PERGAMON

Chemical Engineering Science 54 (1999) 4757–4766

Chemical
Engineering Science

The effect of surface-active additives on bubble coalescence in aqueous media

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Abstract

An experimental study has been aimed at examining the coalescence phenomena in aqueous solutions of aliphatic alcohols and electrolytes and at determining the effect of these surface-active compounds on bubble coalescence in viscous aqueous media with Newtonian and non-Newtonian behaviour, represented by aqueous solutions of 50 and 60 wt%, saccharose, and 0.2 and 0.5 wt%, xanthan, respectively. Bubble coalescence in aqueous solutions of alcohols and electrolytes was significantly hindered by increasing solute concentration and the coalescence percentage ψ exhibited sharp transition from 100% of bubble pairs coalescing to very low values ($\psi \leqslant 10\%$) over a narrow concentration range. Transition concentrations of respective surface-active additives, characterising suppression of coalescence in their aqueous solutions, were successfully correlated as a function of the term $[\sigma^n(\partial\sigma/\partial c)^{-2}]$, with exponent values $n = \frac{1}{3}$ and $\frac{1}{4}$ (or $\frac{1}{6}$) for solutions of alcohols and electrolytes, respectively. The inhibitory effect of alcohols on bubble coalescence increased with the increasing length of the carbon chain and their transition concentrations were successfully correlated as a function of the number of carbon atoms in the alcohol molecule, $c_t = 31 n_C^{-7.2}$. The addition of aliphatic alcohols to fully coalescent viscous solutions of saccharose and xanthan modified significantly coalescence behaviour in these viscous media. Transition concentrations of individual alcohols in 50 wt% saccharose solution and 0.2 wt% xanthan solution were very close to those observed in aqueous alcohol solutions, further increase of medium viscosity resulted, however, in an increase of transition concentrations up to an order of magnitude. The character of their dependence on the number of carbon atoms in the alcohol molecule ($c_t \sim n_C^b$) remained, however, unchanged for all viscous media studied and values of exponent varied only slightly between -7.1 and -7.7. The effect of electrolytes on bubble coalescence in viscous media was less significant, as compared with the alcohol additives, and differed with the nature of medium.

Keywords: Bubble coalescence; Viscous aqueous media; Surface-active additives; Transition concentration

1. Introduction

Hydrodynamic parameters of gas–liquid beds, such as bubble size, gas hold-up and specific interfacial area, are significantly influenced by the liquid-phase ability to support or hinder bubble coalescence. No generally applicable equations describing the relations between the liquid-phase properties and the degree of coalescence (and/or values of respective hydrodynamic parameters) have been, however, available for an a priori prediction of bubble bed behaviour for a given gas–liquid system. The present state of knowledge clearly points to the necessity of diversified approach to different classes of liquid phases, such as pure compounds or their aqueous or non-aqueous solutions and similarly to low- and high-viscous liquids (Newtonian or non-Newtonian). Regarding the description of their behaviour, perhaps the most complex problems have been posed by the aqueous or non-aqueous solutions of surface-active compounds where, in this context, a surface-active compound may be any solute changing behaviour of the interface in comparison with the pure solvent. Obviously, the aliphatic alcohols and electrolytes (namely inorganic salts) represent very important groups of such surface-active solutes, considering their wide practical application. Numerous experimental studies have shown that behaviour of gas–liquid systems containing solutions of such additives cannot be simply described as a function of common physicochemical properties (density, viscosity, surface tension) measured in the bulk liquid phase as it is

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PII: S0009-2509(99)00192-X

determined by preferential adsorption of solutes at the interface (Kaštánek, Zahradník, Kratochvíl & Čermák, 1993). Our previous works (Zahradník, Peter & Kaštánek, 1987, Zahradník, Fialova, Kastanek, Green & Thomas, 1995) showed, in full agreement with data from the literature (Lessard & Zieminski, 1971; Drogaris, 1983), that the coalescence behaviour in such systems can be aptly characterized by the coalescence ratio (percentage) expressing the extent of coalescence in a given gas–liquid system and determined under model conditions simulating contact of two isolated bubbles in a pseudo-infinite medium. Our results further proved the existence of direct relations between such obtained coalescence characteristics and parameters of respective gas–liquid dispersions in bubble columns and aerated stirred tanks (Zahradník et al., 1987,1995; Machoň, Vlček, Zahradník & Fialová, 1996) and thus showed that results of bubble coalescence studies represent a useful information applicable for prediction of behaviour of respective gas–liquid systems in gas–liquid reactors. The present work has been therefore aimed at obtaining quantitative information about the effect of the two above-mentioned groups of surface-active additives (aliphatic alcohols and electrolytes) on bubble coalescence in their aqueous solutions and subsequently at examining the possibility of using these surface-active compounds for modifying the extent of coalescence in liquids with increased viscosity, regarded as typical coalescence-supporting media.

2. Experimental

Surface-active substances were represented by the sequence of aliphatic alcohols C1–C8 and by the set of electrolytes including NaCl, KCl, KI, NaSCN, NaOH, $CaCl_2$, $BaCl_2$, Na_2SO_4 and $MgSO_4$. The selection of electrolytes was made with respect to the data from the literature (Oolman & Blanch, 1986; Linek, Beneš & Holeček, 1988; Prince & Blanch, 1990) to cover the whole range of electrolytes' ability to influence bubble coalescence and to include electrolytes with typically 'coalescent', 'non-coalescent' and 'transition' behaviour. Aqueous solutions of 50 and 60 wt% saccharose ($\mu_L = 14$ mPa s and 54 mPa s resp.) and 0.2 and 0.5 wt% xanthan represented fully coalescent viscous media with Newtonian and non-Newtonian behaviour.

Bubble coalescence was studied in a coalescence cell shown schematically in Fig. 1. All measurements were performed in stagnant liquid. The liquid volume in the cell was 1.3 l, the head of liquid above the gas injection point was 0.37 m. Pairs of bubbles were generated simultaneously at opposite orifices of two stainless-steel capillaries 1.6 mm in diameter, the distance of orifices was 3.5 mm. All experiments were performed with air at constant feed rate. Gas velocity related to the area of capillary orifices was 0.14 m s^{-1}, corresponding frequency of bubble formation in the air–water system was 45 bubble pairs per minute. Mutual interactions of contacted bubble pairs were recorded by video camera and subsequently evaluated. One hundred bubble pairs were contacted in each experimental run and the coalescence percentage, ψ, was then directly obtained as the number of coalescing bubble pair. Values of the transition concentration, c_t, defined by Lessard and Zieminski (1971) as the concentration corresponding to 50% coalescence, were then determined for all respective additives from the graphs ψ vs. c, showing dependence of the coalescence percentage on the concentration of additives.

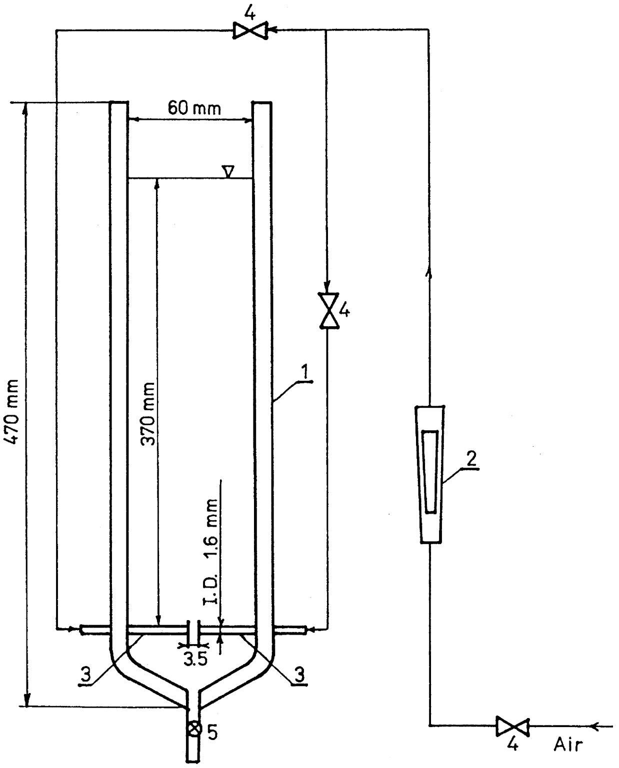

Fig. 1. Scheme of the experimental set-up; 1 – vessel, 2 – rotameter, 3 – capillaries, 4 – regulating valves, and 5 – discharge tap.

Surface tension of aqueous solutions of alcohols was measured with the tensiometer Lauda TE 1 C/2. Concentration dependences σ vs c, obtained for respective alcohols, were approximated by exponential functions and appropriate values $(d\sigma/dc)_t$ were then obtained by derivation of these functions at $c = c_t$. Viscosity of aqueous saccharose solutions was measured with a standard Brookfield viscometer. The rheological parameters of aqueous xanthan solutions were determined using the rheometer Rheostress RS 100 at shear rates of 1–1000 s^{-1}. The flow behaviour of both xanthan solutions was well characterised by the power-law model as $\tau = k\gamma^n$ and $\mu_{eff} = k\gamma^{n-1}$ with the values of the fluid consistency index $k = 0.37$ and 2.58 Pa s^n and flow behaviour index $n = 0.37$ and 0.21 for 0.2 and 0.5 wt% solutions, respectively.

3. Results and discussion

3.1. Bubble coalescence in aqueous solutions of alcohols

Concentration dependences of the coalescence percentage, obtained in aqueous solutions of respective alcohols, are plotted in Fig. 2. In the whole set of alcohols ethanol–octanol, bubble coalescence in their aqueous solutions was hindered by increasing the alcohol concentration. Transition from 100% of the bubble pairs coalescing to complete coalescence suppression was in all cases very sharp and occurred within a narrow concentration region. No effect of methanol addition on bubble coalescence was observed in the experimental concentration region, $c_{\text{met}} \leqslant 10\ \text{kmol m}^{-3}$. While such a finding is in contradiction to the transition concentration $c_t = 1.8\ \text{kmol m}^{-3}$, reported for methanol by Oolman and Blanch (1986), it is in full agreement with the results reported by Drogaris (1983), who observed no bubble coalescence in aqueous methanol solutions for $c_{\text{met}} \leqslant 7\ \text{kmol m}^{-3}$. Values of transition concentration for the sequence ethanol–octanol are summarized in Table 1.

As can be seen from the table, in comparable cases our data agreed well with those reported by Oolman and Blanch (1986). Values of transition concentration exhibited significant decrease with increasing length of carbon chain. Analysis of the data showed that, in the whole set of alcohols ethanol–octanol, this dependence was well described by a power-law functional relation

$$c_t = a\, n_C^b \tag{1}$$

for values of coefficients $a = 31, b = -7.2$ determined from experimental data by linear regression. Comparison shown in Table 1 proves good agreement of experimental c_t data with those calculated from Eq. (1). Evaluation of Drogaris' data showed that Eq. (1) described well values of transition concentration determined in his work for the sequence of aliphatic alcohols ethanol–nonanol. Regression analysis of his experimental data yielded values of coefficients $a = 74, b = -7.3$. Good agreement of the exponent value with that obtained from our data clearly implies identical character of the dependence of c_t values on the number of carbon atoms in the alcohol molecule. Different values of the coefficient a can be ascribed to different geometrical arrangement of Drogaris' experimental cell which, together with different diameter of capillaries ($d_c = 1$ mm), influenced concentration dependences of the coalescence percentage and thus even the absolute values of respective transition concentrations. Herein, it has to be stressed that the above statement reflects the particular features of Drogaris' experimental arrangement rather than the generic issue

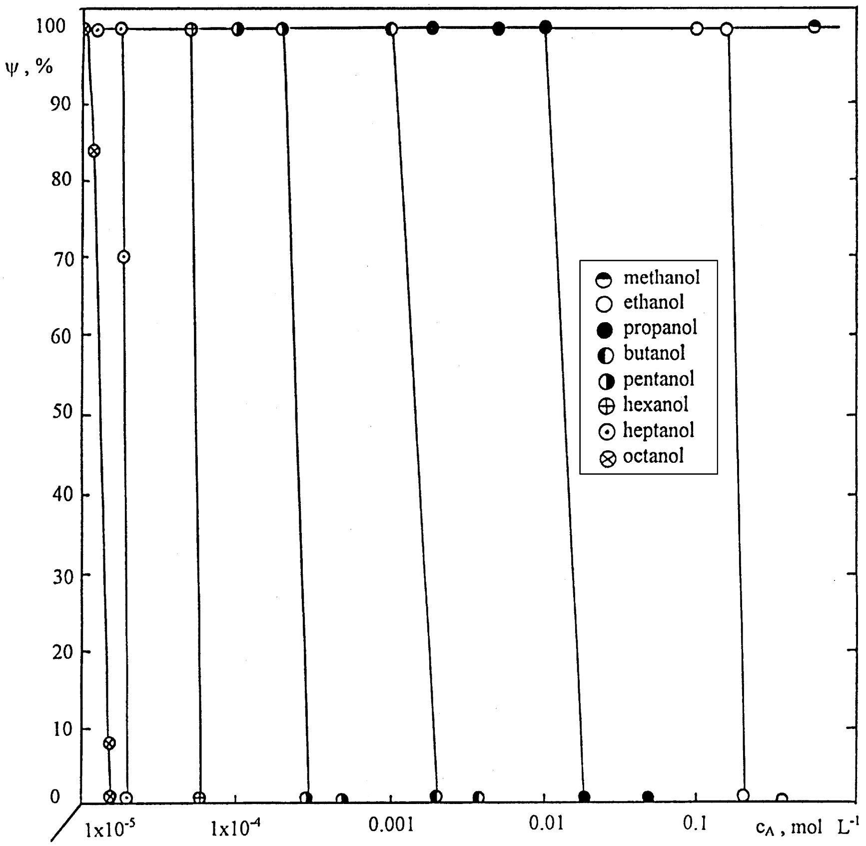

Fig. 2. Coalescence percentage in aqueous solutions of aliphatic alcohols.

of interactions between the system properties and hydrodynamic conditions of bubble contacting. While, indeed, the effect of local hydrodynamics on the rate of drainage of inter-bubble liquid film has to be borne in mind, results of our test experiments, as well as good agreement of our experimental data with those reported by Lessard and Zieminski (1971) and Oolman and Blanch (1986), suggest that the results of our bubble coalescence measurements have been to a large extent independent of the specific hydrodynamic conditions in our experimental device.

Table 1
Transition concentrations of aliphatic alcohols in their aqueous solutions

	c_t (kmol m^{-3})		
	Exp. Data		
	This work	Oolman and Blanch	Calculated from Eq. (1)
Ethanol	0.178	0.14	0.206
Propanol	0.014	—	0.011
Butanol	1.7×10^{-3}	1.8×10^{-3}	1.4×10^{-3}
Pentanol	2.5×10^{-4}	2.1×10^{-4}	2.7×10^{-4}
Hexanol	5.5×10^{-5}	—	7.3×10^{-5}
Heptanol	1.9×10^{-5}	—	2.4×10^{-5}
Octanol	1.3×10^{-5}	—	0.9×10^{-5}

Oolman and Blanch (1986) derived a predictive equation for transition concentrations in volatile surfactant solutions in the form

$$c_t = 0.9 R_g\, T\, t\, k_g (A r_b / 12\pi\sigma)^{1/3} (2\sigma/r_b)(\partial\sigma/\partial c)^{-2} \times (\gamma_i P_i / P)(M_l/\rho_l), \tag{2}$$

where t denotes the bubble contact time, r_b the bubble radius and A the Hamaker constant, characterizing the magnitude of attractive forces between two liquid boundaries. After substitution for r_b from Mersman's relation (1978)

$$d_b = 1.8(\sigma/\Delta\rho g)^{0.5} \tag{3}$$

and further re-arrangement, Eq. (2) can be re-written in the form

$$c_t = K_1 \sigma^{1/3} (\partial\sigma/\partial c)^{-2} \tag{4}$$

for $K_1 = 0.58 R_g\, T\, t\, k_g A^{1/3}\, (\Delta\rho g)^{1/3}\, (\gamma_i P_i/P)(M_l/\rho_l)$. Fig. 3 demonstrates linear dependence of experimental c_t values on the term $[\sigma^{1/3}(\partial\sigma/\partial c)^{-2}]$ for the sequence ethanol–hexanol. Deviations from this linear dependence observed for heptanol and octanol can be ascribed to excessively high values ($d\sigma/dc$) obtained for these low-soluble alcohols from experimentally determined concentration dependences of surface tension.

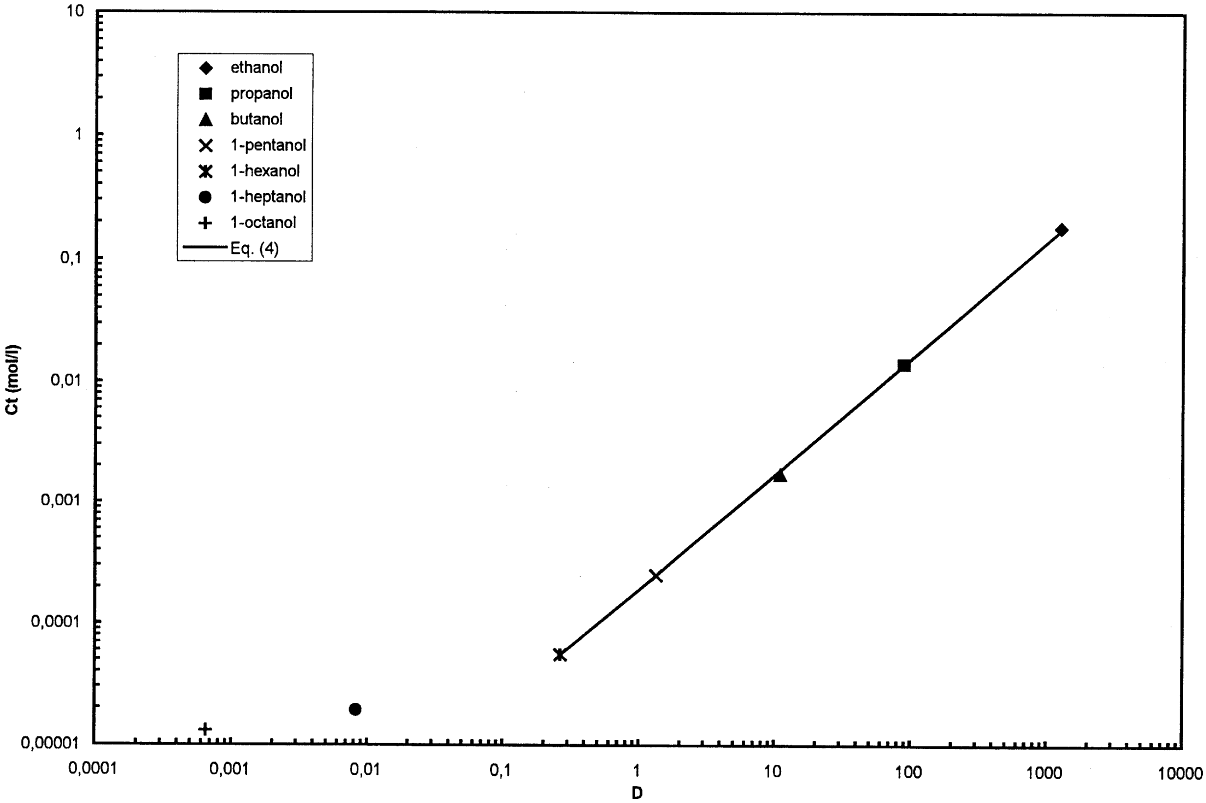

Fig. 3. Correlation of transition concentrations of alcohols by Eq. (4); $D = [\sigma^{1/3}(\partial\sigma/\partial c)^{-2}]$.

3.2. Bubble coalescence in aqueous solutions of electrolytes

Results of bubble coalescence measurements in aqueous solutions of electrolytes are summarized in Fig. 4 in which values of coalescence percentage, obtained in solutions of individual electrolytes, are plotted as a function of the solute concentration. In agreement with the former data of Lessard and Zieminski (1971), the presented concentration dependences demonstrated sharp transition from the complete coalescence to very low values of the coalescence percentage ($\psi \leqslant 10\%$) occurring over a narrow concentration range of respective solutes. Different behaviour of NaSCN solutions, exhibiting 100% coalescence in the whole experimental region of concentrations ($c \leqslant 5$ kmol m^{-3}), corresponded with the literature references pointing to the anomalous behaviour of such solutions in gas–liquid reactors (Španihel, 1987; Kaštánek et al., 1993). These findings can be qualitatively explained, e.g. with reference to the results of Jarvis and Scheinman (1968) who compared the effect of different anions on values of their surface potentials and on concentration dependences of surface tension of aqueous solutions of electrolytes. Values of the surface potential of different sodium salts varied at constant anion concentration (2 mol l^{-1}) with the anion type by more than 100 mV and decreased in the sequence $SO_4^{2-} > CO_3^{2-} > C_2H_5O^- > Cl^- > NO_3^- > Br^- > I^- > SCN^-$ and similarly, the value ($d\sigma/dc$) for NaSCN solutions was considerably lower than those for other electrolytes (see Table 2). Values of the transition concentration, evaluated for individual electrolytes from concentration dependences of coalescence percentage plotted in Fig. 3, are given in Table 3. The table demonstrates good agreement of our experimental results with the data reported by Lessard and Zieminski (1971). Also, the table shows that for the majority of electrolytes our experimental data agreed well with values c_t calculated from the theoretical relation

$$c_t = 1.18 \nu R_g T (B\sigma/r_b)^{1/2} (\partial\sigma/\partial c)^{-2} \tag{5}$$

derived by Prince and Blanch (1990). In Eq. (5), ν represents number of ions formed upon dissociation, r_b is the bubble radius and B the retarded van der Waals coefficient characterizing the force of attraction between two liquid boundaries. We have no immediate explanation for discrepancies between experimental and calculated

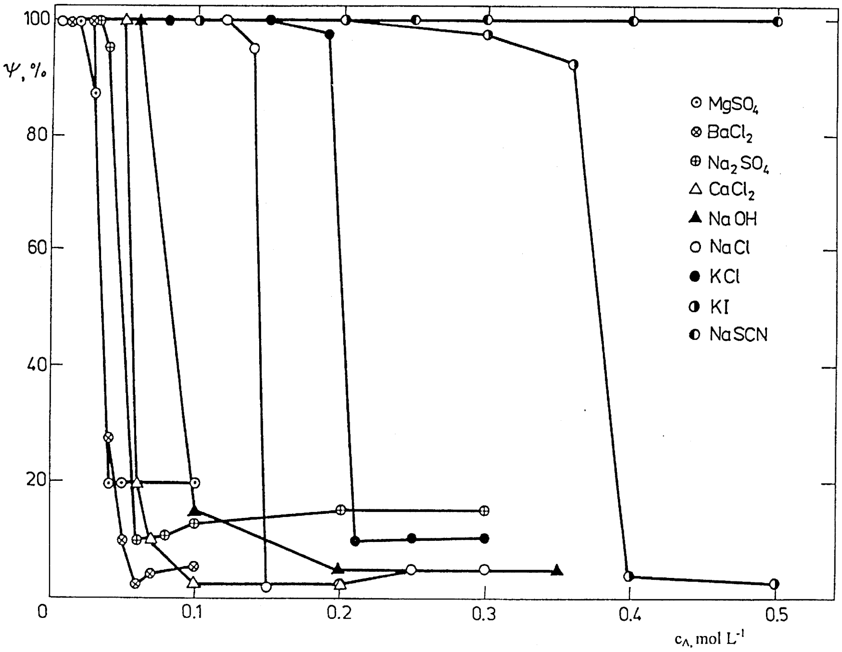

Fig. 4. Coalescence percentage in aqueous solutions of electrolytes.

Table 2
Comparison of values ($d\sigma/dc$) for different electrolytes (Jarvis & Scheinman, 1968)

Electrolyte	Na_2SO_4	$(NH_4)_2SO_4$	NaCl	KCl	KI	NaI	NaSCN
($d\sigma/dc$) × 10^3 (kg m^3 kmol^{-1} s^{-2})	2.95	2.43	1.76	1.53	1.34	1.19	0.55

data observed for Na_2SO_4 and KI. It may be, however interesting to point out that in these two cases our experimental data exhibited excellent agreement with values $c_t = 0.05$ and $0.38\ \mathrm{kmol\ m^{-3}}$ obtained for Na_2SO_4 and KI respectively from the original Marrucci's (1969) equation

$$c_t = 0.084 \nu R_g T (A^2 \sigma / r_b)^{1/3} (\partial\sigma/\partial c)^{-2}, \qquad (6)$$

in which van der Waals coefficient has been replaced by the Hamaker constant. Such a finding may suggest that correction of the Marrucci's equation, proposed by Prince and Blanch (1990) on the basis of modified derivation of the relation for the rate of thinning of the liquid film between the two coalescing bubbles, need not be necessarily justified for all electrolytes.

Table 3
Transition concentrations of electrolytes in their aqueous solutions

	c_t (kmol m^{-3})		
	Exp. Data This work	Lessard and Zieminski	Calculated from Eq. (5)
$MgSO_4$	0.036	0.032	0.042
$BaCl_2$	0.037	—	0.039
Na_2SO_4	0.051	0.061	0.089
$CuCl_2$	0.056	0.055	0.053
NaOH	0.084	—	0.078
NaCl	0.145	0.175	0.150
KCl	0.202	0.230	0.209
KI	0.380	0.620	0.580

If r_b in Eqs. (5) or (6) was expressed from the Mersman's equation (3), the two equations for c_t in electrolyte solutions could be, similarly as in the case of alcohol solutions, re-arranged to the form

$$c_t = K_2 \sigma^n (\partial\sigma/\partial c)^{-2}, \qquad (7)$$

where $K_2 = 1.24\nu\ R_g T B^{1/2} (\Delta\rho g)^{1/4}$ or $0.087\ \nu R_g T A^{2/3} (\Delta\rho g)^{1/6}$ and $n = \frac{1}{4}$ or $\frac{1}{6}$ for Eqs. (5) or (6), respectively. Comparison of Eqs. (4) and (7) clearly shows that, in spite of the different nature of the two groups of surface-active compounds, studied in this work, and the opposite trend of concentration dependences of surface tension of their solutions, transition concentrations of all these additives in their aqueous solutions can be correlated by a formally identical relation as a linear function of the term $[\sigma^n(\partial\sigma/\partial c)^{-2}]$, for appropriate values of the exponent n.

3.3. The effect of surface-active additives on bubble coalescence in viscous media

Concentration dependences of the coalescence percentage plotted in Figs. 5 and 6 clearly show suppression of bubble coalescence in aqueous solutions of saccharose

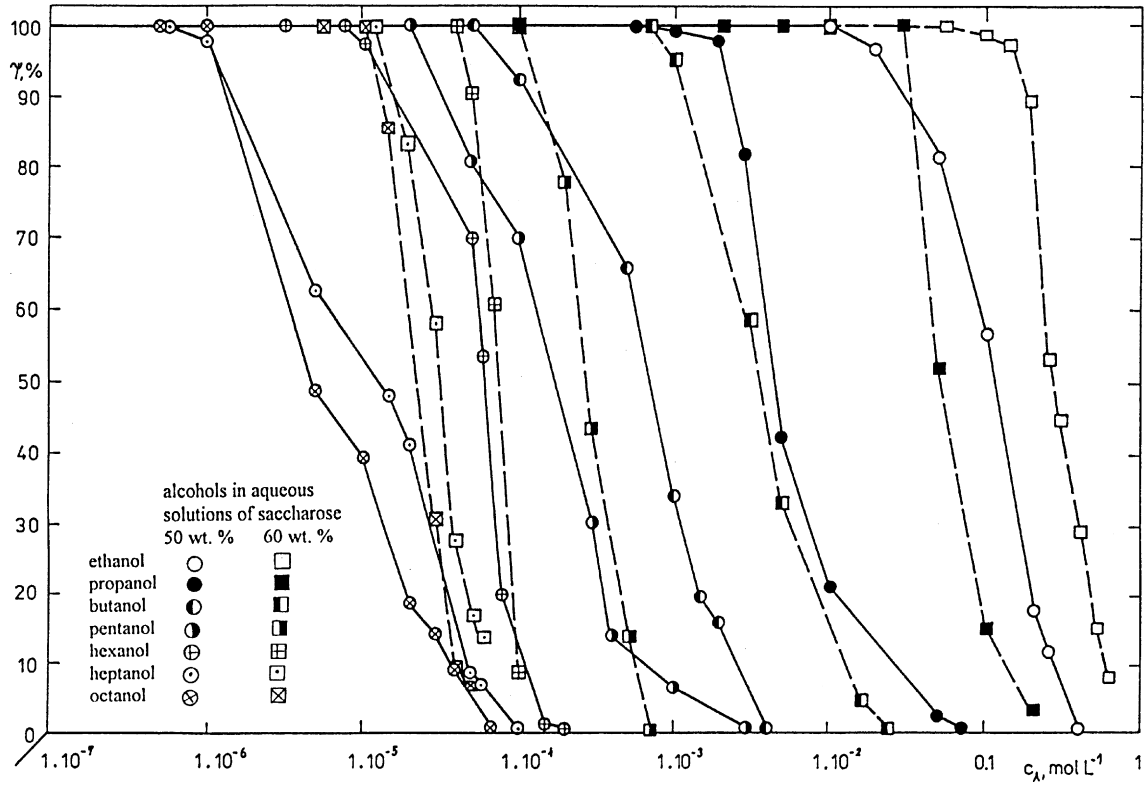

Fig. 5. Dependence of the coalescence percentage on alcohol concentrations in the aqueous solutions of saccharose: 50 wt% (full lines) and 60 wt% (dashed lines).

and xanthan due to the addition of individual aliphatic alcohols. The graphs convincingly demonstrate that the extent of bubble coalescence in viscous aqueous media has been, in the whole experimental range of viscosity and rheological behaviour, significantly reduced by the addition of aliphatic alcohols, compensating thus for the negative effect of increased viscosity on bubble coalescence. Respective values of transition concentrations of individual alcohols in the saccharose and xanthan solutions are summarized in Table 4, together with corresponding data for aqueous solutions of alcohols. Comparison of the data, as well as inspection of

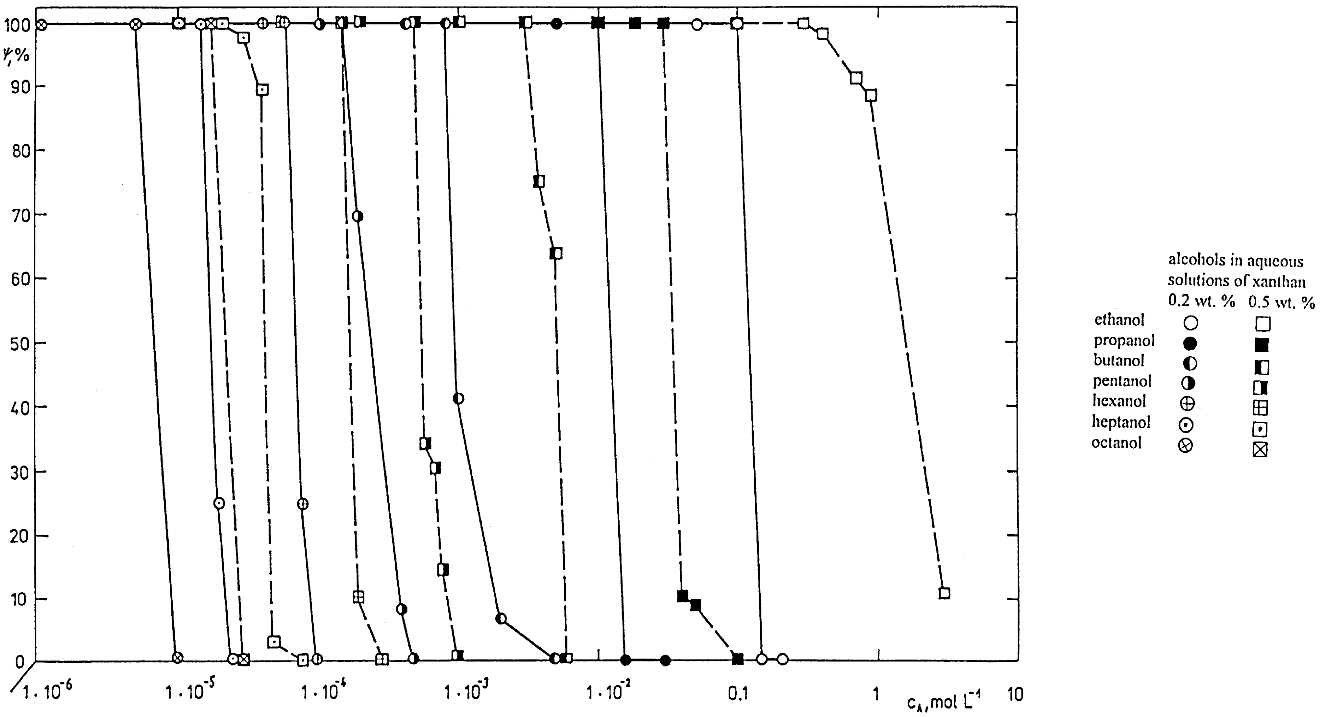

Fig. 6. Dependence of the coalescence percentage on alcohol concentrations in the aqueous solutions of xanthan: 0.2 wt% (full lines) and 0.5 wt% (dashed lines).

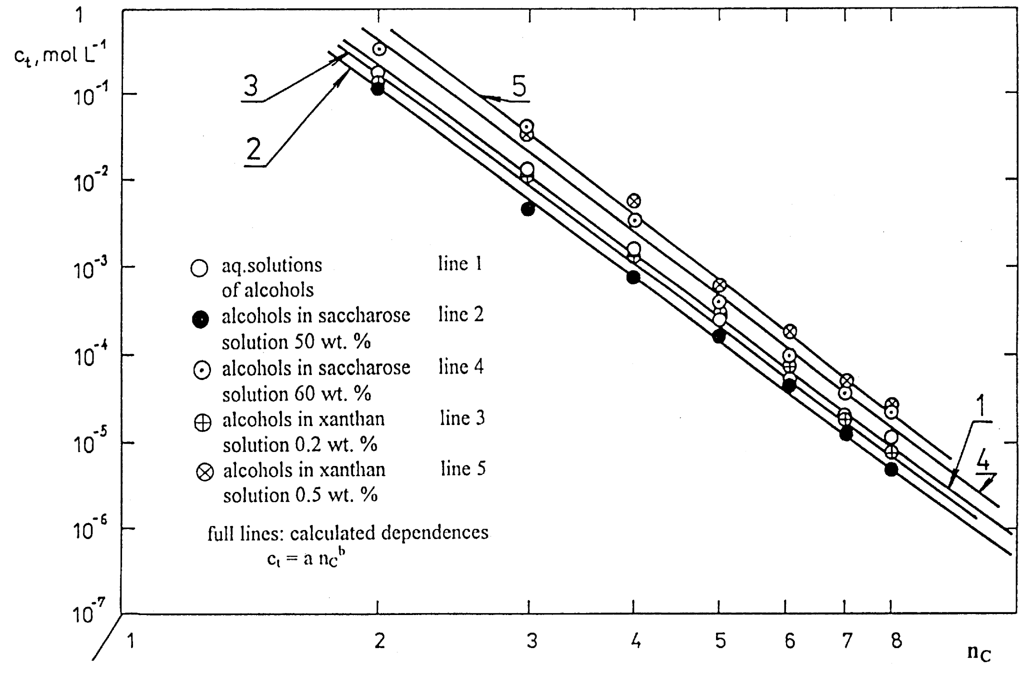

Fig. 7. Transition concentrations of aliphatic alcohols as a function of the number of carbon atoms in the alcohol molecule.

Table 4
Transition concentrations of alcohols in their aqueous solutions and in aqueous solutions of saccharose (50 and 60 wt%) and xanthan (0.2 and 0.5 wt%)

	c_t (kmol m^{-3})				
	Aqueous solutions of alcohols	Saccharose solution		Xanthan solution	
		50 wt%	60 wt%	0.2 wt%	0.5 wt%
Ethanol	0.178	0.120	0.266	0.124	1.58
Propanol	0.014	0.0046	0.052	0.012	0.036
Butanol	1.7×10^{-3}	7.5×10^{-4}	3.5×10^{-3}	1.4×10^{-3}	5.2×10^{-3}
Pentanol	2.5×10^{-4}	1.7×10^{-4}	2.7×10^{-4}	2.6×10^{-4}	5.7×10^{-4}
Hexanol	5.5×10^{-5}	5.2×10^{-5}	7.7×10^{-5}	7.0×10^{-5}	1.8×10^{-4}
Heptanol	1.9×10^{-5}	1.4×10^{-5}	3.6×10^{-5}	1.8×10^{-5}	4.4×10^{-5}
Octanol	1.3×10^{-5}	4.4×10^{-6}	2.3×10^{-5}	7.5×10^{-6}	2.3×10^{-5}

Table 5
Coefficients of Eq. (1)

	a	b
Aqueous solutions of alcohols	31	− 7.2
Saccharose solutions, 50 wt%	14.5	− 7.1
Saccharose solutions, 60 wt%	74.5	− 7.4
Xanthan solutions, 0.2 wt%	23.5	− 7.1
Xanthan solutions, 0.5 wt%	184	− 7.7

Table 6
Transition concentrations of electrolytes in their aqueous solutions and in the aqueous solution of xanthan (0.2 wt%)

	c_t (kmol m^3)	
	Aqueous solutions of electrolytes	Aqueous solution of xanthan 0.2 wt%
Na_2SO_4	0.051	0.106
NaCl	0.145	0.330
KI	0.380	1.950

graphical dependences plotted in Figs. 2, 5 and 6, shows that transition concentrations of individual alcohols in solutions with moderately increased viscosity (50 wt% saccharose solution and 0.2 wt% xanthan solution) were very close (or even slightly lower) to those observed in aqueous alcohol solutions. Further increase of viscosity resulted, however, in a clearly pronounced increase of transition concentration values, up to an order of magnitude. The dependence of transition concentrations on the number of carbon atoms in the alcohol molecule could be in all cases well described by Eq. (1) with values of exponent b varying only slightly between -7.1 and -7.7. Obviously, such a finding indicates that the dependence of transition concentration on the length of carbon chain of alcohol additives has been almost independent of the nature of aqueous viscous medium. Comparison of experimental and calculated dependences $c_t = c_t\,(n_C)$, plotted for all systems studied in logarithmic coordinates in Fig. 7, demonstrates good fit of experimental data with calculations from Eq. (1) for respective values of coefficients a and b summarized in Table 5.

The effect of electrolytes on bubble coalescence in viscous solutions was less pronounced in comparison with the effect of alcohols and differed with the solvent nature. Comparison presented in Table 6 shows that the transition concentrations of Na_2SO_4, NaCl, and KI, i.e. salts covering the whole range of inhibitory effect of electrolytes on bubble coalescence in their aqueous solutions (see Fig. 4), were already in 0.2 wt% xanthan solution (i.e. at moderately increased viscosity) significantly higher than in their aqueous solutions. In the aqueous solution of 50 wt% sacharose, no effect of electrolyte addition was observed within the whole experimental range of electrolyte concentrations ($c \leqslant 3$ kmol m^{-3}).

4. Conclusions

An experimental study has been aimed at examining the coalescence phenomena in aqueous solutions of aliphatic alcohols and electrolytes and at determining the effect of these surface-active additives on bubble coalescence in aqueous solutions of saccharose and xanthan, representing fully coalescent viscous media with Newtonian and non-Newtonian behaviour. Transition concentrations of respective surface-active additives, characterizing suppression of coalescence in their aqueous solutions, were successfully correlated as a function of the term $[\sigma^n(\partial\sigma/\partial c)^{-2}]$, with exponent values $n = \frac{1}{3}$ and $\frac{1}{4}$ (or $\frac{1}{6}$) for solutions of alcohols and electrolytes respectively. The inhibitory effect of alcohols on bubble coalescence increased with the length of their carbon chain, within the whole experimental set of alcohols. Parallel investigation of the effect of alcohols and electrolytes on bubble coalescence in viscous aqueous solutions of saccharose and xanthan showed significant differences in the effect of both respective groups of surface-active compounds. The addition of aliphatic alcohols to the fully coalescent viscous media with both Newtonian and non-Newtonian behaviour reduced significantly the extent of coalescence in these media and ultimately resulted in its total suppression. Transition concentrations of alcohols in solutions of saccharose 50 and 60 wt% and xanthan 0.2 and 0.5 wt% increased moderately (within an order of magnitude) with increasing medium viscosity and within the whole range of viscosity and rheological behaviour exhibited almost identical power-law dependence on the number of carbon atoms in the alcohol molecule, $c_t \approx n_C^{(-7.1)\text{-}(-7.7)}$. No effect of electrolytes on bubble coalescence in the saccharose solution was observed within the whole experimental region of electrolyte concentration ($c \leqslant 3\ \mathrm{kmol\,m^{-3}}$), while the transition concentrations of respective electrolytes in the xanthan solution (0.2 wt%) were considerably higher than those observed in their aqueous solutions. Unlike the aliphatic alcohols, the electrolytes thus cannot be generally recommended for modifying the behaviour of viscous aerated batches. It is, nevertheless, advisable to examine the simultaneous, potentially cumulative effect of alcohols and electrolytes on bubble coalescence in their aqueous solutions as well as on coalescence behaviour in viscous media (both aqueous and non-aqueous) as a logical further step towards understanding of bubble coalescence phenomena in complex industrial media.

Notation

a, b	coefficients in Eq. (1)
A	Hamaker constant, J
B	retarded van der Waals coefficient, J m
c	concentration, $\mathrm{kmol\,m^{-3}}$
c_t	transition concentration, $\mathrm{kmol\,m^{-3}}$
g	gravity acceleration, $\mathrm{m^2\,s^{-1}}$
k	fluid consistency index, $\mathrm{Pa\,s}^n$
k_g	gas-side mass transfer coefficient, $\mathrm{kmol\,m^{-2}\,s^{-1}\,Pa^{-1}}$
K_1, K_2	coefficients in Eqs. (4) and (7) resp.
P	pressure, Pa
M	molar mass, $\mathrm{kg\,kmol^{-1}}$
n	flow-behaviour index
n_C	number of carbon atoms in the alcohol molecule
r_b	bubble radius, m
R_g	gas constant, $\mathrm{J\,mol^{-1}\,K^{-1}}$
t	time of bubble contact, s
T	temperature, K

Greek letters

$\Delta\rho$	density difference between the liquid and gas phases, $\mathrm{kg\,m^{-3}}$
γ	shear rate, $\mathrm{s^{-1}}$
γ_i	activity coefficient
μ	dynamic viscosity, Pa s
μ_{eff}	effective dynamic viscosity, Pa s
v	number of ions formed upon dissociation, Eqs. (5) and (6)
ρ	density, $\mathrm{kg\,m^{-3}}$
ψ	coalescence percentage, %
σ	surface tension, $\mathrm{N\,m^{-1}}$
τ	shear stress, Pa

Subscripts

g	gas phase
l	liquid phase
i	component i

Acknowledgements

The authors gratefully acknowledge financial support from the Grant Agency of the Czech Republic through the Grant No.104/97/1170 and from the Commission of the European Communities under COPERNICUS contract No.CIPA-CT94-0179.

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