R & D NOTES

Some Hydrodynamics and Power Input Data In Mechanically Agitated Gas-Liquid Contactors

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The dependency of the transfer parameters and particularly interfacial area in mechanically agitated gas-liquid contactor on the agitation power input has been clearly shown by the experimental work of Calderbank (1958) and Reith (1968). Even for the standard configuration defined by Holland and Chapman (1966), the a priori prediction of the agitation power is not easy (Oyama and Endoh, 1955; Calderbank, 1958; Reith, 1968). The aim of this paper is to present experimental gas holdup and agitation power data concerning ten gasses with aqueous, organic, and foaming liquid systems inside small vessels complementary to those presented by Michel and Miller (1962) and Pharamond et al. (1975) for vessels having nearly similar geometrical configuration.

Most of the experiments were carried out in a flat bottom, cylindrical, 8.9 l tank (diameter $T = 22$ cm) agitated by a six flat-blade Rushton type of disk turbine. Metered air was introduced beneath the turbine by an open-end tube (1 cm diameter). The agitator (diameter $D = T/3$) was located at a distance $T/3$ above the bottom. The reactor is fully baffled (four baffles of width $T/10$). In all experiments, the dispersion height was kept constant and equal to the tank diameter (the same conditions as in the Reith's experiments). This last condition is appreciably different from the experimental conditions of the other literature works, where for $N = 0$ and $Q_G = 0$, the initial liquid height $H_L = T$. The dispersion height was kept constant because the contactor was actually working in semiflow batch as a first step in further research on continuous flow. Complementary experimental results were performed in a 5.5 l reactor where the gas sparger was either an open tube (0.8 cm diameter), a perforated ring (6 cm diameter with thirty holes, 0.1 cm diameter), or a porous ring (6 cm diameter).

The usual agitator speed N ranges are 300 to 1 650 rev/min, and the gas superficial velocity u_s was varied between 0.07 and 4.7 cm/s (with complementary experiments till upper limits $N = 3\,000$ rev/min and $u_s = 8.5$ cm/s). Liquid properties and power numbers N_p that characterize the agitation of the vessel in absence of the gas phase are presented in Table 1. The experiments were carried out either in turbulent ($N_p =$ const) or intermediate regimes (N_p variable with Re), and in each case the values of N_p were measured for $H_L = T$.

In the presence of a gas flow rate, the water sugar solution (36 wt %) and the aqueous sulfite solution (0.8 M) have a tendency to foam when they are agitated. This is characterized by a significant increase in gas holdup which does not occur with the other solutions, either electrolytic or not. However, it was not possible to attribute this a priori to the physicochemical parameters. The agitation power input was obtained by a turntable that eliminates the friction, this device being similar to that described by Novak and Rieger (1973). The accuracy of the measure of the torque is about 3%. The gas holdup α was measured by an original device described by Loiseau (1976), where the liquid overflow is aspirated at the level T.

Table 1. Summary of Systems Studied

Key	Type of liquid	Liquid	ρ, 10^3 kg/m^3	μ, 10^{-3} Pa · s	σ, 10^{-3} N/m	N_p	u_s, 10^{-2} m/s	Rev/min
△	Pure liquids	Water	1.0	1.0	72.0	3.80 ± 0.15	0.07-2.12	340-1 650
×		Glycol	1.11	19.75	48.1	Variable with Re	0.07-0.62	350-1 400
○	Nonfoaming solutions	Water + lauric Alcohol (1.7 p.p.m)	1.0	1.0	23.0	3.72 ± 0.11	0.07-0.62	440-1 500
▲		Ethanol (95% by volume)	0.803	1.50	23.9	3.59 ± 0.15	0.07-0.62	380-1 600
+		Water + sugar (60 wt %)	1.278	48.50	53.5	Variable with Re	0.07-0.62	400-1 400
●		Water + HCl (5N) + CuCl (0.9 M)	1.145	1.25	44.4	3.38 ± 0.08	0.64-4.7	480-1 720
■		Aqueous sodium Sulfite sodium (0.2 M)	1.028	1.12	61.0	3.68 ± 0.11	0.27-2.12	340-1 625
□		Acetic acid + propionaldehyde (2M)	1.024	1.22	28.0	3.28 ± 0.13	0.27-2.12	350-1 500
★	Foaming solutions	Water + sugar (36 wt %)	1.158	5.40	54.0	3.51 ± 0.11	0.07-0.62	400-1 650
◇		Aqueous sodium* Sulfite solution (0.8 M)	1.085	1.50	56.1	4.56 ± 0.11 3.63 ± 0.12	0.07-8.5	300-3 000

* $N_p = 4.56$ for $T = 0.19$ m $V_L = 5.5 \cdot 10^{-3}$ m^3.
$N_p = 3.63$ for $T = 0.22$ m $V_L = 8.9 \cdot 10^{-3}$ m^3.

RESULTS

Gas Holdup

The variations of the gas holdup for the aqueous solution of sodium sulfite as a function of the superficial gas velocity u_s and the agitator speed are shown in Figure 1*a*. The trends of these curves are similar to those presented by Westertep et al. (1963). At constant gas velocity, with the open-end tube as distributor, a bypass zone is observed for small agitator speeds where the gas bubbles flow through the tank without recirculation (inefficient regime). Then, with an increase of *N*, the gas phase is effectively dispersed in the loading zone, where there exists an affine relationship between α and *N* (inertial regime). At last for higher agitator speeds, the holdup curves reach a maximum, and there is no more holdup variation with N. This is the flooding zone (superficial regime). A similar trend is observed with the porous plate as distributor, where the gas is subdivided at the introduction except in the loading zone, where a single curve is observed when $u_s < 5$ cm/s (Loiseau, 1976). Variations of the gas holdup with the liquid properties are shown in Figure 1*b*. All things being equal, the highest values of α are obtained for foaming fluids for which the bubble coalescence is weak. Inversely, the smallest gas holdups are obtained with nonfoaming viscous solutions due to the small bubble recirculation rate, and the flooding is then reached for relatively small agitation speeds.

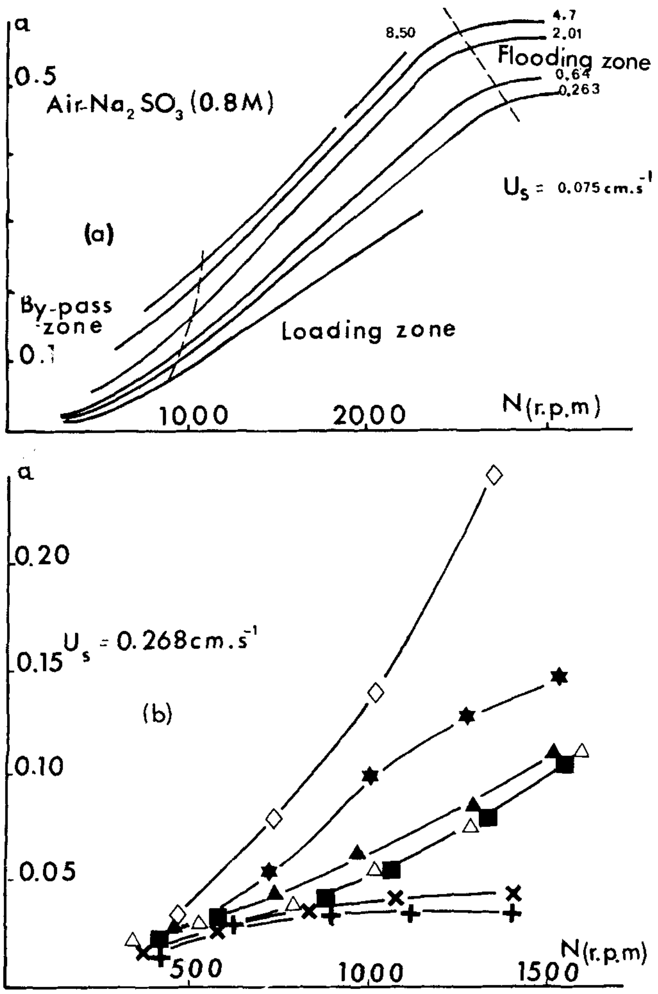

Fig. 1. Variation of gas holdup with hydrodynamics and liquid properties. (See Table 1 for key of Figure 1b.)

It must be noted that it was not possible to correlate these results satisfactorily with the existing correlations (Calderbank, 1958; Van Dierendonck et al., 1968; Sterbacek and Sachova, 1976), mainly because the surface tension is not a satisfactory physicochemical parameter to take into account the foaming phenomena. So two correlations are proposed (Figure 2): for nonfoaming systems

$$\alpha = 0.011\, u_s^{0.36}\, \sigma^{-0.36}\, \mu^{-0.056}\, (\epsilon_A + \epsilon_D)^{0.27} \qquad (1)$$

with a 20% accuracy and for foaming systems

$$\alpha = 0.0051\, u_s^{0.24}\, (\epsilon_A + \epsilon_D)^{0.57} \qquad (2)$$

with a 30% accuracy. ϵ_A and ϵ_D are, respectively, the mechanical agitation power in gas-liquid dispersion and the sparge gas isothermal expansion power per unit volume of clear liquid [$\epsilon_D = \rho_G Q_G\, RT/M_G V_L \ln\, (p_s/p_o)$].

Moreover, Midoux (1977) has recently shown that the comparison of the empirical Equation (2) with the data published in the literature for electrolytic aqueous solutions with ionic strength comprised between 0.097 and 2.4 ion g/l has led to a good agreement if α in Equation (2) is replaced by $\alpha/(1 - \alpha)$ for experiments

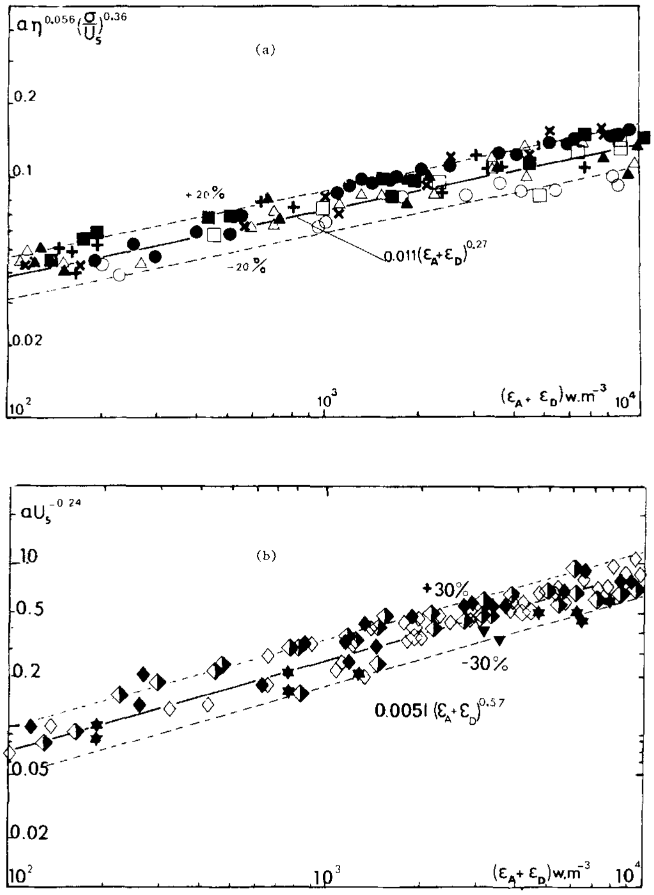

Fig. 2. Variation of gas holdup with liquid properties and specific total power input for nonfoaming liquids (2*a*) and for foaming liquids (2*b*). (See Table 1 for key of Figure 2*a*.)

Key for Figure 2*b*	*T* (m)	Gas distributor	Liquid
◇	0.191	Open-end tube	Na_2SO_3 (0.8M)
◈	0.191	Porous plate	Na_2SO_3 (0.8M)
◆	0.225	Open-end tube	Na_2SO_3 (0.8M)
★	0.225	Open-end tube	Water + sugar (36 wt %)

where the initial liquid height H_L was kept constant. This is justified in assuming that the trajectories of the gas recirculation have the scale of a fixed dimension of the contactor, that is, T. Thus, if the dispersion height is constant, H_E = const = hT, the residence time of the gas is $t_s = (hT/u_s)\alpha$. If the liquid height is constant, H_L = const = hT, the residence time is then $t_s = (hT/u_s)(\alpha/1-\alpha)$. The previous representation correlates α or $\alpha/(1-\alpha)$, quantities that vary as the residence time for a given tank geometry.

It is also worthwhile to note that the ionic strength may have some effect on the foaming phenomena, but this effect is ill defined. Indeed, the water sugar solution (36 wt%) is foaming, whereas the acid cuprous solution (I = 5.5 ion-g/l) is not foaming. Such foaming phenomena have also been observed for hydrocarbons flowing down in trickle bed (Favier and Charpentier, 1975). For all these reasons, it does not seem possible at the present time to make an a priori evaluation or an extrapolation of the gas holdup, and Equations (1) and (2) should be considered only as the best fit of the present data.

Agitated Power

Similar to the air-water experiments presented recently by Van't Riet et al. (1976) and Edney and Edwards (1976), the experimental results of this study were not correlated by the correlations proposed by Calderbank (1958) (plot of P_a/P_o against the aeration number N_a) nor by the correlation proposed by Pharamond et al. (1975) (plot of $1 - P_a/P_o$ against $Q_{vvm}D^{0.63}$). Indeed, in all cases a family of curves was obtained for each agitator speed.

As shown in Figure 3, the data for both vessels can be fitted by correlations like the Michel and Miller relationship (1962)

$$P_a = C\left[\frac{P_oND^3}{Q_G^{0.56}}\right]^n = C\,M^n \tag{3}$$

with, for nonfoaming systems

$$P_a = 0.83\,M^{0.45} \tag{4}$$

and for foaming systems

$$P_a = 0.69\,M^{0.45} \qquad \text{if } M < 2.10^3 \tag{5a}$$

or

$$P_a = 1.88\,M^{0.31} \qquad \text{if } M \geqq 2.10^3 \tag{5b}$$

The accuracy is 20% (S.I. units). It is interesting to note that the data concerning the aqueous solution of lauric alcohol that is a strong surfactant are included within the accuracy of the correlation (4).

The location of the experimental data of this study for nonfoaming liquids is compared on Figure 4 with those of Michel and Miller (1962) for water, carbon tetrachloride, glycerol, and mineral oil in 22 l tanks, with those of Pharamond et al. (1975) for water in 18.7, 87, and 785 l tanks, with those of Van't Riet et al. (1976) for water in tanks of 19 and 44 cm diameter with different liquid heights, and with those of Oyama and Endoh (1955) for water in a tank of 27 cm diameter. The agreement between the various authors on the experimental area is mainly of the order of ± 30%. It therefore seems that the power required by an agitator impeller dispersing gas

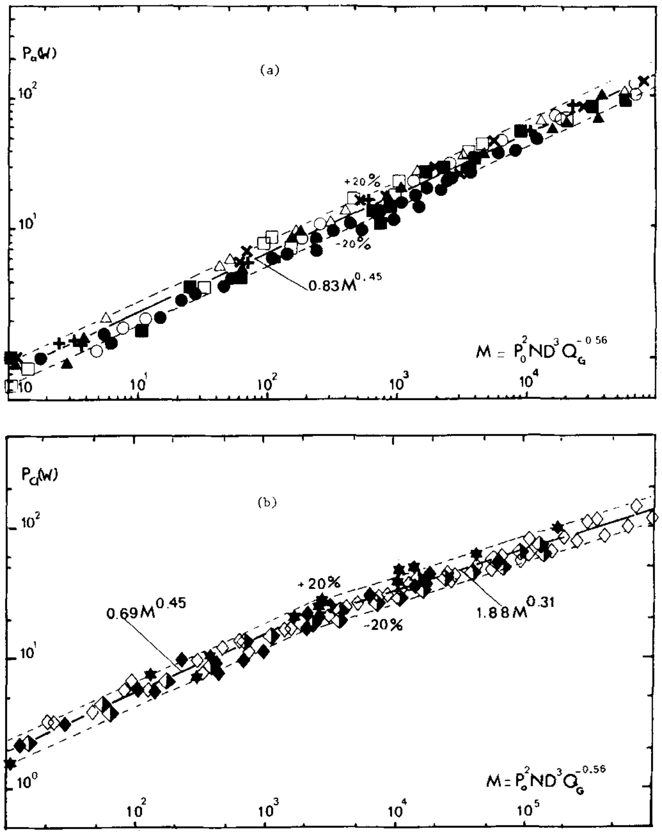

Fig. 3. Variation of agitation power for nonfoaming liquids (3*a*) and for foaming liquids (3*b*). (See Table 1 for key of Figure 3*a*, and the key of Figure 3*b* is the same as the key of Figure 2*b*).

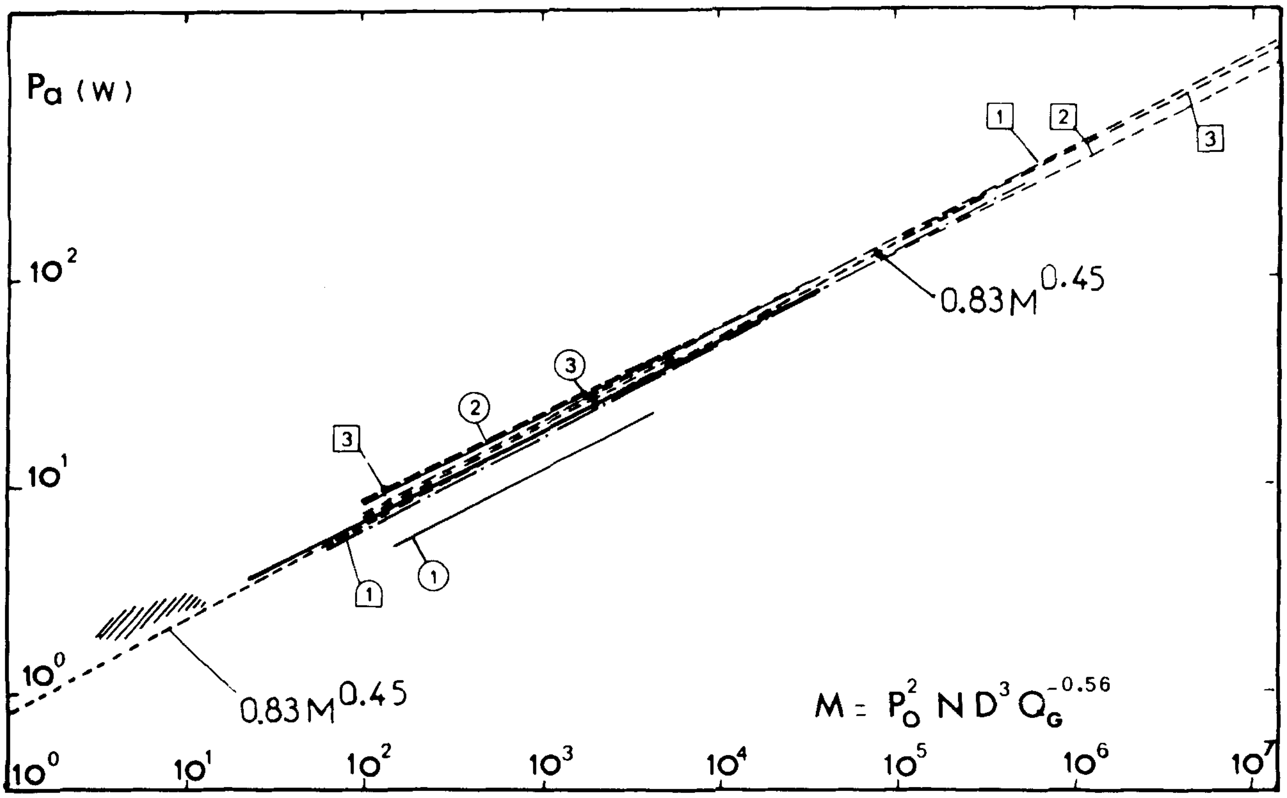

Fig. 4. Comparison of the literature data.

	Author	Liquid	T (m)	D/T	H_L/T	H_A/T	U_s (10^{-2} m/s)
①	Michel and Miller (1962)	CCl_4, water, glycerol	0.165	0.46	0.92	1.33	<1.04
②			0.305	0.25	0.75	1; 0.75	<0.72
③				0.33			
/////	Oyama and Endoh (1955)	Water	0.27	0.33			
[1]	Pharamond et al. (1975)	Water	0.29	0.33	1	0.56	0.084
[2]			0.48			1.0	to
[3]			1.0			1.52	1.41
[①]	Van't Riet et al. (1976)	Water (NaCl)	0.19	0.4	>1	0.2	<1.8
			0.4				

into a liquid for a vessel where the dispersion height is constant and equal to the tank diameter can be calculated with a reasonable accuracy by the previous empirical Equation (4) with the complementary conditions $0.05 < u_s < 9$ cm/s and $1 < P_o^2ND^3/Q_G^{0.56} < 10^7$. Also, present data concerning pure liquids, nonfoaming ionic, and nonionic solutions or liquids containing a surface active agent show that the correlation of the type of the Michel and Miller relationship [Equation (4)] can be used reasonably to predict the aerated power input by mechanical agitation for vessel diameter up to 1 m³ when the geometrical configuration is relatively similar.

For liquids presenting a net tendency to foam, a significant increase in gas holdup is observed, and the agitation power is reduced compared to that for nonfoaming liquid in the same size tank and at the same agitation-aeration rate conditions.

NOTATION

C = constant defined in Equation (3)
D = agitator diameter
h = H_E/T or H_L/T, dimensionless
H_A = distance of the agitator from the bottom, m
H_E,H_L = height of dispersion, clear liquid in the vessel, m
I = ionic strength, ion $g \cdot l^{-1}$
M_G = molar mass, $kg \cdot mole^{-1}$
n = exponent defined in Equation (3)
N = rotational speed of impeller, rev/min
N_a = aeration number = (Q_G/ND^3), dimensionless
N_p = power number = $(P_o/\rho N^3D^5)$, dimensionless
P_a = aerated power input by mechanical agitation, W
P_o = unaerated power input by mechanical agitation, W
p_s,p_o = absolute pressures at the sparger and above the liquid respectively, Pa
Q_G = volumetric flow rate of gas, $m^3 \cdot s^{-1}$
Q_{vvm} = air flow rate ratio (air volume per liquid volume and per minute)
R = gas constant, $J \cdot mole^{-1} \cdot {}^\circ K^{-1}$
Re = agitator Reynolds number = $(\rho ND^2/\mu)$, dimensionless
T = tank diameter, m, or Kelvin temperature, °K
t_s = residence time of the gas, s
u_s = superficial gas velocity based on the cross section of the tank, $m \cdot s^{-1}$
V_L = volume of liquid in the tank, m³

Greek Letters

α = gas holdup
ϵ_A = mechanical agitation power in gas-liquid dispersion per unit volume of clear liquid, $W \cdot m^{-3}$,

$(\epsilon_A = Pa/V_L)$

ϵ_D = sparge gas isothermal expansion power per unit volume of clear liquid $W \cdot m^{-3}$

μ = liquid viscosity, $Pa \cdot s$

ρ = liquid density, $kg \cdot m^{-3}$

ρ_G = gas density, $kg \cdot m^{-3}$

σ = liquid surface tension, $N \cdot m^{-1}$

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A Simplified Model of Electro-Aerodynamic Atomization

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This study represents an attempt to provide an analytical description of the atomization process of a liquid by the combined action of an electrostatic field and a parallel air stream that creates waves on the liquid surface.

The physical phenomenon is extremely complicated, and the theoretical description given is a simplified one. The opposing molecular and electrical forces which occur at the liquid surface whenever an electric charge concentrates on the surface of the liquid could be responsible for the disintegration of the liquid volume into numerous electrically charged droplets. Analyzed like this, the problem seems particularly simple; however, the case under consideration presents the additional complication of an air stream that will atomize the liquid even if there is no electric field.

From the previous consideration, it can be concluded that the model we are trying to develop will have to be based on two factors: hydrodynamics of perturbed liquid surfaces and the characteristics of electrical conduction in liquids. When we take into account the complexity of the phenomenon under study, gross approximations must be made in constructing a theoretical model.

This work is an extension of a work originally published by Mayer (1961), and the modification sought is one that will allow the consideration of electrostatic field effects on the atomization process.

MATHEMATICAL MODEL

The forces acting on a planar liquid surface are assumed to affect the perturbations in such a way that motion is restricted to the coordinate normal to the liquid surface. If the fluid surface is perturbed by small cosine waves, the equation of the surface can be taken as

$$z = z_o \cos(\omega t) \cos\left(\frac{2\pi x}{\lambda}\right) \qquad (1)$$

Let us assume that $\epsilon_L > \epsilon_o$; this assumption leads to the following expressions for the electric fields if E_o is the field outside the liquid at a distance where it is not perturbed by the surface instabilities, and the liquid molecules are rapidly oriented:

$$E_{z_o} = \frac{2\pi}{\lambda} E_o z_o e^{-\frac{2\pi z}{\lambda}} \cos\left(\frac{2\pi x}{\lambda}\right) \cos(\omega t) + E_o \quad z > 0 \qquad (2)$$

$$E_{zL} = \frac{\epsilon_o}{\epsilon_L} \frac{2\pi}{\lambda} E_o z_o e^{\frac{2\pi z}{\lambda}} \cos\left(\frac{2\pi x}{\lambda}\right) \cos(\omega t) + \frac{\epsilon_o}{\epsilon_L} E_o \quad z < 0 \qquad (3)$$

Remembering that the forces in a field are given by the product charge times field and that the charge at the surface is given by

$$q_{\text{surface}} = \epsilon_o \left(1 - \frac{\epsilon_o}{\epsilon_L}\right) E_{z_o} = \epsilon_L \left(1 - \frac{\epsilon_o}{\epsilon_L}\right) E_{zL} \qquad (4)$$

We can estimate the electrostatic forces acting at the liquid surface.

If the expressions for electrostatic field are used, the electrostatic pressure equation can be obtained. The fol-