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PROGRESS REPORT

DROP OSCILLATION AND MASS TRANSFER IN ALTERNATING ELECTRIC FIELDS

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Thomas E. Carleson, Associate Professor
Wenrui Yang, Doctoral Student

Department of Chemical Engineering
University of Idaho
Moscow, Idaho 83843

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After the second annual progress report to DOE in July 1990, we continued the experimental work for another liquid system. The mathematical model was also improved to include secondary effects due to drop deformation and charge redistribution on the deformed drop surface.

Originally, we planned to study a mass transfer process after the hydrodynamic modelling. Due to difficulty in measuring drop concentration during oscillations, we decided to study a heat transfer process instead. Using the analogy between the mass transfer and the heat transfer, we can easily extend the results for the heat transfer study to the mass transfer problem.

PROGRESS IN THEORETICAL MODELLING

In the first period of the project, we established a zero order perturbation model for a charged drop oscillating in an alternating electric field. With a zero order perturbation, the variables are accurate to zero order with respect to drop deformation, and the boundary conditions are applied at the undeformed spherical interface, which is a zero order approximation for the actual interface. The primary effects of the electric fields and the net charge can be predicted by the zero order perturbation, but the secondary effects caused by drop deformation are all neglected. Consequently, the predicted motions are independent of the magnitude of drop deformation. As the drop deformation increases, secondary effects become more and more significant, and the zero order perturbation becomes less and less accurate. Results of the zero order perturbation are discussed in more details in the attached paper, which was presented at AIChE 1990 Annual Meeting (Yang and Carleson 1990) and has been submitted to AIChE Journal for publication.

In order to include the secondary effects, a first order perturbation has to be used. Mathematical manipulation is much more complicated for a first order perturbation than for a zero order one. A symbolic manipulator (muMATH) was used to aid the derivation of the equations. In a first order perturbation, the variables are accurate to first order with respect to the deformation, and the boundary conditions are applied at a deformed interface which is also accurate to first order.

The first order perturbation model predicts that secondary oscillations may happen in four modes (first, second, third, fourth) with two frequencies for each mode. Among these eight oscillations, the second mode oscillation with twice the frequency of the electric field is the most significant one. Its contribution to the overall second mode oscillation increases with electric field strength and the net charge density and may

become comparable to that of the primary oscillation. Other secondary oscillations are much smaller and are insignificant in comparison with the primary oscillations.

The secondary contribution to the second mode oscillation not only affects the amplitude of the oscillation but also affects the resonant behavior. As the intensities of the electric stresses increase, the scanning frequency response curve shifts in the direction of decreasing frequency while at the same time it changes magnitude. This trend agrees qualitatively with Trinh and Wang's experimental observation for a prolate-oblate drop oscillation driven by acoustic waves (Trinh and Wang 1982). Consequently, the resonant frequency decreases with increasing electric field strength as well as with net charge density. The relation between the resonant frequency and the net charge density predicted by the present model when the viscous effects and the electric field strength approach zero agrees with Rayleigh's theory (1882) for the free oscillation of a charged inviscid drop in a small charge density range. The discrepancy in a large charge density region is probably caused by large relative significance of the secondary oscillation. Viscosities of the fluids have large influence on the secondary oscillation. The relative significance of the secondary oscillation decreases with increasing viscous effects. Therefore, the first order perturbation method can be used in a larger range of electric field strength and net charge density with fluids of larger viscosities. The first order perturbation is discussed in more details in a paper which will be presented at AIChE 1991 Annual Meeting in Los Angeles.

PROGRESS IN EXPERIMENTS

In the second annual progress report (July, 1990), we described experimental results for a fluid system of a water drop (with 0.3 g NaCl in 100 ml water) in a mixture of a silicone fluid (350 cSt) and tetrachloroethylene (C_2Cl_4 , 7.0% wt.). There was no resonant peak for the second mode oscillation for that system due to a large viscous effect in the continuous phase. In order to observe the resonant peak, experiments were conducted for a second fluid system with the same water drop in a mixture of a silicone fluid (50 cSt) and tetrachloroethylene (9.5% wt.).

Experiments were conducted to observe the relationship between the oscillation amplitude and the electric field strength as well as the net charge density. The scanning frequency response curves were also recorded. For this system, a resonant peak appeared for the second mode oscillation. All the experimental results agreed very well with the theoretical predictions.

Originally we planned to study the effects of the electric fields on the mass transfer

process. An experimental study on the mass transfer involves measuring composition of the drop phase during the oscillations. This requires that samples of the drop phase be taken during the oscillations so that the end effects due to drop formation and coalescence can be excluded. Because there is no proper way to do this, an experimental study on the mass transfer is very difficult to carry out. On the other hand, a heat transfer study can be done by using Thermochromic Liquid Crystal particles. A TLC exhibits different colors at different temperatures in a proper temperature range. These TLC particles can be mixed with the liquid to indicate the temperature distribution. By detecting the color of the TLC particles in the drop, we can measure the drop temperature while it is oscillating. The results of the heat transfer measurements can be extended to mass transfer using the analogy between mass transfer and heat transfer.

The experimental set-up for the heat transfer study involves an optical system for the generation of a light sheet to illuminate a slice of the drop, a square glass column with a special nozzle to hold the liquid system and to generate drops at a different temperature from the continuous phase, and a camera to take color pictures in the direction perpendicular to the light sheet. The moving-camera method which has been used successfully in the hydrodynamic study will be used here to record drop colors at a constant time interval so that the rate of temperature variation can be calculated. The apparatus is under construction. We expect that the study will last for more than a year. A request for extending the project for another year is being submitted with this report.

REFERENCES

Rayleigh, J. W. S. 1882, *Phil. Mag.* **14**, 184-186.

Trinh, E. and Wang, T. G. 1982, *J. Fluid Mech.* **122**, 315-338.

Yang, W. and Carleson, T. E. 1990, *Proceedings of AIChE 1990 Annual Meeting*, paper 259B.

WORK PROPOSED FOR THE EXTENDED PERIOD OF THE PROJECT

In the proposed extension period, we will continue the experimental study of the effects of the electric field on the heat transfer process. A nozzle with a water jacket will be built so that the temperature of the incoming drop phase can be adjusted by water running in the jacket. As the drop oscillates in the medium, its temperature changes with time. The temperature of the drop is indicated by the color of Thermochromic Liquid Crystal particles dispersed in the drop phase. The moving-camera method will be used to record the color change of the TLC particles. An optical system will be built to convert the light from a strobe into a thin light sheet so that only a slice of the drop will be illuminated. To do this, the light from the strobe will first be focused and collimated and then transformed into a sheet by passing it through a cylinder lens. The thickness of the light sheet can be finally adjusted by a slit. The experimental results will be correlated to the flow field predicted by the hydrodynamic model. Attempts will also be made to explain the results with existing heat/mass transfer models for oscillating drops.

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