Motion of Charged Drops in a Non-Newtonian Liquid-Liquid System

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Introduction

The design of liquid-liquid contacting equipment requires knowledge of drop size and distribution in order that mass transfer and reaction rate equations can be formulated. The context here is intensive liquid-liquid contacting in which the dispersion of an aqueous phase into a solvent phase is achieved by electrostatic spraying **(1-5)**. An electrical charge is placed upon drops as they emerge from a nozzle into an immiscible second liquid phase. This is achieved by connecting the nozzle to a high tension electrical source, also placing an electrical field across the continuous phase. The drops move under the influence of the field and are thus accelerated. The main requirement is that the dispersed phase must be of relatively high conductivity and high dielectric constant. The continuous phase must be of relatively low conductivity to ensure that there is minimal electric current flowing inside the column.

The advantages of electrostatic dispersion include significant reduction in the drop size, enhancement of mass transfer, and enhanced rates of phase separation. The reduction in drop size can be very large and is one of the principal factors in the intensification of mass transfer **(6)**. There is also evidence that electrically enhanced contacting may offer significant advantages in the presence of impurities such as surface-active agents, non-Newtonian rheology, and in the presence of biopolymers **(7)**. For example viscous biologically active media can be dispersed electrostatically with relative ease and in a manner which gives rise to an unstable dispersion, which is readily coalesced. Earlier studies **(8-11)** have accurately predicted charged droplet motion in Newtonian systems as a function of charge, external geometry and physical properties using novel finite element techniques.

Here we present a preliminary study of the motion of charged drops comprising viscous Newtonian fluids, and viscous non-Newtonian fluids. The goal of the work was to determine the effect of electrical charge and electrical field upon the drop motion of discrete charged drops.

Methods and Materials

The droplet phases comprised solutions of sugar in water, and carboxymethyl cellulose in water, see Table 1. These provided Newtonian solutions of known viscosity, and the latter provided non-Newtonian solutions of known shear stress / shear rate properties. The continuous phase was n-decanol which was pre-equilibrated with each of the aqueous phases to ensure the absence of mass transfer.

(a) **Table 1.** (b)

Solution	Sugar concentration [g l^{-1}]
1	0
2	50
3	100
4	150

Solution	CMC concentration [wt %]
1	0
2	1
3	2
4	3

The viscosity of the equilibrated solution was measured at different temperatures using a HAAKE RV 20 concentric cylinder viscometer. The density of the continuous and dispersed phase was measured at different temperatures using a PAAR digital density meter. Droplet size data measured optically using high-speed video and SigmaScan Pro software were used to calculate interfacial tension.

The column used for the drop trajectory determinations was of rectangular symmetry comprising a PVC base with four plane glass sides, Figure 1, equipped with a feed nozzle located at the top, and a lower cylindrical electrode located along the axis of symmetry. The column was silanised and loaded with the continuous phase. A constant voltage of 2 kV was applied to the electrode from a stabilised power supply unit (Brandenburg 2735) for 30 minutes prior to injection of the drop phase to ensure completion of space-charge migration.

A syringe pump (Perfusor IV) was used to accurately meter the drops into the column and their trajectories scanned for analysis using a high-speed video camera. The coordinates and size of each droplet were determined according to the pixel values, which were translated into actual values using the appropriate scale factor.

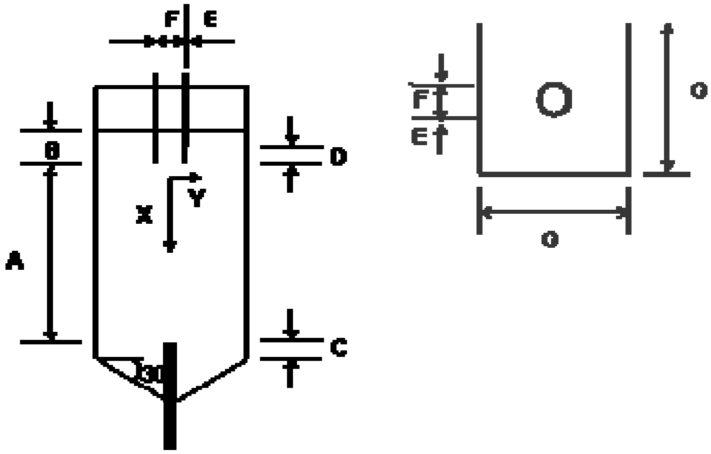

Figure 1 - Layout and essential dimensions [mm] of the contactor

A = Distance between electrodes 200mm
B = Electrode insertion depth 20mm
C = Distance between electrode and top of cone 10mm
D = Exposed electrode length 4.2mm

E = Inner diameter	2.35mm
F = Outer diameter	3.3mm
G = Column side length	100mm

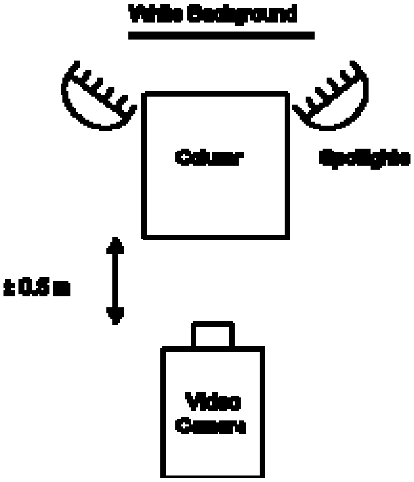

Figure 2 - Experimental set-up for droplet trajectory tracking

Results

Figures 3 and 4 shows the average droplet trajectories in the X and Y directions respectively, for the sugar solution drops and the CMC solution drops. The distance traveled by the droplet at any time decreases with increasing concentration and thus increasing viscosity. The droplet size had a significant influence on the trajectory and, surprisingly, the smaller droplets appeared to move faster than the larger droplets.

The distance traveled by the droplets in a fixed time, decreases with increasing viscosity. The difference between the trajectory of water and the trajectory of the 1% CMC solution is substantial and is explained by the enhanced viscous stress, which is likely to increase the inertial forces acting on the droplet, thus decreasing the velocity.

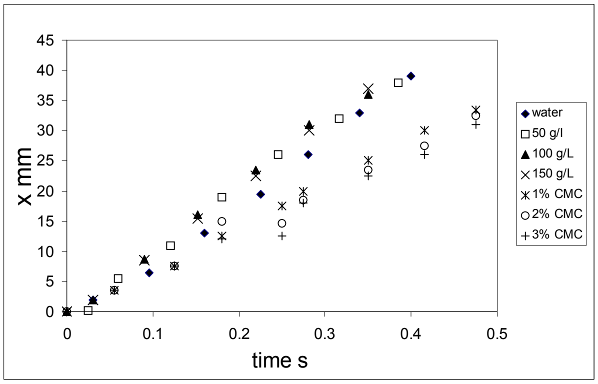

Figure 3 - Average droplet trajectories x - direction for 0, 50,100,and 150g l^{-1} sugar solutions; 1%, 2%, 3% CMC as a function of time

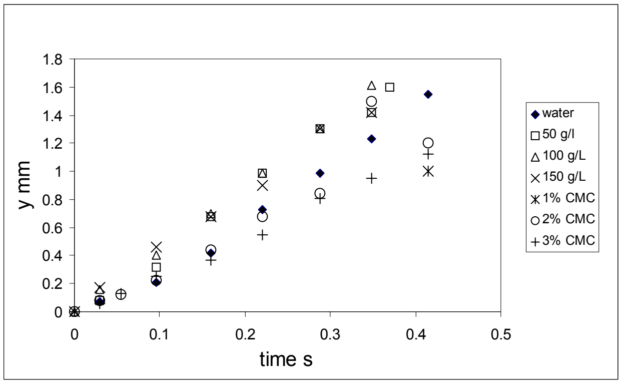

Figure 4 - Average droplet trajectories y - direction for 0, 50, 100, and 150 g l^{-1} sugar solutions; 1%, 2%, 3% CMC as a function of time

Figure 5 shows the velocity profiles for the sugar solution drops as a function of time.
For all solutions a sharp increase in velocity is seen during an initial period of approximately 0.25 seconds after which terminal velocity is attained.

The maximum velocities for the different solutions show significant variation. This may be partially explained by variations in droplet volume, droplet charge and by the degree of oscillation. Normally the droplet velocity increases with increasing diameter and increasing droplet charge and decreases with oscillation.

The peak terminal velocity (U_P) in terms of the physical system may be expressed [(10)] as follows:

$$U_p = 1.23\left(\frac{\gamma}{\mu_c}\right)N_P^{-0.238}$$

Where,

$$N_P = \frac{\gamma^3 \rho_c^{\ 2}}{g \mu_c^{\ 4} \Delta\rho}$$

γ - Interfacial Tension
μ_c - Viscosity of the continuous phase
$\Delta\rho$ - Density difference
ρ_c - Density of the continuous phase
g - Gravitational acceleration constant

Compared to velocity profiles measured for charged drop in low viscosity systems [(7)], the droplets measured here reached maximum velocity relatively quickly. By comparison n-decanol has a relatively low electrical relaxation time hence droplets tend to lose electrical charge quickly after detachment. The effects of the electric field on the droplets motion will be less and buoyancy and drag forces will be dominant.

Figure 6 shows the velocity profiles for the CMC solutions. Here again we see a sharp increase in velocity, which stabilized after 0.25 seconds. The measurements for the CMC solutions show less scatter than for the sugar solutions with the maximum velocity decreasing with increasing CMC concentration.

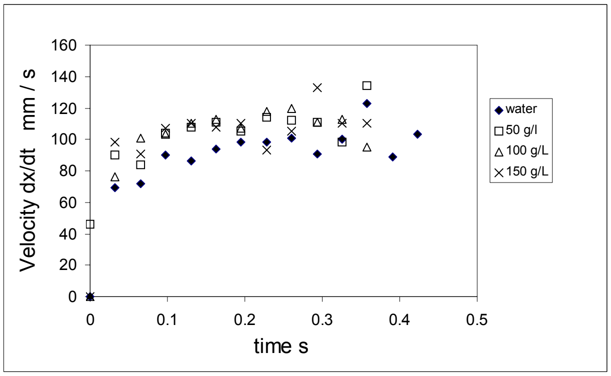

Figure 5 - Average droplet velocity x - direction for 0, 50, 100, and 150 g l^{-1} sugar

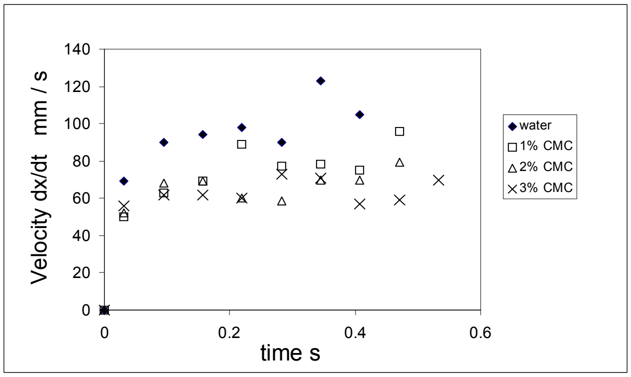

Figure 6 - Average droplet velocity x - direction 1%, 2%, 3% CMC as a function of time

In each case the theoretical peak velocity value, Table 2 is higher than the experimental value for every solution. The experimental peak velocity was expected to be higher than the predicted value since the electric field would tend to enhance the acceleration of each drop One explanation is that the drops relax very quickly, thus losing charge very quickly after detachment. Another factor, requiring further investigation, is the influence of drop polarisation. Under certain conditions especially in a non-linear electrical field the net force acting on the drop can reverse direction resulting in a net upward force on the drop thus decreasing the axial velocity component in the downward direction. This is in line with recent theoretical predictions of reverse drop motion close to the charged electrodes (11).

Table 2. Terminal velocity for sugar and CMC solutions in electric field and theoretical peak velocities

Solution	Terminal Velocity [mm s^{-1}]	Peak Velocity [mm s^{-1}]
0 g l^{-1} Sugar	96.8	154
50 g l^{-1} Sugar	108.8	198
100 g l^{-1} Sugar	108.9	206
150 g l^{-1} Sugar	108.2	220
1.0 % CMC	76.0	162
2.0 % CMC	72.0	156
3.0 % CMC	59.0	144

Conclusions and Recommendations

Increases of the drop viscosity, and the presence of non-Newtonian rheology, can inhibit drop motion in electrically charged liquid-liquid systems.

There is potential for enhancing liquid-liquid contacting by imposing an electrical charge on the dispersed phase and there are potential advantages when the dispersed phase is viscous or exhibits non-Newtonian behaviour. The ability to spray drops of viscous liquids is evident and mass transfer can be increased

The enhanced acceleration of charged drops following dispersion is not necessarily observed and the motion is influenced by a combination of factors including rheological properties, changes in oscillation behaviour, electrical relaxation, and non-linearities in the local electrical field through which the drops are moving.

Further experimentation is required to quantify the effect of a range of electrical field strengths upon drop motion in non-Newtonian system, including an examination of the effect of the properties of the continuous phase and a detailed comparison with uncharged drops of different sizes and rheological properties.

In more complex systems like systems of swarming droplets, there is inter-dependency of local mixing in the continuous phase on the droplet trajectory and droplet size occurring, which is not well understood. Not much work has been done on the backmixing occurring in these systems. The experience from the above work can be used to predict the relationship between continuous phase residence time distributions, liquid properties, drop size and trajectory, velocity and electrical field for systems of swarming drops.

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