

Surface pK_a of Saturated Carboxylic Acids at the Air/Water Interface: A Quantum Chemical Approach

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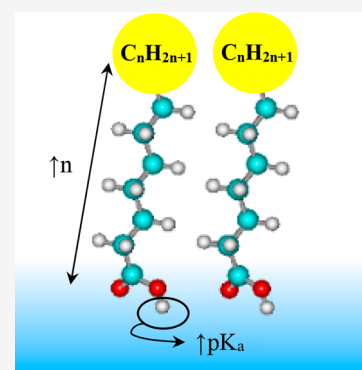
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ABSTRACT: In the present study a theoretical approach is proposed for the pK_a estimation of monolayers at the air/water interface on the basis of saturated carboxylic acids. This model involves calculating only the Gibbs energies of formation and dimerization of carboxylic acid associates in the neutral and dissociated forms, as well as the corresponding monomers in the water and gas phases. The model does not require the construction of any thermodynamic cycles. The calculations are performed using semiempirical quantum chemical methods PM3 and PM6 within the framework of the conductor-like screening model for monomers and dimers of carboxylic acids $C_nH_{2n+1}COOH$ ($n = 6–16$). It is shown that the minimum clusterization Gibbs energy corresponds to associates with the degree of dissociation $\alpha = 0.5$. A relationship is derived between the surface and bulk pK_a values. In particular, it follows from this that, unlike the bulk pK_a , the surface pK_a depends on the alkyl chain length of the surfactant. It is due to the difference between the solvation energies of the alkyl chains of the corresponding neutral and dissociated monomers. Thus, the calculated data show that the lengthening of the carboxylic acid chain by one CH_2 fragment leads to an increase in the surface pK_a by 0.43 units. The obtained results are in good agreement with the available experimental data.



INTRODUCTION

The ability of a substance to attach or give away a proton is crucial in biology, organic synthesis, pharmacy, toxicology, and other fields. The ionization degree of a substance determines largely its solubility in various media that is especially important when predicting its behavior at different interfaces. As of today, a large number of methods for the experimental determination of pK_a have been developed: potentiometry, spectroscopy, conductometry, solubility analysis, electrophoresis, NMR, polarography, chromatography, fluorometry, calorimetry, etc.¹ Since the capabilities of modern PCs have been developed, calculation methods for estimating pK_a have also been added to the experimental methods.^{2,3} The following calculation methods can be distinguished: the construction of thermodynamic cycles,^{4–9} isodesmic reactions,^{10,11} and the establishment of correlation relationships between structural parameters and physical properties of substances (quantitative structure–activity relationships descriptors).^{12–14} In addition, the method of valence bonds and bond lengths is used to determine the pK_a value; also, the correlation between the pK_a value and the energy of the highest occupied molecular orbital is established.¹⁵ An analysis of the accuracy of pK_a calculations using amino acids containing various functional groups capable of attaching or donating a proton was carried out using various quantum chemical methods: Hartree–Fock and perturbation theory, composite methods, and exchange–correlation functionals in density functional theory.¹⁶ Besides, the authors varied the basis sets, solvation models, and cavities used in the

solvent models. The smallest error in the description of pK_a is characteristic of the LC- ω PBE/6-31+G(d) method with PCM-SMD/UFF in the framework of the density functional theory. It amounted to 0.15 pK_a units. In general, at the moment, the accuracy of pK_a determination within one or even two units is considered quite acceptable.^{4,17–19}

Despite a very wide range of experimental and calculation determination methods, in most cases they are used to assess the pK_a of substances in the bulk phase. However, information on the surface layer of amphiphilic compounds is much less, and the available data are rather scattered and sometimes contradictory. For instance, the authors of refs 20–22 consider that the pK_a value of carboxylic acids in the surface layer is practically no different from that for the bulk phase. This contradicts other experimental data, the analysis of which allowed us to formulate the following regularity: with lengthening of the alkyl chain of the carboxylic acid their ability to remove the proton decreases, and, consequently, the pK_a value increases.^{23–32} The same regularity is characteristic of various micellar structures and surfactant bilayers.^{33,34}

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Another question arises on the absolute pK_a values in the monolayer and the contribution from the increment of one methylene fragment of the carboxylic acid chain. The analysis of the available data has shown that an increase in the carboxylic acid chain by one methylene fragment shifts the pK_a value from 0.1 to 0.7 units. In addition, the pK_a value is strongly influenced by the presence of additives of various ions in the aqueous phase, the type of buffer solution, and the pH value.^{24,35,36}

In this regard, the objective of this work is to reveal the dependence of the surface dissociation constant of saturated carboxylic acids $C_nH_{2n+1}COOH$ ($n = 6-16$) at the air/water interface on the chain length, using the quantum chemical approach developed and successfully tested by us previously when the film formation of 11 classes of nonionic surfactants was described.³⁷

METHODS

The calculation of monomers and associates of carboxylic acid is carried out in the Mopac2000 software package as a part of the quantum chemical semiempirical PM3 method. Our previous studies^{38,39} devoted to the calculation of the enthalpy, entropy, and Gibbs energy of carboxylic acid clusterization at the water surface show that the PM3 method adequately describes the dependence of these parameters on the surfactant alkyl chain length. In particular, it allows one to predict with a sufficient degree of accuracy the threshold length of the surfactant chain at which the formation of crystalline monolayers is possible, as well as to assess the geometric parameters of the unit cell of the obtained films. It gives us the opportunity to use this method in the present work.

To calculate the parameters of monomers and clusters of acids in water, we used the conductor-like screening model (COSMO), which is very popular and often used along with COSMO-RS in pK_a calculations.⁴⁰⁻⁴⁴ In the COSMO model each solvent is presented as a continuous medium with a dielectric constant ϵ , in which there is a cavity containing a dissolved substance. In most cases, a cavity is a collection of spheres centered on atoms with radii of $\sim 20\%$ larger than van der Waals values. The relative error of COSMO is $1/2\epsilon$, which makes this model more preferable for polar solvents, in particular for water ($\epsilon = 78.3$).

As a comparison with experimental data we also performed pK_a calculations in a later version of Mopac2016 using the PM6 method. This software package implements the use of the COSMO model for the direct calculation of the acid dissociation constant using the “ pK_a ” keyword.

THEORY

To assess the pK_a value of carboxylic acids in the monolayer, it is necessary to estimate the clusterization Gibbs energy of neutral as well as ionized molecules. Previously in literature^{45,46} as well as in our work,³⁸ it was shown that the values of the thermodynamic parameters of surfactant formation and clusterization are pairwise additive. This makes it possible to estimate the clusterization Gibbs energy of large and infinite associates using the dimerization Gibbs energy of carboxylic acids in two directions of the film propagation. Clusterization ΔG of an associate with a varying degree of dissociation α can be represented as the sum of the corresponding parameters for a neutral (nonionized) dimer and dimers, where one or both monomers are present in ionized form (see Figure 1). Note

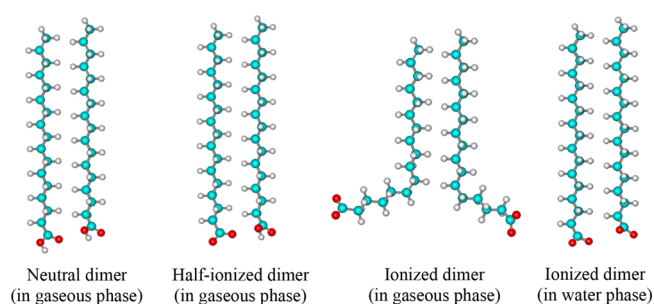


Figure 1. Optimized geometric structures of carboxylic acid dimers.

that the geometrical structures of these dimers are optimized in the gas phase because the clusterization thermodynamic parameters of carboxylic acid calculated exactly in the gas phase are involved in further calculations of pK_a . When optimizing the last of the dimers with both monomers in the form of anions, the obtained structure in the gas phase differs significantly from those for the other two types of dimers in Figure 1 due to the strong mutual repulsion of two negatively charged COO^- groups. When the geometric structure of such a dimer is optimized in the COSMO approximation, it looks like two other dimers in a nonionized and half-ionized form; i.e., strong repulsion of COO^- groups is not observed. However, according to the dimerization Gibbs energy such a dimer is the least energetically favorable among the others.

In the case when $\alpha < 0.5$, neutral dimers and dimers with one anion prevail in the cluster or film, but if $\alpha > 0.5$, then the content of dimers with fully and half-dissociated monomers predominates. Figure 2 shows the dependence of the

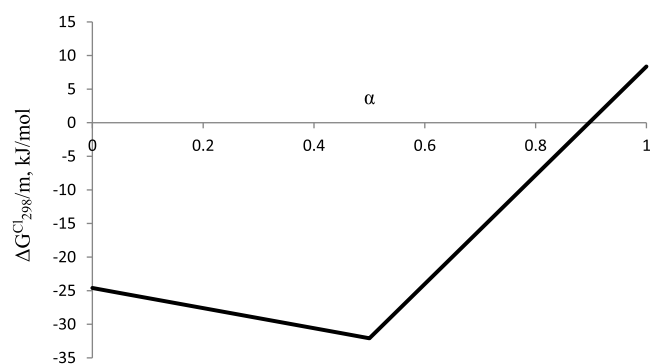


Figure 2. Dependence of the clusterization Gibbs energy of association on the dissociation degree of carboxylic acids (an example of heptadecanoic acid in the gas phase).

clusterization Gibbs energy per one monomer of the associate consisting of dimers with monomers in neutral form, with one anion and two anions, using heptadecanoic acid as an example. This dependence is obtained on the basis of the dimerization Gibbs energies per monomer for different types of dimers taken in a weighted average ratio depending on the value of the dissociation degree. It can be seen that the graph has a minimum corresponding to the dissociation degree $\alpha = 0.5$. Note that the obtained graph illustrates the $\Delta G_{298}^{Cl}/m$ dependence obtained on the basis of the direct calculation of carboxylic acid dimers in the gas phase. However, we obtained a similar dependence based on calculations done with taking into account the aqueous phase in COSMO. In this case, the only difference is that this dependence is shifted downward of the ordinate axis by about 30 kJ/mol.

Different pH values stipulate different values of α and *vice versa*. Since the process of dissociation is spontaneous, by the ΔG criterion it will occur in the direction of achieving such a structure that corresponds to a minimum (i.e., $\alpha = 0.5$). The advantage of structures with a ratio neutral molecule:anion = 1:1 is confirmed by available experimental data concerning the surface properties of soap foams with different chain lengths from 10 to 16 carbon atoms.²⁶ The maximum height of the foam, the half-life, the overall stability of the foam, and the stability of a single foam bubble, for example, for $C_{11}H_{23}COO^-Na^+$, are in the pH range equal to surface $pK_a = 7.5$. The minimum area per one molecule and the contact angle also correspond to a pH range equal to the surface pK_a . This allows us to estimate the surface pK_a value from the thermodynamic point of view through the dimerization Gibbs energy of dimers with $\alpha = 0.5$. This is also consistent with the idea of the authors of ref 47, where they say that systems with an ionized and nonionized form of acids in a 1:1 ratio allow simulating the pH value. It should be kept in mind that the surface pK_a calculated according to this approach will characterize a single act of proton detachment from the acid. Since the monolayer contains m surfactant molecules, all thermodynamic quantities involved in the calculation of pK_a should be reduced to one monomer in the cluster.

Figure 3 shows a simplified scheme for the dissociation of a carboxylic acid associate. In an associate consisting of m

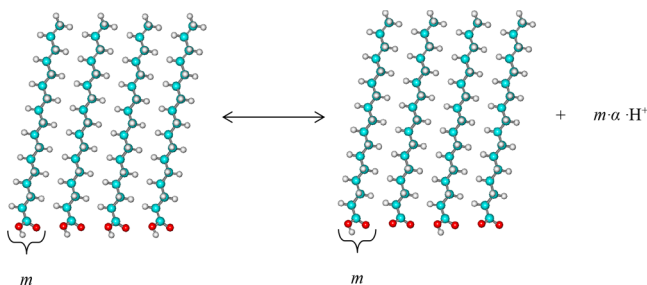


Figure 3. Scheme for dissociation of a carboxylic acid cluster.

neutral molecules of carboxylic acids, half of the molecules dissociate in such a way that the dissociated and neutral molecules are in staggered order. This is consistent with the above-described greater preference for such interactions. In this case, $m \cdot \alpha$ hydrogen ions pass into the aqueous phase. Figure 3 presents the case corresponding to the degree of dissociation $\alpha = 0.5$, when the resulting carboxylic acid associate contains an equal number of dissociated and nondissociated molecules, although the general case allows any value of α .

The equilibrium constant for this process can be written as follows:

$$K^{\text{surf}} = \frac{[\text{an}][\text{H}^+]^{m \cdot \alpha}}{[\text{neu}]} \quad (1)$$

where $[\text{neu}]$, $[\text{an}]$, and $[\text{H}^+]$ are the concentrations of neutral and dissociated clusters, as well as released protons; m is the number of monomers in the cluster; and α is the degree of dissociation.

At the same time the equilibrium constant of the reaction can be calculated by determining the change in the Gibbs energy of the process:

$$\ln K^{\text{surf}} = -\frac{\Delta G}{RT} = -\frac{\Delta G_{\text{an}} - \Delta G_{\text{neu}} + m \cdot \alpha \cdot \Delta G_{\text{H}^+}}{RT} \quad (2)$$

or

$$-RT \ln K^{\text{surf}} = \Delta G_{\text{an}} - \Delta G_{\text{neu}} + m \cdot \alpha \cdot \Delta G_{\text{H}^+} \quad (3)$$

Here ΔG_{neu} , ΔG_{an} , and ΔG_{H^+} are the formation Gibbs energies of a neutral associate and associate with dissociated monomers with respect to the given α , the Gibbs energy of a solvated proton.

For the clusterization Gibbs energy of associates in a neutral and dissociated form we can write

$$\Delta G_{\text{neu}}^{\text{Cl}} = \Delta G_{\text{neu}} - m \cdot \Delta G_{\text{neu}}^{\text{air}} \text{ and } \Delta G_{\text{an}}^{\text{Cl}} = \Delta G_{\text{an}} - m \cdot \alpha \cdot \Delta G_{\text{an}}^{\text{air}} - m(1 - \alpha) \cdot \Delta G_{\text{neu}}^{\text{air}} \quad (4)$$

where $\Delta G_{\text{neu}}^{\text{air}}$ and $\Delta G_{\text{an}}^{\text{air}}$ are the formation Gibbs energies of neutral and dissociated monomers of carboxylic acids calculated in the gas phase.

Then, expressing ΔG_{neu} and ΔG_{an} from eq 4 and substituting them in eq 3, we obtain

$$\begin{aligned} -RT \ln K^{\text{surf}} &= \Delta G_{\text{an}}^{\text{Cl}} - \Delta G_{\text{neu}}^{\text{Cl}} + m \cdot \alpha (\Delta G_{\text{an}}^{\text{air}} - \Delta G_{\text{neu}}^{\text{air}} + \Delta G_{\text{H}^+}) \end{aligned} \quad (5)$$

We rewrite this expression per one act of proton separation, i.e., divide eq 5 by $m \cdot \alpha$:

$$\begin{aligned} -RT \ln K_a^{\text{surf}} &= \frac{\Delta G_{\text{an}}^{\text{Cl}}}{m \cdot \alpha} - \frac{\Delta G_{\text{neu}}^{\text{Cl}}}{m \cdot \alpha} + \Delta G_{\text{an}}^{\text{air}} - \Delta G_{\text{neu}}^{\text{air}} + \Delta G_{\text{H}^+} \end{aligned} \quad (6)$$

The values of the dissociation constants in eqs 1–5 and 6 are interconnected as follows:

$$K_a^{\text{surf}} = m \cdot \alpha \sqrt{K^{\text{surf}}} \quad (7)$$

For the dissociation of the monomer molecules in the bulk phase, we can write

$$-RT \ln K_a^{\text{bulk}} = \Delta G_{\text{an}}^{\text{water}} - \Delta G_{\text{neu}}^{\text{water}} + \Delta G_{\text{H}^+} \quad (8)$$

where $\Delta G_{\text{neu}}^{\text{water}}$ and $\Delta G_{\text{an}}^{\text{water}}$ are the formation Gibbs energies of the neutral and dissociated monomers of carboxylic acids calculated in the aqueous phase.

Then, expressing ΔG_{H^+} from eq 8 and substituting it into eq 6, we obtain after some transformations

$$-RT \ln \frac{K_a^{\text{surf}}}{K_a^{\text{bulk}}} = \frac{\Delta G_{\text{an}}^{\text{Cl}}}{m \cdot \alpha} - \frac{\Delta G_{\text{neu}}^{\text{Cl}}}{m \cdot \alpha} - \Delta G_{\text{an}}^{\text{solv}} + \Delta G_{\text{neu}}^{\text{solv}} \quad (9)$$

where $\Delta G_{\text{neu}}^{\text{solv}}$ and $\Delta G_{\text{an}}^{\text{solv}}$ are the solvation Gibbs energies of the neutral and ionized monomers calculated in the aqueous phase.

The values $\Delta G_{\text{neu}}^{\text{Cl}}/m$ and $\Delta G_{\text{an}}^{\text{Cl}}/m$ are the clusterization Gibbs energies of the neutral and ionized monolayer per one monomer. It is easy to express the value pK_a^{surf} from eq 9:

$$\begin{aligned} pK_a^{\text{surf}} &= pK_a^{\text{bulk}} \\ &+ 0.434 \frac{\left(\frac{\Delta G_{\text{an}}^{\text{Cl}}}{m} - \frac{\Delta G_{\text{neu}}^{\text{Cl}}}{m} \right) / \alpha - \Delta G_{\text{an}}^{\text{solv}} + \Delta G_{\text{neu}}^{\text{solv}}}{RT} \end{aligned} \quad (10)$$

This approach allows one to avoid a direct estimation of the formation Gibbs energy of the solvated proton, which depends on the chosen experimental or theoretical estimation technique. The use of the values available in the literature is quite controversial since this value varies from -253 to -271 kcal/mol,^{8,18,48–50} which is $-(1059–1134)$ kJ/mol.

RESULTS AND DISCUSSION

Monomers. In this paper we consider a series of monomers with a chain length from 2 to 17 carbon atoms. According to the conclusions of experimental studies⁵¹ and the data of our previous works,^{38,39} the surfactant monomers in the crystalline monolayer are in the most elongated “linear” conformation. As found in refs 38 and 39, devoted to the study of the thermodynamics of the film formation of carboxylic acids, the most energetically favorable conformation of carboxylic acids is a structure with the following torsion angles in the functional group: $\angle C_2-C_1-O_1-H = 180^\circ$ and $\angle C_3-C_2-C_1-O_2 = -78^\circ$ (see Figure 4).

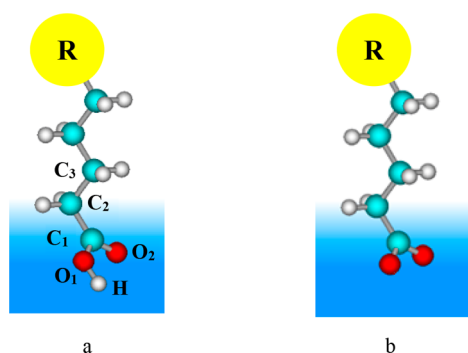


Figure 4. Optimized geometric structures of carboxylic acid monomers: (a) neutral form and (b) ionized form (R is a hydrocarbon radical).

The calculated values of enthalpy, absolute entropy, and Gibbs energy of formation for carboxylic acid monomers in neutral and ionized form calculated in the gas and water phases are given in Table 1. The correlation dependences of the thermodynamic parameters of monomer formation on the acid chain length are constructed using the calculated values. For gas-phase calculations the values of correlation coefficients in equations of the form $y = (a \pm \Delta a) \cdot n + (b \pm \Delta b)$, where n is the number of carbon atoms in the alkyl chain for the neutral form of carboxylic acids and anions, respectively, are the following: for enthalpy $a = -22.67$ and -23.18 , $b = -376.84$ and -452.11 kJ/mol; for absolute entropy $a = 32.03$ and 32.38 , $b = 229.99$ and 223.98 J/(mol·K); for Gibbs energy $a = 8.39$ and 7.78 , $b = -384.27$ and -477.20 kJ/mol. For solvent-based calculations the correlation coefficients for the neutral form of carboxylic acids and anions, respectively, are the following: for enthalpy $a = -18.63$ and -20.18 , $b = -419.83$ and -480.78 kJ/mol; for absolute entropy: $a = 30.40$ and 30.14 , $b = 227.69$ and 228.48 J/(mol·K); for Gibbs energy $a = 12.92$ and 11.44 , $b = -426.58$ and -507.21 kJ/mol. The corresponding correlation coefficients are in the range of 0.96–0.99.

The calculated pK_a values of acids estimated by the Stewart methodology⁵² in the Mopac2016 software package using the PM6 method⁵³ are given in Table 2. Note that the described pK_a values refer to the bulk, and at the moment there is no such software package that allows the calculation of the

surface pK_a values of a surfactant monolayer at the interface. As seen from eq 8 there is a linear relation between the bulk pK_a and the difference in the Gibbs energies of the formation of the neutral and ionized monomer in water $\Delta G_{an}^{water} - \Delta G_{neu}^{water}$. There are numerous studies which do linear fitting of deprotonation Gibbs energy to the pK_a value obtained both theoretically and experimentally.^{8,49} Here, we can propose a similar linear expression using the calculated data for the considered compounds in the PM3 method, given in Table 1. This dependence is obtained on the basis of the agreement with the available experimental data (for acids from acetic to nonanoic) and has the following form:

$$pK_a^{bulk} = 0.434 \frac{\Delta G_{an}^{water} - \Delta G_{neu}^{water}}{RT} + 4.15 \quad (11)$$

The values of bulk pK_a calculated from it are also given in Table 2. It is seen that the calculated data for bulk pK_a obtained as a result of direct calculation in PM6 and eq 11 are in good agreement with the experimental values available for short-chained representatives of the homologous series of carboxylic acids.

Dimers. The thermodynamic parameters of formation and dimerization in gaseous and water phases are calculated for neutral and half-dissociated dimers as shown in Figure 1. Note that in the dimers shown in Figure 1 the relative position of the hydrophilic parts of the molecules corresponds to the “diagonal” one. In our previous works it has been shown that it is possible to form films of carboxylic acids with an oblique unit cell, where the dipole moments of the hydrophilic parts of the surfactant are located “diagonally” (see Figure 5).⁵⁷ The arrows show the direction of the vector conventionally drawn from the carbonyl oxygen to hydroxyl hydrogen in the COOH group of the carboxylic acid molecule.

For the case when calculations take into account the solvent in COSMO (see Table 3), there are data for a number of acids with an alkyl chain length from 7 to 12 carbon atoms. Based on the obtained data, the correlation dependences of the thermodynamic parameters of dimerization on the number of intermolecular CH \cdots HC interactions are constructed. The values of the contributions of the CH \cdots HC interactions and the interactions of the functional groups in the dimerization Gibbs energy are summarized in Table 4. As can be seen, the contributions of the intermolecular CH \cdots HC interactions to the dimerization Gibbs energy differ by almost 5 times for systems in vacuum and water, and the contributions of the interaction of functional groups by 2–4 times, respectively. Figure 6 shows the graphical dependences ΔG_{298}^{dim} for associates calculated in both phases. The solid lines correspond to the values obtained from the correlation dependences, and the points correspond to the results of the direct calculation with the PM3 method. Despite the fact that the calculation results taking into account the solvent in the COSMO model have a larger standard deviation, it can be seen that the dimerization of carboxylic acids in the aqueous phase begins for compounds with a shorter chain length than in the gaseous phase. It should be noted that the obtained calculation results are consistent with the available experimental data obtained for oleic acid. It was shown in ref 58 that the minimum surface tension was recorded for monolayers at pH = 9–10 corresponding to the surface pK_a of this acid. This minimum value of the surface tension is caused by the most favorable interaction between the neutral molecule and the ionized acid molecule, which leads to the formation of the corresponding complex at the interface

Table 1. Formation Thermodynamic Parameters of Carboxylic Acids at 298 K

system	calculation in gaseous phase			calculation in water (COSMO)		
	$\Delta H_{298,mon}^0$ kJ/mol	$S_{298,mon}^0$ J/(mol·K)	$\Delta G_{298,mon}^0$ kJ/mol	$\Delta H_{298,mon}^0$ kJ/mol	$S_{298,mon}^0$ J/(mol·K)	$\Delta G_{298,mon}^0$ kJ/mol
Neutral Molecule						
C ₂ H ₄ O ₂	-426.77	294.85	-372.32	-479.67	296.13	-425.61
C ₃ H ₆ O ₂	-445.09	327.42	-359.74	-494.20	323.46	-407.67
C ₄ H ₈ O ₃	-467.68	361.87	-351.99	-515.83	355.85	-398.35
C ₅ H ₁₀ O ₂	-490.21	391.92	-342.87	-484.80	387.85	-336.25
C ₆ H ₁₂ O ₂	-512.85	424.55	-334.63	-506.86	409.61	-324.19
C ₇ H ₁₄ O ₂	-535.49	456.25	-326.11	-529.90	445.11	-317.20
C ₈ H ₁₆ O ₂	-558.15	487.94	-317.61	-552.28	462.25	-304.08
C ₉ H ₁₈ O ₂	-580.81	520.01	-309.23	-574.34	507.90	-299.14
C ₁₀ H ₂₀ O ₂	-603.49	551.14	-300.57	-593.85	518.97	-281.35
C ₁₁ H ₂₂ O ₂	-626.16	583.94	-292.41	-619.14	561.03	-278.56
C ₁₂ H ₂₄ O ₂	-648.73	613.51	-283.18	-638.81	571.53	-260.76
C ₁₃ H ₂₆ O ₂	-671.50	647.16	-275.38	-663.91	617.90	-259.07
C ₁₄ H ₂₈ O ₂	-694.19	676.88	-266.32	-683.38	634.87	-242.99
C ₁₅ H ₃₀ O ₂	-716.83	710.16	-258.28	-706.41	680.08	-238.89
C ₁₆ H ₃₂ O ₂	-739.49	740.25	-249.30	-733.94	732.22	-241.36
C ₁₇ H ₃₄ O ₂	-762.24	772.44	-241.03	-753.81	765.90	-230.65
Anion						
C ₂ H ₄ O ₂	-500.61	298.96	-466.84	-521.12	288.74	-484.30
C ₃ H ₆ O ₂	-522.54	320.61	-454.61	-557.53	310.64	-486.63
C ₄ H ₈ O ₃	-546.88	354.68	-448.50	-563.20	338.03	-459.86
C ₅ H ₁₀ O ₂	-570.28	386.76	-440.85	-579.90	380.51	-448.61
C ₆ H ₁₂ O ₂	-593.52	419.80	-433.34	-600.07	398.48	-433.53
C ₇ H ₁₄ O ₂	-616.49	452.23	-425.36	-617.24	448.83	-425.10
C ₈ H ₁₆ O ₂	-639.39	483.09	-416.85	-636.76	477.03	-412.41
C ₉ H ₁₈ O ₂	-662.20	510.62	-407.26	-656.88	511.06	-402.07
C ₁₀ H ₂₀ O ₂	-684.99	550.33	-401.28	-676.85	545.16	-391.60
C ₁₁ H ₂₂ O ₂	-707.74	581.41	-392.68	-699.22	562.63	-378.57
C ₁₂ H ₂₄ O ₂	-730.47	608.60	-382.91	-720.11	582.62	-364.81
C ₁₃ H ₂₆ O ₂	-753.19	646.07	-376.19	-742.55	622.55	-358.55
C ₁₄ H ₂₈ O ₂	-775.91	675.69	-367.13	-763.97	661.74	-351.04
C ₁₅ H ₃₀ O ₂	-798.61	708.13	-358.90	-786.42	677.51	-337.58
C ₁₆ H ₃₂ O ₂	-821.32	747.61	-352.76	-808.57	697.05	-324.95
C ₁₇ H ₃₄ O ₂	-844.01	771.76	-342.05	-829.67	733.75	-316.38

with higher surface activity than the simple associate of neutral acid molecules.^{27,59}

The dimerization Gibbs energy obtained from the correlation dependences is used to calculate the pK_a of acid dimers at the interface using eq 10. For this, instead of $\Delta G_{neu}^{Cl}/m$ and $\Delta G_{an}^{Cl}/m$ we used ΔG_{298}^{dim} as given in Table 4 for a neutral and half-dissociated dimer. In this case the corresponding values of the dimerization Gibbs energies are divided by 2 to obtain specific values per one monomer. As pK_a^{bulk} we used the values for monomers calculated in the PM6 method since the experimental values of bulk pK_a for carboxylic acids are available for homologues no longer than nonanoic carboxylic acid. It is also possible to use the bulk pK_a values estimated according eq 11. However, since the difference between the corresponding values of these pK_a varies within the range of 0.02–0.09 units, for calculation of the surface pK_a of dimers it is quite enough to limit ourselves to pK_a^{bulk} estimated only by one of the methods (in this case, the PM6 method). The calculated results for the dimers are as follows: for C₇H₁₄O₂ the pK_a value is 4.67, for C₈H₁₆O₂–5.10, C₉H₁₈O₂–5.47, C₁₀H₂₀O₂–5.90, C₁₁H₂₂O₂–6.29, C₁₂H₂₄O₂–6.70, C₁₃H₂₆O₂–7.08, C₁₄H₂₈O₂–7.52, C₁₅H₃₀O₂–7.89, C₁₆H₃₂O₂–8.33, C₁₇H₃₄O₂–8.70, C₁₈H₃₆O₂–9.12, C₁₉H₃₈O₂–9.54, C₂₀H₄₀O₂–9.96, and C₂₁H₄₂O₂–10.38. It should be noted

that the direct calculation of pK_a for dimers using the corresponding keyword in the Mopac2016 software package in the framework of the PM6 method did not give any satisfactory results. The obtained pK_a value does not depend on the alkyl chain length of the monomers comprising the dimer and is 4.38–4.43. This indicates the inadequacy of the calculation formulas introduced in this method for determining of pK_a for surfactant associates and speaks in favor of our proposed scheme in the framework of the PM3 method.

In addition, the dependence for dimers is obtained similar to eq 11 for monomers, which relates the bulk pK_a to the difference in formation Gibbs energies of a neutral and half-ionized dimer in water. The only difference for the case of dimers is that the value of the free term is 4.18 pK_a units, and the value $\Delta G_{an}^{water} - \Delta G_{neu}^{water}$ for dimers does not depend on the alkyl chain length. Its average value is -110.21 kJ/mol. In this case, the calculated data are used for dimers with an alkyl chain length from 7 to 12 carbon atoms, and the experimental data are used for acids with an alkyl chain length from 7 to 9 carbon atoms. Involvement of the monomers with a shorter alkyl chain length in the calculation of the corresponding dimers leads to the fact that a sufficient number of intermolecular CH \cdots HC interactions that have a decisive role in the further formation of monolayers will not be realized in the optimized structures of

Table 2. Bulk and Surface pK_a Values for the Homologues Series of Carboxylic Acids

acid	bulk pK_a (monomers)			surface pK_a (monolayer)		
	calcd in PM6	calcd in PM3 using eq 11	exptl	calcd values using eq 10		exptl
				without correction	with correction	
C ₂ H ₄ O ₂	4.97	4.75	4.76 ⁵⁴	—	—	—
C ₃ H ₆ O ₂	4.73	4.81	4.87 ⁵⁴	—	—	—
C ₄ H ₈ O ₃	4.84	4.76	4.81 ⁵⁴	—	—	—
C ₅ H ₁₀ O ₂	4.77	4.87	4.81 ⁵⁴	—	—	—
C ₆ H ₁₂ O ₂	4.84	4.87	4.85 ⁵⁴	—	—	—
C ₇ H ₁₄ O ₂	4.84	4.87	4.85 ⁵⁴	7.99	5.28	—
C ₈ H ₁₆ O ₂	4.84	4.87	4.85 ⁵⁵	8.42	5.71	—
C ₉ H ₁₈ O ₂	4.84	4.86	4.97 ⁵⁶	8.86	6.15	5.8 ^{a,25}
C ₁₀ H ₂₀ O ₂	4.83	4.87	—	9.29	6.58	6.1, ³² 6.4, ²⁵ 6.8, ³¹ 7.1–7.3 ²⁶
C ₁₁ H ₂₂ O ₂	4.85	4.85	—	9.74	7.03	—
C ₁₂ H ₂₄ O ₂	4.82	4.86	—	10.15	7.44	5.3, ⁶⁰ 6.6, ³³ 7.0, ⁶¹ 7.07, ³⁰ 7.5, ²⁶ 8.0 ³¹
C ₁₃ H ₂₆ O ₂	4.83	4.85	—	10.59	7.88	—
C ₁₄ H ₂₈ O ₂	4.83	4.87	—	11.03	8.32	6.3, ⁶⁰ 7.88, ³⁰ 7.9, ⁶² 8.1–8.2 ²⁶
C ₁₅ H ₃₀ O ₂	4.83	4.85	—	11.46	8.75	—
C ₁₆ H ₃₂ O ₂	4.84	4.82	—	11.90	9.19	8.34, ³⁰ 8.5, ⁶³ 8.6–8.8, ²⁶ 9.7 ⁶²
C ₁₇ H ₃₄ O ₂	4.83	4.82	—	12.33	9.62	—
C ₁₈ H ₃₆ O ₂	4.84	4.75	—	12.76	10.05	8.0, ²⁸ 8.2–8.9, ³⁵ 9.5, ²⁹ 9.89, ³⁰ 10.2 ²⁶
C ₁₉ H ₃₈ O ₂	4.84	4.81	—	13.19	10.49	—
C ₂₀ H ₄₀ O ₂	4.84	4.76	—	13.63	10.92	9.82, ³⁰ 11.0 ²³
C ₂₁ H ₄₂ O ₂	4.83	4.87	—	14.06	11.35	—

^aBold experimental data for pK_a of monolayers used to determine the standard deviation of calculation results from experimental values.

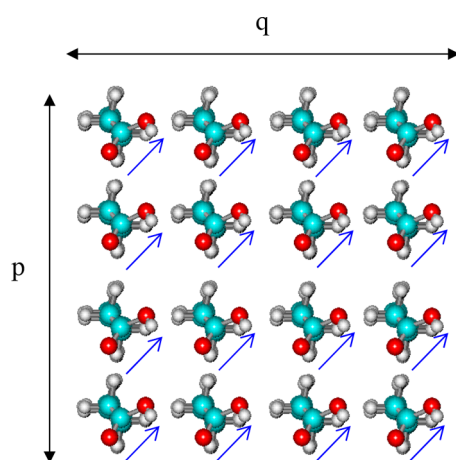


Figure 5. Fragment of a 2D film of carboxylic acids with “diagonal” dipole moments of the hydrophilic parts of the monomers (bottom view).

the dimers. The structure of such short-chained dimers in water will have a completely different type, not related to interactions realized in a monolayer. The pK_a values obtained in this way for dimers with CH \cdots HC interactions occurring during the formation of monolayers (provided that one proton is detached) are C₇H₁₄O₂–4.91, C₈H₁₆O₂–4.89, C₉H₁₈O₂–4.87, C₁₀H₂₀O₂–4.92, C₁₁H₂₂O₂–4.88, and C₁₂H₂₄O₂–4.91. This differs slightly from the values estimated in the PM6 method but also does not correspond to the experimentally recorded dependence of the pK_a value of the acids on the alkyl chain length during their association. All of the above mentioned speaks in favor of the approach using eq 10 proposed by us.

2D Films. To assess the clusterization thermodynamic parameters per monomer of a 2D film, we used the “simple method” that was developed by us earlier.⁵⁷ This method

allows calculating the values of $\Delta H_{298}^{Cl}/m$, $\Delta S_{298}^{Cl}/m$, and $\Delta G_{298}^{Cl}/m$ for monolayers using the corresponding parameters only for dimers with a certain arrangement of the dipole moments of the monomer head groups in them. As shown by calculations for alcohols, thioalcohols, amines, nitriles, α -hydroxylic acids, and dialkyl-substituted melamine, the contribution of interactions of “parallel” hydrophilic parts of molecules in a dimer is smaller to the clusterization Gibbs energy than for “sequentially” arranged head groups. For carboxylic acids in the resulting films with an oblique unit cell, the dipole moments of the hydrophilic parts of the monomers are located “diagonally”. This allows the estimation of the values of the clusterization thermodynamic parameters of such films using only the values of the contributions of functional group interactions for dimers, and not to calculate large clusters for the construction of an additive scheme. For this purpose the values used in the equations for calculation of the dimerization thermodynamic parameters should be doubled. Note that the nature of the intermolecular CH \cdots HC interactions realized between hydrophobic chains is the same for all 11 surfactant classes examined earlier.⁶⁴ Therefore, here we will use the values of these contributions to the clusterization Gibbs energy estimated in ref 61. Then the obtained dependences for the clusterization Gibbs energy per one molecule of the film have the following form:

$$\text{for neutral monolayer } \Delta G_{\text{neu}}^{Cl}/m = -7.44 \cdot \left\{ \frac{n}{2} \right\} + 46.55 \quad (12)$$

and

for the monolayer with dissociation degree $\alpha = 0.5$

$$\Delta G_{\text{an}}^{Cl}/m = -7.44 \cdot \left\{ \frac{n}{2} \right\} + 31.10 \quad (13)$$

Table 3. Dimerization Thermodynamic Parameters of Carboxylic Acids at 298 K

system	calculation in gaseous phase			calculation in water (COSMO)		
	$\Delta H_{298}^{\text{dim}}$, kJ/mol	$\Delta S_{298}^{\text{dim}}$, J/(mol·K)	$\Delta G_{298}^{\text{dim}}$, kJ/mol	$\Delta H_{298}^{\text{dim}}$, kJ/mol	$\Delta S_{298}^{\text{dim}}$, J/(mol·K)	$\Delta G_{298}^{\text{dim}}$, kJ/mol
Neutral Dimer						
C ₇ H ₁₄ O ₂	-30.19	-161.62	17.97	-30.93	-185.58	24.38
C ₈ H ₁₆ O ₂	-32.89	-183.43	21.78	-32.68	-180.08	20.99
C ₉ H ₁₈ O ₂	-40.38	-188.56	15.81	-45.99	-152.88	-0.44
C ₁₀ H ₂₀ O ₂	-42.94	-200.36	16.76	-48.71	-173.00	2.85
C ₁₁ H ₂₂ O ₂	-50.68	-215.86	13.65	-56.22	-172.69	-4.75
C ₁₂ H ₂₄ O ₂	-53.46	-224.26	13.37	-57.44	-174.71	-5.37
C ₁₃ H ₂₆ O ₂	-61.04	-242.08	11.10	-	-	-
C ₁₄ H ₂₈ O ₂	-63.53	-249.93	10.95	-	-	-
C ₁₅ H ₃₀ O ₂	-71.43	-267.15	8.18	-	-	-
C ₁₆ H ₃₂ O ₂	-73.99	-273.99	7.66	-	-	-
C ₁₇ H ₃₄ O ₂	-81.80	-289.45	4.46	-	-	-
Half-Dissociated Dimer						
C ₇ H ₁₄ O ₂	-46.12	-180.63	7.70	-39.79	-185.88	15.60
C ₈ H ₁₆ O ₂	-49.10	-194.67	8.91	-40.06	-215.26	24.09
C ₉ H ₁₈ O ₂	-56.48	-201.43	3.54	-52.97	-205.44	8.25
C ₁₀ H ₂₀ O ₂	-59.12	-215.80	5.19	-63.36	-180.01	-9.72
C ₁₁ H ₂₂ O ₂	-66.87	-235.52	3.31	-74.15	-223.11	-7.66
C ₁₂ H ₂₄ O ₂	-69.60	-235.68	0.64	-73.16	-175.94	-20.73
C ₁₃ H ₂₆ O ₂	-77.36	-261.22	0.48	-	-	-
C ₁₄ H ₂₈ O ₂	-79.89	-265.57	-0.75	-	-	-
C ₁₅ H ₃₀ O ₂	-87.65	-285.36	-2.62	-	-	-
C ₁₆ H ₃₂ O ₂	-90.27	-299.89	-0.90	-	-	-
C ₁₇ H ₃₄ O ₂	-98.21	-307.85	-6.47	-	-	-

Table 4. Parameters of Partial Correlations for Carboxylic Acid Dimers: $y = (a \pm \Delta a) \cdot K_a + (b \pm \Delta b)^a$

system	$(a \pm \Delta a)$	$(b \pm \Delta b)$	reg. coefficient	stand. deviation
$\Delta G_{298}^{\text{dim}}$, kJ/mol				
neutral dimer	-2.97 ± 0.18	28.52 ± 1.02	0.983	0.98
half-dissociated dimer	-2.62 ± 0.22	15.55 ± 1.29	0.967	1.22
neutral dimer (COSMO)	-13.87 ± 2.49	61.77 ± 9.60	0.974	4.70
half-dissociated dimer (COSMO)	-17.02 ± 3.48	71.99 ± 14.25	0.943	6.95

$^a K_a$ is the number of intermolecular CH \cdots HC interactions realized in the considered dimer; sampling amount $N = 11$ or 6 for COSMO.

where n is the number of methylene fragments in the chain of carboxylic acids and braces $\{\dots\}$ denote the integer part of the number.

Then, using eq 10 as in the case of dimers and substituting expressions 12 and 13 for $\Delta G^{\text{Cl}}/m$ into it, we can calculate the pK_a values for monolayers of carboxylic acids with different chain lengths. An analysis of the contributions of the clusterization and solvation Gibbs energies for the neutral and anionic forms of carboxylic acid molecules shows that an increase of the surfactant chain length does not affect the contribution from the difference in the clusterization Gibbs energies of neutral monolayer and monolayer with $\alpha = 0.5$. This contribution makes 15.45 kJ/mol. The solvation Gibbs energy of the neutral monomer is significantly less dependent on the alkyl chain length than that for the anion. The contributions of one methylene group to the solvation Gibbs energy for them are 0.23 and 2.70 kJ/mol, respectively. This

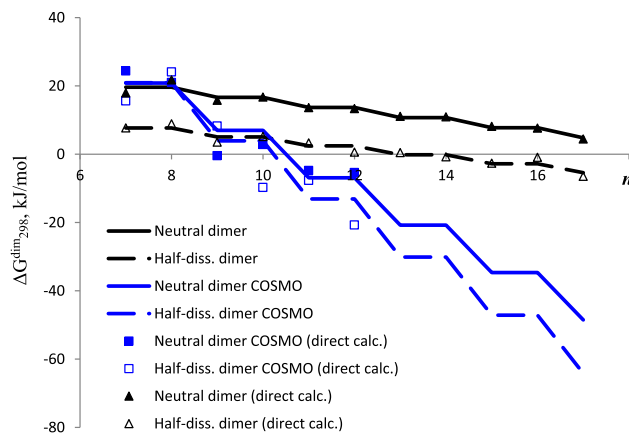


Figure 6. Dependence of the dimerization Gibbs energy on the chain length of the carboxylic acids.

leads to the fact that the surface pK_a of the monolayer, in contrast to that of the bulk, becomes dependent on the surfactant chain length. The contribution of one methylene fragment to the change in surface pK_a is 0.43 units.

The obtained surface pK_a values are given in Table 2. Comparing the data obtained for the pK_a of the monolayer and the pK_a of the dimers, it can be seen that the pK_a for the monolayer is 3.3–3.7 units higher on average than the corresponding values for the dimers. This is due to two factors. To a smaller extent, for calculation of the monolayer pK_a the values of contributions of CH \cdots HC interactions and interactions of the acid functional groups are used, which were earlier assessed in ref 64, and to a larger extent, a greater number of CH \cdots HC interactions is present for one monomer of the film than for a dimer when calculating $\Delta G^{\text{Cl}}/m$. It should be noted that this picture is consistent with the results

of coarse-grained modeling for polymethacrylic acid. The authors of ref 65 recorded that the difference in pK_a between the dimer and the 20-mer of methacrylic acid is 2.57. In the study of ref 24, the authors noted an increase in pK_a up to 3.5–3.8 units per monolayer for eicosanoic acid in comparison with the soluble short-chained homologues. Comparing the data given in Table 2, it can be noted that our results and the experimental results concerning carboxylic acids of various chain lengths are in fairly good agreement, especially for dimers. The best agreement between the calculated data is observed with the results of Kanicky²⁶ and McLean.³⁰ In his work, Kanicky²⁶ noted that in solutions of carboxylic acids with an alkyl chain length of 8–12 carbon atoms, changes in the pK_a value are observed due to the premicellar aggregation of these surfactants. If we take into account the fact that the formation of carboxylic acid monolayers proceeds through the predominant aggregation of dimers and trimers,³⁸ it is possible to assume that the experimentally recorded pK_a values of carboxylic acids are close to the calculated values just for these small clusters.

It should also be taken into account that the PM3 method has such parametrization that it overestimates the energy of intermolecular $CH\cdots HC$ interactions.⁶⁶ This leads to the fact that the clusterization Gibbs energy per one monomer of the carboxylic acid film is almost two times higher than the corresponding value estimated on the basis of experimental data using the theoretical equation of state valid for Langmuir monolayers derived by the rigorous thermodynamic treatment described in ref 67. As a result, the surface pK_a values estimated from eq 10 with the values $\Delta G_{neu}^{Cl}/m$ and $\Delta G_{an}^{Cl}/m$ calculated from eqs 12 and 13 have a standard deviation from experimental data of 2.82. In this case, the standard deviation that is estimated provided the best agreement between the available experimental data and the corresponding calculated values. In this regard it is reasonable to use halved values of $\Delta G_{neu}^{Cl}/m$ and $\Delta G_{an}^{Cl}/m$ in the calculation of eq 10. In Table 2 the column “without correction” contains the results of calculation of the surface pK_a using the values $\Delta G_{neu}^{Cl}/m$ and $\Delta G_{an}^{Cl}/m$ obtained according to expressions 12 and 13. The column “with correction” shows the surface pK_a values calculated under the condition that the values of $\Delta G_{neu}^{Cl}/m$ and $\Delta G_{an}^{Cl}/m$ from eqs 12 and 13 were halved. In the latter case the standard deviation of the calculated pK_a values is only 0.22 pK_a units. This suggests that the proposed approach for the assessment of surface pK_a is not inferior by the accuracy criterion to those available in the literature.

Note that as pK_a^{bulk} one can use both experimental and calculated data for the monomers given in Table 2 for the calculation of the surface pK_a . However, since a number of experimentally estimated bulk pK_a values are limited by nonanoic acid, we use the results of the direct calculation obtained in the PM6 method. As mentioned previously for the case of the surface pK_a for dimers, one can also use the calculated values of bulk pK_a obtained on the basis of eq 11. Moreover, the agreement between the calculated and the experimental data does not become worse.

Undoubtedly, during the experimental determination of pK_a the result is affected by many factors, in particular, concentration, type of buffer solution, and the presence of various concomitant ions in the water. In this regard, the scheme developed by us has predictive value and can be used as a less resource-intensive substitute for a labor-intensive experiment.

CONCLUSIONS

Within the framework of the semiempirical quantum chemical PM3 method, an approach is proposed that allows the estimation of the surface pK_a of amphiphilic compounds at the air/water interface. This approach is based on the pairwise additivity of intermolecular $CH\cdots HC$ interactions realized between surfactant molecules. This allows us to confine ourselves to the calculation of the formation Gibbs energies only of monomers and dimers of neutral and dissociated forms of carboxylic acids in the aqueous and gas phases. The calculation showed that

- (1) the formation of associates with neutral and dissociated acid molecules in a ratio of 1:1 is energetically the most preferable;
- (2) the surface pK_a value of carboxylic acids differs from that for the bulk phase and depends on the surfactant chain length, which is due to the difference in the contributions of methylene chain units and functional groups to the Gibbs energy of solvation of neutral and dissociated monomers;
- (3) lengthening of the carboxylic acid alkyl chain by one methylene fragment leads to a shift of pK_a by 0.43 unit in the region of large values.

The described approach establishes a linkage between bulk and surface pK_a values, which makes it universal and makes it possible to use both theoretical and experimental data. The proposed scheme has good predictive ability and provides an adequate theoretical justification for the available experimental data.

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Notes

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