of micellization. It suggests that micelles with this composition have a compact structure minimizing the water-hydrocarbon contact and the area per micellised polar headgroup at the Stern layer. This in turn gives a high micelle surface potential which captures a large quantity of counterions. Since in these micelles HTAB is in excess, the captured counterions must be Br^- , which are attracted to the micelle surface not only by its positive charge but also by van der Waals interactions due to its high polarizability. Actually, this caused the inclusion of bromide ions in the Stern layer of catanionic micelles having an excess of negative surfactant ions [53].

The micelle ionization degree has been plotted as a function of the micelle composition in Fig. 9 and as a function of α_{NaDHC} in Fig. 4.

The micelle ionization degrees of all the mixed micelles are higher than those of the pure surfactant micelles as a consequence of a combination of factors: part of the charge of the predominant headgroups is neutralized by the charge of the other surfactant; the rigid and open cholesteric backbone intercalated in the HTAB palisade produces a separation of charges in the micelle Stern layer, thus reducing the micelle surface potential, which in turn diminishes the electrostatic attraction to counterions; and the lower CMC of mixtures reduces the ionic strength producing the same effect.

The Evans' method detects the counterions not attached to the micelle Stern layer, which in pure surfactant micelles is the effective

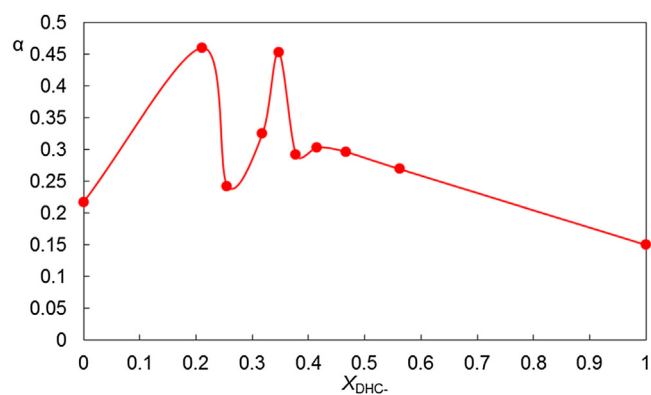


Fig. 9. The micelle ionization degree as a function of the mixed micelle composition (obtained with EOMMM with asymmetric Margules formulations).

charge per micellised surfactant molecule. In pure surfactant micelles, $\alpha = (n-m)/n$, where n is the number of surface active ions in the micelle (i.e., the aggregation number) and m the number of counterions in the micelle's Stern layer. The micelle ionization degree may also be interpreted as the charge per micellised surfactant molecule. However, in catanionic micelles the value of α derived from this method is no longer this property. In surfactant mixtures, there are one Na^+ and one Br^- ion in solution for each hexadecyltrimethylammonium dehydrocholate (HTA-DHC) pair in the micelle. Besides, in systems in which one surfactant (NaDHC or HTAB) is in excess, there are free counterions coming from the ionization of the non-paired surfactant molecules in the micelles. Since for all x_{DHC^-} the ionization degree is not unity, there are some counterions attached to the Stern layer in all mixed micelles. Notice that in the mixed micelles α is related to the fraction of charge of the excess (non-paired) surfactant and does not reflect the real micelle charge. The effective micelle charge is the difference among the charge of the ions in higher proportion in micelles (HTA^+) and those of the surface-active ions in minor proportion (DHC^-) and the counterions attached to the Stern layer.

From Fig. 9 it can be seen that there are two maxima, one for $x_{\text{DHC}^-} = 0.21$ ($\alpha_{\text{NaDHC}} = 0.1$) and $x_{\text{DHC}^-} = 0.35$ ($\alpha_{\text{NaDHC}} = 0.5$). This is surprising, because one may expect that this situation must occur at $x_{\text{DHC}^-} = 0.5$. The origin of this behavior is probably the very different nature of the hydrophobic groups belonging to both surfactants. Both compositions show slight minima in the CMC, but probably the maxima in α are caused by a reduction of the surface potential of micelles by the inclusion of DHC^- ions. In view of their structure (see Fig. 1), it is probably that part of the bulky cholesteric backbone is situated in the Stern layer of the mixed micelle due to the formation of hydrogen bonds between water and the oxygen atoms of the carbonyl groups.

A similar dependence of α on the surfactant mixture composition was found in other catanionic systems [4,54]. The value of α for pure HTAB micelles is in agreement with the values obtained for cationic surfactants and reflects the hydrophobicity of the bromide ion [39] and its high polarizability, which favors its adsorption at the micelle surface [55].

6. Concluding remarks

The system NaDHC-HTAB has been analyzed on the basis of the EOMMM employing asymmetric Margules formulations proving to provide a realistic analysis of the mixed micelles' thermodynamics when the structure of the surface active components is very different. The addressed system showed a non-ideal and asymmetric behavior with attractive interaction between the components, as reflected by the interaction parameters: the affinity of DHC^- ions

for HTAB micelles ($W_{\text{DHC-HTA}}/RT = -4.77$) is stronger than that of HTA⁺ ions for NaDHC ones ($W_{\text{HTA-DHC}}/RT = -0.0419$). This is consequence of the different structures of the pure micelles: micelles of HTAB have a hydrocarbon core with scarce water inclusion, while NaDHC micelles have a more open hydrocarbon structure which allows the contact between water and the hydrocarbon tail of HTA⁺ when it enters into the NaDHC micelles. The compositions of the micelles determined with this procedure show that for $\alpha_{\text{NaDHC}} \geq 0.3$, $x_{\text{DHC}} < \alpha_{\text{NaDHC}}$.

The mixed micelles formed at the CMC are very conductive because they are highly charged. However, at higher concentrations the counterions are incorporated into the micelle Stern layer and the differential conductivity decreases. There is evidence that premicelles are formed at very low concentrations and that the inclusion of NaDHC in the system induces the formation of anisometric micelles above the CMC.

The mixture with composition $\alpha_{\text{NaDHC}} = 0.2$ has the minimum total free energy and thus $x_{\text{DHC}} = 0.25$ is the thermodynamically more favorable micelle composition, having the minimal ionization degree. This is interpreted by a combination of factors: the tight micelle structure reduces the water-hydrocarbon contact and minimizes the micelle surface area per polar headgroup increasing the surface potential, and an additional van der Waals attraction between bromide ions and the micelle surface. Besides, the micelle ionization degree of the mixed micelles is higher than that of the pure surfactant micelles, attributed to changes in the micelle structure reducing the micelle surface potential and the diminution of the CMC on mixing, causing a reduction of the ionic strength in the intermicellar solution and an increase in the Debye distance.

The use of a treatment based on a symmetric thermodynamic model such as the RST in systems that are evidently asymmetric leads to erroneous values of the computed properties such as the micelles compositions, the activity coefficients of the components in the mixed micelles or the excess free energy of mixed micellization. On the contrary, applying a procedure that contemplates asymmetry, not only contemplates the possibility that the system is actually symmetric (the EOMMM-ASYM will give $W_{ij} = W_{ji}$) but gives a more detailed thermodynamic description of the system with information that would be masked otherwise.

Acknowledgements

EPS, GAD and HR are adjunct, assistant and independent researchers of the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET) respectively. This work was partially supported by grants PGI-UNS 24/Q073; PGI-UNS 24/F067 and PGI-MayDS 24/MA09 of Universidad Nacional del Sur and PICT 2013 (D) Nro 2070 of Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.colsurfa.2016.08.092>.

References

- [1] R.M. Minardi, P.C. Schulz, B. Vuano, The aggregation of aqueous dodecylphosphonic acid in dodecyltrimethylammonium hydroxide mixtures, *Colloid Polym. Sci.* 274 (1996) 669–677.
- [2] P.C. Schulz, R.M. Minardi, B. Vuano, Solubilization of styrene in the catanionic system dodecyltrimethylammonium hydroxide-*n*'-dodecanephosphonic acid, *Colloid Polym. Sci.* 276 (1998) 278–281.
- [3] R.M. Minardi, P.C. Schulz, B. Vuano, The catanionic system dodecyltrimethylammonium hydroxide-*n*-dodecanephosphonic acid-water. Triangular phase diagram, *Colloid Polym. Sci.* 276 (1998) 589–594.
- [4] N. El Kadi, F. Martins, D. Clause, P.C. Schulz, Critical micelle concentrations of aqueous hexadecyltrimethylammonium bromide-sodium oleate mixtures, *Colloid Polym. Sci.* 281 (2003) 353–362.
- [5] P. Messina, M.A. Morini, P.C. Schulz, Aqueous sodium oleate-sodium dehydrocholate mixtures at low concentration, *Colloid Polym. Sci.* 281 (2003) 1082–1091.
- [6] Z.E. Proverbio, P.C. Schulz, J.E. Puig, Aggregation of the aqueous dodecyltrimethylammonium bromide-didodecyltrimethylammonium bromide system at low concentration, *Colloid Polym. Sci.* 280 (2002) 1045–1091.
- [7] Q. Zhou, M.J. Rosen, Molecular interactions of surfactants in mixed monolayers at the Air/Aqueous solution interface and in mixed micelles in aqueous Media: the regular solution approach, *Langmuir* 19 (2003) 4555–4562.
- [8] P.M. Holland, Chapter 2: modeling mixed surfactant systems, in: P.M. Holland, D.N. Rubingh (Eds.), *Mixed Surfactant Systems*, American Chemical Society, Washington D.C., 1992, pp. 31–44.
- [9] E.P. Schulz, G.A. Durand, Equation oriented mixed micellization modeling based on asymmetric Margules-type formulations, *Comput. Chem. Eng.* 87 (2016) 145–153.
- [10] D. Madenci, S.U. Egelhaaf, Self-assembly in aqueous bile salt solutions, *Curr. Opin. Colloid Interface Sci.* 15 (2010) 108–115.
- [11] J.P. Kratochvil, W.P. Hsu, D.I. Kwok, How large are the micelles of di- α -hydroxyl bile salts at the critical micellisation concentrations in aqueous electrolyte solutions? Results for sodium taurodeoxycholate and sodium deoxycholate, *Langmuir* 2 (1986) 256–258.
- [12] M. Janich, J. Lange, H. Graener, R. Neubert, Extended light scattering investigation on dihydroxi bile salt micelles in low-salt aqueous solution, *J. Phys. Chem. B* 102 (1998) 5957–5962.
- [13] D.M. Cirin, M.M. Posa, V.S. Krstonosik, Interaction between selected bile salts and triton X-100 or sodium lauril ether sulfate, *Chem. Central J.* 5 (2011) 89–97.
- [14] M.S. Vethamuthu, M. Almgren, W. Brown, E. Mukhtar, Aggregate structure gelling, and coacervation within the L₁ phase of the quasi-ternary system alkyltrimethylammonium bromide- sodium deoxycholate-water, *J. Colloid Interface Sci.* 174 (1995) 461–479.
- [15] B.K. Roy, S.P. Moulik, Interfacial and micellar properties of binary mixtures of sodium cholate and sodium deoxycholate with cethyl pyridinium chloride, *J. Surf. Sci. Technol.* 12 (1–4) (1996) 86–94.
- [16] Y. Yunomiya, T. Kunitake, T. Tanaka, K. Suzuki, T. Hasegawa, Y. Takamura, K. Takahashi, H. Asano, M. Ueno, Behavior of sodium taurocholate and sodium taurodeoxycholate in binary mixed micelles of bile salt and nonionic surfactant, *Langmuir* 12 (1996) 5536–5540.
- [17] Y. Yunomiya, T. Kunitake, T. Tanaka, G. Sugihara, T. Nakashima, Micellization of mixed system of bile salt and nonionic surfactant: sodium deoxycholate and decanoyl-*N*-methylglucamide, *J. Colloid Interface Sci.* 208 (1988) 1–5.
- [18] J.E. Stagers, O. Hernell, R.J. Stafford, M.C. Carey, Physical-chemical behavior of dietary and biliary lipids during intestinal digestion and absorption. 1. Phase behavior and aggregation states of model lipid systems patterned after aqueous duodenal contents of healthy adult human beings, *Biochemistry* 29 (1990) 2028–2040.
- [19] R.B. Russell, N. Frederick Hicken, A.I. Finlayson, The effect of dehydrocholic acid upon biliary pressure and its clinical application, *Ann. Surg.* 110 (1939) 67–80.
- [20] S.M. Strasberg, Mechanisms of solute secretion into bile, in: M.M. Fisher, C.A. Goresky, E.A. Shaffer, S.M. Strasberg (Eds.), *Gallstones*, Springer, U.S., New York, 1979, pp. 47–69.
- [21] L. Barbara, R.H. Dowling, A. Hofman, E. Roda, *Workshops in Bile Acids Research: Serum Bile Acids in Health and Disease and the Pathophysiology of the Enterohepatic Circulation*, MTP Press Ltd., Lancaster (England), 1983.
- [22] H.J. Dworken, *Gastroenterology: Pathophysiology and Clinical Applications*, Butterworths, Boston-London, 1982.
- [23] D.N. Rubingh, Mixed micelle solutions, in: K.L. Mittal (Ed.), *Solution Chemistry of Surfactants*, vol. 1, Springer, New York, 1979, pp. 337–354.
- [24] P.M. Holland, D.N. Rubingh, Nonideal multicomponent mixed micelle model, *J. Phys. Chem.* 87 (1983) 1984–1990.
- [25] Phenomena in Mixed Surfactant Systems, ACS Symposium Series 311, in: J.F. Scamehorn (Ed.), American Chemical Society, Washington D.C., 1986.
- [26] M. Miura, M. Kodama, The second CMC of the aqueous solution of sodium dodecyl sulfate. I. Conductivity, *Bull. Chem. Soc. Jpn.* 45 (1972) 428–431.
- [27] D. Stigter, On the interpretation of the conductivity of soap solutions, *Recl. Trav. Chim. Pays-Bas* 73 (1954) 611–625.
- [28] H.C. Evans, Alkyl sulphates. Part I. Critical micelle concentrations of the sodium salts, *J. Chem. Soc. O* (1956) 579–586.
- [29] P.C. Schulz, Steric fitting of the spherical micelle size, *Colloid Polym. Sci.* 269 (1991) 612–619.
- [30] P.C. Schulz, Steric fitting of the rodlike micelle size, *J. Colloid Interface Sci.* 152 (1992) 333–337.
- [31] N. Filipović-Vinceković, Ion decontamination with a mixture of cationic and anionic surfactants, *J. Radioanal. Nucl. Chem.* 99 (1986) 89–96.
- [32] *Handbook of Chemistry and Physics*, in: R.C. West (Ed.), 56th ed., CRS Press, Cleveland, 1975.
- [33] J. Mandel, *The Statistical Analysis of Experimental Data*, Wiley & Sons, New York, 1964.

- [34] M.A. Morini, R.M. Minardi, P.C. Schulz, J.E. Puig, M.E. Hernández-Vargas, Basicity of dodecyltrimethylammonium hydroxide, *Colloids Surf., A* 103 (1995) 37–40.
- [35] J. Lucassen, Hydrolysis and precipitates in carboxylate soap solutions, *J. Phys. Chem.* 70 (1966) 1824–1830.
- [36] G. Stainsby, A.E. Alexander, Studies of soap solutions. Part I. The fatty acid soaps and their hydrolysis in aqueous solutions, *Trans. Faraday Soc.* 45 (1949) 585–597.
- [37] M.J. McDowell, C.A. Kraus, Properties of electrolytic solutions. L. effect of substituent groups on the properties of long chain ions, *J. Am. Chem. Soc.* 73 (1951) 2173–2176.
- [38] P.C. Schulz, M.E. Hernández Vargas, J.E. Puig, Do micelles contribute to the total conductivity of ionic micellar systems? *Lat. Am. Appl. Res.* 25 (1995) 153–159.
- [39] M.A. Morini, P.C. Schulz, J.E. Puig, Counterion specificity of the micelle surface and its implications on micellar catalysis, *Colloid Polym. Sci.* 274 (1996) 662–668.
- [40] S. Ozeki, S. Ikeda, The difference in solubilization power between spherical and rodlike micelles of dodecyltrimethylammonium chloride in aqueous solutions, *J. Phys. Chem.* 89 (1985) 5088–5093.
- [41] Y.S. Lee, K.W. Woo, Micelle studies of dodecyltrimethylammonium bromide in water as probed by benzene. Effect in shapes and sizes of micelles, *Bull. Korean Chem. Soc.* 14 (1993) 599–602.
- [42] P. Mukerjee, J.R. Cardinal, Benzene derivatives and naphthalene solubilized in micelles. Polarity of microenvironments, location and distribution in micelles, and correlation with surface activity in hydrocarbon-water systems, *J. Phys. Chem.* 82 (1978) 1620–1627.
- [43] P. Mukerjee, Odd-even alternation in the chain length variation of micellar properties, *Colloid Polym. Sci.* 236 (1970) 76–79.
- [44] P. Mukerjee, Formation and some properties of micelles, *Ber. Bunsen-Ges.* 82 (1978) 931–937.
- [45] S.M. Meyerhoffer, L.B. Mc Gown, Critical micelle concentration behavior of sodium taurocholate in water, *Langmuir* 6 (1990) 187–191.
- [46] N. Funasaki, R. Ueshiba, S. Hada, S. Neya, Stepwise self-association of sodium taurocholate and taurodeoxycholate as revealed by chromatography, *J. Phys. Chem.* 98 (1994) 11541–11548.
- [47] K. Kano, S. Tatemoto, S. Hashimoto, Specific interactions between sodium deoxycholate and its water insoluble analogues, mechanisms for premicelles and micelle formation of sodium, deoxycholate, *J. Phys. Chem.* 95 (1991) 966–970.
- [48] K.R. Francisco, M.A. da Silva, E.A. Saadini, G. Karlsson, C.A. Dreiss, Effect of monomers and polymeric co-solutes on cetyltrimethylammonium bromide wormlike micelles: rheology, Cryo-TEM and small-angle neutron scattering, *J. Colloid Interface Sci.* 345 (2010) 351–359.
- [49] T. Shikata, S.I. Imai, Y. Morishima, Molecular motions in threadlike micelles, *Langmuir* 13 (1997) 5229–5234.
- [50] T. Shikata, H. Hirata, T. Kotaka, Micelle formation of detergent molecules in aqueous media: viscoelastic properties of aqueous cetyltrimethylammonium bromide solutions, *Langmuir* 3 (1987) 1081–1086.
- [51] J.H. Clint, *Surfactant Aggregation*, Springer, New York, 1992.
- [52] M. Swanson-Vethamuthu, M. Almgren, P. Hansson, J. Zhao, Surface tension studies of cetyltrimethylammonium bromide-bile salt association, *Langmuir* 12 (1996) 2186–2189.
- [53] P.C. Schulz, R.M. Minardi, B. Vuano, Dodecyltrimethylammonium bromide–disodium dodecanephosphonate mixed micelles, *Colloid Polym. Sci.* 277 (1999) 837–845.
- [54] A. Hildebrand, P. Garidel, R. Neubert, A. Blume, Thermodynamics of demicellization of mixed micelles composed of sodium oleate and bile salts, *Langmuir* 20 (2004) 320–328.
- [55] J.L. Rodríguez, R.M. Minardi, E.P. Schulz, O. Pieroni, P.C. Schulz, The composition of mixed micelles formed by dodecyl trimethyl ammonium bromide and benzethonium chloride in water, *J. Surfactants Deterg.* 15 (2012) 147–155.

Glossary

- α : Ionization degree of micelles
- α_i : Mole fraction of the component i in the overall surfactant mixture without considering the solvent
- β_M : Intramicellar interaction parameter in the RST
- β_{Mij} : Intramicellar interaction parameter for the inclusion of the i surfactant component in the pure j amphiphile micelle in the EOMMM
- C_{10E8} : Octaethyleneglicol monododecyl ether
- $C_{av} = (C_1 + C_2)/2$: Average concentration. corresponds to the point at which a given Δ_{dif} value is computed
- CMC: Critical micelle concentration
- DeTAB: Decyltrimethylammonium bromide
- $\Delta\kappa = \kappa - \kappa_{extrap}$: The difference between the measured specific conductivity and that extrapolated from the pre-CMC region at the same concentration
- ΔG_{mix}^{excess} : Excess free energy of mixed micellization
- EOMMM: Equation oriented mixed micellization model
- HDPC: Hexadecylpyridinium chloride
- HTAB: Hexadecyltrimethylammonium bromide
- $\Lambda_{dif} = \partial\kappa/\partial C$: the differential conductivity: derivative of the specific conductivity with respect to the concentration
- MEGA-10: Decanoyl-*N*-methyl glucamide
- n : Aggregation number
- NaC: Sodium cholate
- NaDHC: Sodium dehydrocholate
- NaDOC: Sodium deoxycholate
- NaTC: Sodium taurocholate
- NaTDOC: Sodium taurodeoxycholate
- RST: Regular solution theory for mixed micellization thermodynamics
- Rubingh's Model: Rst
- SDeS: Sodium decylsulphate
- W_{ij} : Margules parameter in the EOMMM
- x_i : Mole fraction of the component i in the mixed micelle