Drop Interactions in Electrostatic Liquid-Liquid Contactors

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This work discusses the performance of a novel type of electrostatic liquid-liquid contactor equipped with inclined parallel-plate electrodes. In the previous article, we (Mochizuki et al., 1990) studied bouncing motions that single drops would make between two electrodes facing each other, across which a steady electric field is applied, while the drops pass along the electrodes due to gravity. As the second step before studying heat or mass transfer between bouncing drops and the medium liquid, we consider in this work an interaction of drops in a practical multidrop system. The interaction may result in a collision and coalescence of some neighboring drops moving in a contactor and thereby brings the contactor to a failure in stable operation.

Experimental Studies

The scheme of the experiments was generally the same as the one described in our preceding work (Mochizuki et al., 1990). The major change made this time was the use of two nozzles laterally aligned near the entrance of the test section confined by a pair of inclined parallel-plate electrodes, each 170 mm wide and 353 mm long. The spacing between the electrodes was adjusted at 25 mm and filled with a silicone oil [KF96 (50cSt) fluid prepared by Shin-etsu Chemical Co., Tokyo].

First, we determined, with only one of the two nozzles set to work, the critical conditions for the occurrence of a coalescence during the successive passings of 100 (or more) water drops over the whole length of the electrodes. The average x-directional interval between drops under each of the critical conditions for coalescence, L_x^*, was measured. And then, we observed the motions of drops released simultaneously (but not in synchronism) from the two nozzles and thereby marching in two lines. The minimum lateral distance between the two nozzles that did not result in any lateral drop coalescence, L_z^*, was determined analogously to L_x^*.

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It is important to note that in the experiment particular drop pairs were formed accidentally in a train of drops issued from each nozzle, in each of which two drops attracted each other far more strongly than other neighboring drops, thereby promoting their mutual contact and coalescence. Formations of such drop pairs may have resulted from a minute irregularity in the initial motion of drops as they just entered the test section.

Throughout the experiment, every paired drops that once appeared to contact each other coalesced immediately into one drop. After a coalesced drop had been formed in the middle part of the test section in the presence of a rather strong electric field, it coalesced with its preceding drops until it grew so large that it deformed into a bridge, thus short-circuiting the electrodes.

Theoretical Predictions

The experimental observations suggest that the critical condition for coalescence is controlled by particular paired drops accidentally set from the beginning in the most favorable condition for their interactions. As the drops increasingly come closer to each other due to their interaction, the very interaction becomes even stronger, while the interactions between each of these drops and other drops continuously weaken. Therefore, the critical condition for coalescence can be predicted with a reasonable accuracy by considering the behavior of an isolated pair of drops initially set in such an extreme arrangement as to induce possibly the largest attractive force between them.

Like the single-drop model (Mochizuki et al., 1990), we assume that each of the drops forming a pair to be an electrically-conducting sphere which is suspended in a perfect dielectric medium and is subjected to gravity and an electric field (Figure 1). The electric field is uniform, if not disturbed by the drops, and therefore it is represented by a y-directional vector E having a magnitude $E_n \equiv \phi/l$. The external forces considered toward the motion of each drop are gravitational force due to the density difference between the drop and the medium, a drag force F_D relevant to the instantaneous motion

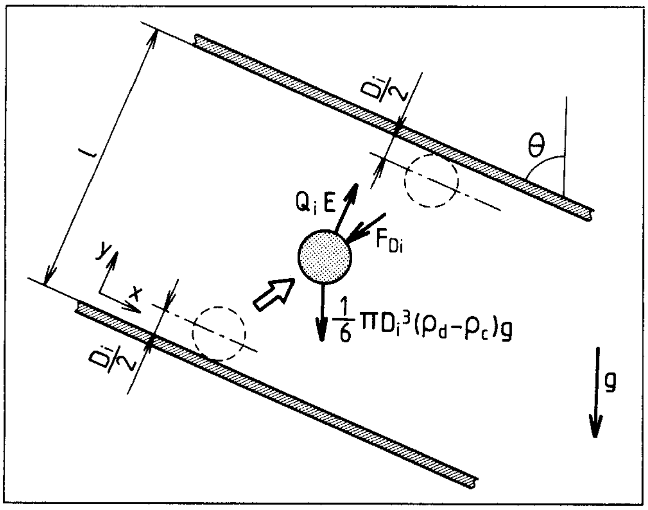

Figure 1. External forces working on a drop viewed as an electrically-conducting sphere.

The coulombic force on the drop carrying a net charge Q_i should be different from Q_iE_n under the presence of another drop in the vicinity of the drop.

of the drop, and a Coulombic force F_E, which may deviate, due to an electrostatic interaction with other drops, from QE_n that holds only for an isolated drop as shown in Figure 1.

The two drops forming a pair may be on the same x-y plane simulating the drops issued from the same nozzle or on different x-y planes simulating those issued from different nozzles arranged in parallel. In either case, we assumed that the two drops were initially set in such an extreme arrangement as shown in Figure 2. One drop lies on the lower electrode, and the other is in contact with the upper electrode. For convenience of mathematical formulation, we defined a particular plane that is normal to the electrodes and always involves the centers of the both drops. On this plane, we placed X-Z coordinates in such a way that the drop centers lie on Z axis.

The force balance on each of paired drops is written as:

$$\frac{1}{6}\pi D_i^3\left(\rho_d+\frac{1}{2}\rho_c\right)\frac{dv_i}{dt}=\frac{1}{6}\pi D_i^3(\rho_d-\rho_c)g+F_{Ei}+F_{Di} \quad (1)$$

where subscript i (= 1 or 2) refers to drop 1 or 2 as indicated in Figure 2. The drag on drop i, F_{Di}, is evaluated just the same as before (Mochizuki et al., 1990). For evaluating F_{Ei}, we employ the solution given by Davis (1964) to the problem of two charged conducting spheres. The solution is written in terms of X- and Z-components of the force on, say, drop 1 as:

$$F_{X1}=4\pi\epsilon_c\left(E_n\frac{D_1}{2}\right)^2F_8\sin 2\psi$$
$$+E_n\sin\psi(F_9Q_2+F_{10}Q_1)+E_nQ_1\sin\psi \quad (2a)$$

$$F_{Z1}=4\pi\epsilon_c\left(E_n\frac{D_1}{2}\right)^2(F_1\cos^2\psi+F_2\sin^2\psi)+E_n\cos\psi(F_3Q_2+F_4Q_1)$$
$$+\frac{1}{\pi\epsilon_cD_1^2}(F_5Q_2^2+F_6Q_1Q_2+F_7Q_1^2)+E_nQ_1\cos\psi \quad (2b)$$

where the force coefficients—F_1, F_2, F_3, ..., F_{10}—are functions of D_1, D_2, and L. The force components given above can be transformed into those relevant to x-y-z coordinates, that is:

$$F_{E1,x}=-F_{E2,x}=(-F_{X1}\cos\psi+F_{Z1}\sin\psi)\frac{x_2-x_1}{\sqrt{L_x^2+L_z^2}} \quad (3a)$$

$$F_{E1,y}=F_{X1}\sin\psi+F_{Z1}\cos\psi \quad (3b)$$

$$F_{E2,y}=(Q_1+Q_2)E_n-F_{E1,y} \quad (3c)$$

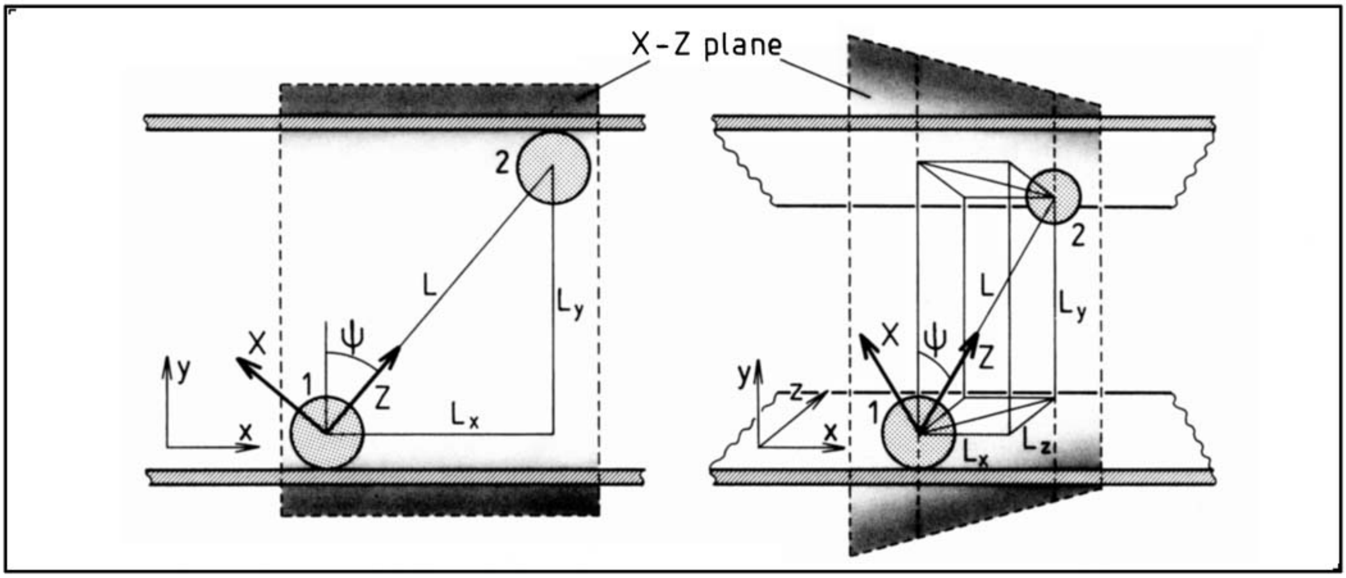

Figure 2. Initial arrangements of paired drops assumed in calculating the minimum x-directional drop spacing L_x (a) and z-directional drop spacing L_z (b) that need to be taken initially to prevent the drop from mutual coalescence.

$$F_{E1,z} = -F_{E2,z} = (-F_{X1}\cos\psi + F_{Z1}\sin\psi)\frac{L_z}{\sqrt{L_x^2+L_z^2}} \quad (3d)$$

where

$$\sin\psi = \frac{\sqrt{L_x^2+L_z^2}}{L}$$
$$\cos\psi = \frac{y_2-y_1}{L} \quad (4)$$

As in the preceding work (Mochizuki et al., 1990), the magnitude of Q_i, the net charge on drop i, is evaluated to be a charge that a conducting sphere of diameter D_i would have when in contact with a plane electrode surface at equilibrium. It is given by (Félici, 1966):

$$|Q_i| = \frac{1}{6}\pi^3\epsilon_c D_i^2 E_n \quad (5)$$

In solving Eq. 1, with the aid of Eqs. 2-5, to obtain the trajectories of respective drops, we need to specify the drop-to-electrode collision condition. For this, we assumed the *stick condition*, in which each drop is assumed to lose its momentum completely at each collision with electrode surface and stick on the surface but for an infinitesimal period. The condition was confirmed to meet the actual motion of single drops (Mochizuki et al., 1990).

The procedure to achieve the predictions of L_x^* and L_z^* is iterative. First, a length $L^\dagger$, the initial x- or z-directional drop spacing, is assumed arbitrarily. The computation is advanced with a time increment of 0.1 ms, finding the loci of the centers of the two drops, until L reduces to $(D_1+D_2)/2$, resulting in the contact of the drops with each other. The length along the x-axis that drop 1 has passed until it contacts drop 2, L_t, may be longer or shorter than 353 mm, which is the total length of the drop passage set in the experiments. The computation is repeated, substituting a different length for $L^\dagger$, until L_t agrees with 353 mm. The particular length $L^\dagger$ thus determined iteratively is no longer than L_x^* or L_z^*.

Experimental vs. Theoretical Results

The experimental and theoretical results on L_x^* or L_z^* are compared in Figure 3. The data on D_0, the diameters of drops for drop-interval data, are also plotted. D_0 was not held constant enough throughout the experiments. When we changed the water flow rate through each nozzle to change the drop-formation frequency, D_0 inevitably changed somewhat. Besides, D_0's generated at the two different nozzles, which were used simultaneously in determining L_z^*, were rarely identical within the accuracy of the measurements. (Both D_0's, which are not identical, are plotted in parallel in Figure 3.) Consequently, the drop-interval data in Figure 3 represent not only the effects of θ and E_n, but also, though implicitly, an effect of D_0.

The theoretical predictions in Figure 3 are, of course, based on the corresponding D_0 data. Concerning L_z^*, two predictions are made for each operational condition: one is based on different D_0's actually measured with drops released from the different nozzles; the other is based on the arithmetic mean of the two D_0's.

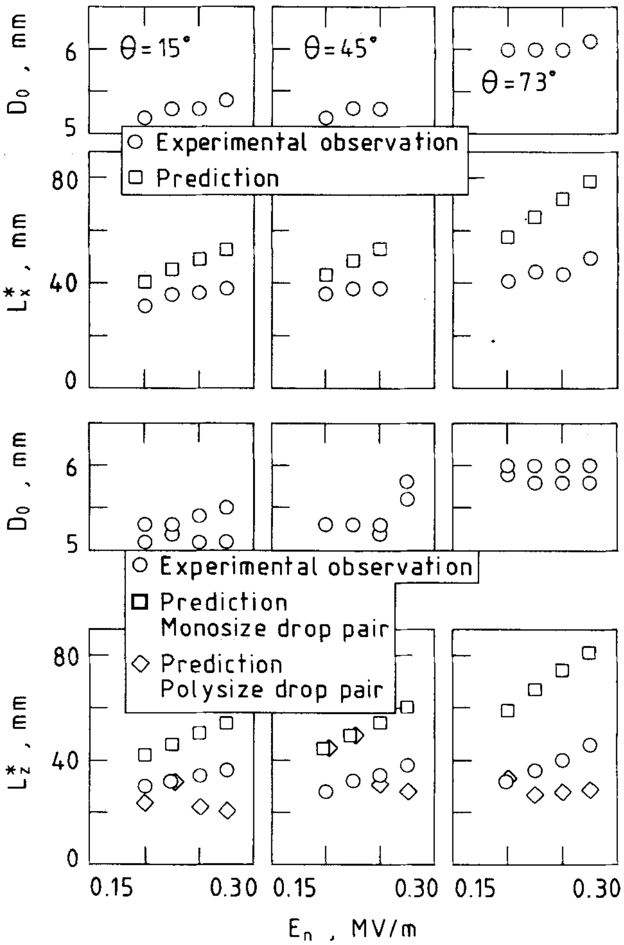

Figure 3. Theoretical predictions vs. experimental results for L_t = 353 mm and l = 25 mm.

It seems that the drop-pair theory generally overestimates the x-directional critical drop intervals. The extent of the overestimation tends to increase with an increase in the tilt angle, θ. If the paired drops are assumed to be the same size in theory, it overestimates L_z^*. The reverse, however, may be the case, if an unequality in drop diameter is actually taken into account in theory. It should be noted that only a slight difference in D can cause a considerable difference in predictions of L_z^*, particularly when θ is large. In conclusion, it is safe to use the theory to get conservative predictions of the critical drop intervals for coalescence in monodisperse systems.

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Notation

D, D_0 = diameter of sphere and equivalent spherical diameter of drop
E, E_n = electric field and its magnitude
$F_1 \cdots F_{10}$ = force coefficients defined by Davis (1964)
F_D = drag on drop

F_E = electrostatic force on drop
F_{X1}, F_{Z1} = X- and Z-components of an electrostatic force acting on drop 1
g = acceleration due to gravity
l = spacing between parallel-plate electrodes
L = distance between drops
L_t = x-directional distance passed by drops before coalescence
L_x, L_y, L_z = x-, y- and z-components of distance between drops
L_x^*, L_z^* = initial x- and z-directional drop intervals critical for coalescence
$L^\dagger$ = initial x- or z-directional distance between paired drops
Q = net electric charge on drop
v = instantaneous velocity of drop
x, y, z = coordinates defined in Figures 1 and 2
X, Z = coordinates defined in Figure 2

Greek letters

ϵ = electrical permittivity
θ = tilt angle of column axis and electrodes from vertical
ν = kinematic viscosity
ρ = mass density
ϕ = voltage difference between electrodes
ψ = angle between E- and Z-axes

Subscripts

i = number for identifying drops, $i=1, 2$
c, d = medium liquid and drop
x, y, z = components in x-, y- and z-directions

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