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D. W. DePaoli[a]; O. A. Basaran[a]; J. Q. Feng[b]; T. C. Scott[a]
[a] Chemical Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN [b] Department of Chemical Engineering, University of Tennessee, Knoxville, TN

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FORCED OSCILLATIONS OF PENDANT DROPS

D. W. DePaoli,[1] O. A. Basaran,[1] J. Q. Feng,[2] and T. C. Scott[1]

[1]Chemical Technology Division
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, TN 37831-6224

[2]Department of Chemical Engineering
University of Tennessee
Knoxville, TN 37996

ABSTRACT

The efficiency of droplet/bubble breakup in multiphase contactors can be increased by applying external fields at resonance frequencies of the drops/bubbles. Experimental and theoretical techniques, developed for the study of forced oscillation of pendant drops on nozzles, are used to gain a fundamental understanding of drop response as a function of forcing frequency. Preliminary results of drop oscillations caused by electrical and flow perturbation techniques indicate that the relationship of resonance frequency to drop size for a given fluid system is not affected by the means of excitation. Computational techniques may be used to gain insight into phenomena which are difficult to probe by experiment, such as internal flow fields. The understanding gained by use of these techniques will be indispensable in design and operation of future multiphase contacting devices.

INTRODUCTION

The performance of multiphase separations equipment, such as liquid-liquid extractors, spray towers, and bubble columns, is dependent upon the intimacy of contact

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of the two phases. One means of increasing mass transfer rates is to produce smaller droplets or bubbles, thereby providing greater amounts of interfacial area per unit volume. This is commonly achieved by intense agitation or high-velocity spray from fine nozzles, but the desired drop or bubble size reduction may also be achieved with lower power requirements by applying external fields, such as electrical, mechanical, or acoustic fields, to the dispersed-phase fluid entering the device.

Significant examples of this approach for fine droplet production include the emulsion-phase contactor (EPC) (1) and the electric dispersion reactor (2) which use high-voltage direct-current (DC) fields to disperse a conductive liquid into a nonconductive continuous phase. The EPC has been shown to provide multistage extraction performance, with energy requirements three orders of magnitude lower than stirred contactors (3). To date, the EPC approach has been employed in two industrial applications: a commercial device for automated extraction of aqueous samples for contaminant analysis (4) and a column for removal of catalyst poisons from methyl tertiary butyl ether reactor feed (5).

A means to further improve such devices is to determine relationships between the properties of the fluids being contacted and the frequency of the applied field which minimizes power consumption required for drop/bubble breakup. The bubble size of air injected into flowing water has been shown to be a function of flow pulse frequency (6), while the field strength required for breakup of drops exiting a nozzle using an electric field has also been shown to be frequency dependent (7). These results suggest that breakup at a nozzle may be most effectively achieved by applying external forces at resonance frequencies of the droplets exiting the nozzle, in similar fashion as has been shown for enhancement of heat transfer and breakup of free drops (8,9).

Our previous work (10) was aimed at experimentally measuring the resonance frequencies of pendant droplets subjected to periodic mechanical forces generated by small flow perturbations. The results indicated that resonance frequencies of drops are greatly affected by the presence of a solid support. Qualitative agreement was found with the analytic theory of Strani and Sabetta (11), with better agreement for drops whose radii are large in relation to those of the nozzles. The restrictive geometry of Strani and Sabetta's analytic theory, particularly the requirement of a spherical bowl-shaped support of the same radius as the drop, limits its application to more practical problems; thus, numerical simulations are necessary [see, e.g. (12,13)].

This paper presents an extension of our previous work, providing experimental measurements of resonance frequencies of drops excited by electrical means as well as by the flow-perturbation technique used in the earlier work (10). In addition, numerical techniques have been developed to solve the nonlinear viscous-flow problem of drop oscillations induced by each of these excitation techniques for practical geometries. Preliminary results of the experiments and computations are presented for a liquid-in-air system.

METHODS

Problem Definition

Figure 1 shows a conceptual drawing of the system treated by theory and experiments. A drop of density ρ, viscosity μ (and kinematic viscosity ν), surface tension σ, and volume V is suspended on a nozzle with outside radius R. The drop shape in the absence of external forces will be a spherical section, while gravitational acceleration g causes the drop to deform in a prolate shape. Upon action of an external force, the drop will oscillate about this equilibrium shape.

As detailed in a separate paper on free oscillations of pendant drops on rods (13), the system may be concisely described using dimensionless parameters. The length scale is taken to be the nozzle radius R, while the time scale is defined by $(\rho R^3/\sigma)^{1/2}$. Using these bases, the Reynolds number is defined as $Re \equiv (1/\nu)(\sigma R/\rho)^{1/2}$, and the gravitational Bond number, signifying the importance of gravitational force relative to surface forces, is defined as $G \equiv \rho g R^2/\sigma$. In addition, the size of the drop relative to the nozzle can be described in terms of a spherical section having the same volume as the pendant drop. The drop size parameter, $\alpha = h/D$, where h is the vertical distance between the center of the spherical section and the nozzle outlet and D is the radius of the spherical section, is especially convenient; its values range from $\alpha = -1$ for an infinitesimally small volume extending out of the nozzle to $\alpha = 0$ for a hemisphere to $\alpha = 1$ for an infinitely large drop. Frequency of oscillation may be made dimensionless by multiplying by the time scale; hence, the dimensionless frequency is $\omega = 2\pi f(\rho R^3/\sigma)^{1/2}$, where f is the frequency in Hz.

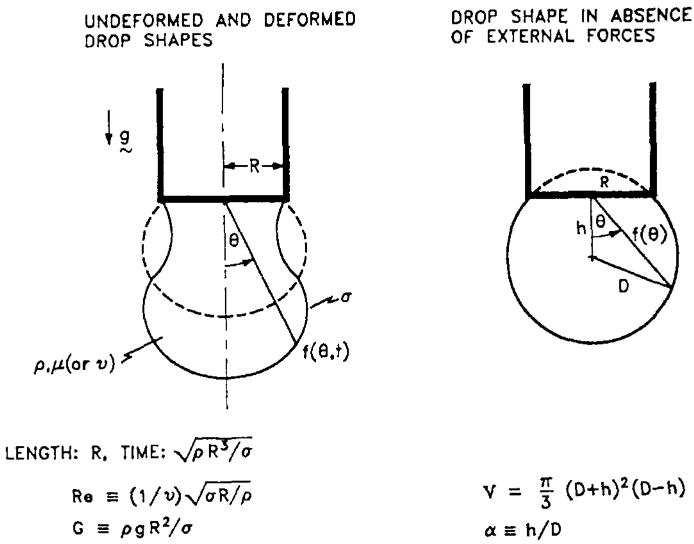

Figure 1. Oscillating pendant drop: definition sketch, scaling parameters and dimensionless groups.

Experimental

Figure 2 shows a schematic of the apparatus assembled for these studies. The grounded 15-cm-long nozzle supporting the drops was positioned perpendicular to, and coaxial with, a 7.6-cm-diameter circular metal electrode. The nozzle-electrode separation was approximately 2.2 cm. These items were held in a cylindrical enclosure with a 10-cm inside diameter constructed from polyvinyl chloride and Teflon®. The nozzle was connected by 0.3-cm-diameter tubing to a micrometer syringe. A portion of this was flexible silicone tubing, held by a vibrational transducer controlled by a 25-W amplifier with frequency range of 2 to 20,000 Hz (Alpha-M, models AV-6 and OC-25). The electrode was connected to a high-voltage pulse generator (Velonex, model 660). An oscilloscope (Nicolet, model PRO50) was used to measure the frequency of each forcing function. Two video cameras (Tri-Tronics Inc. model PCSM-5600) were used in the experiments. Images of each entire drop were collected using a frame grabber board (Data Translation, model DT2851) installed in a personal computer. The images were

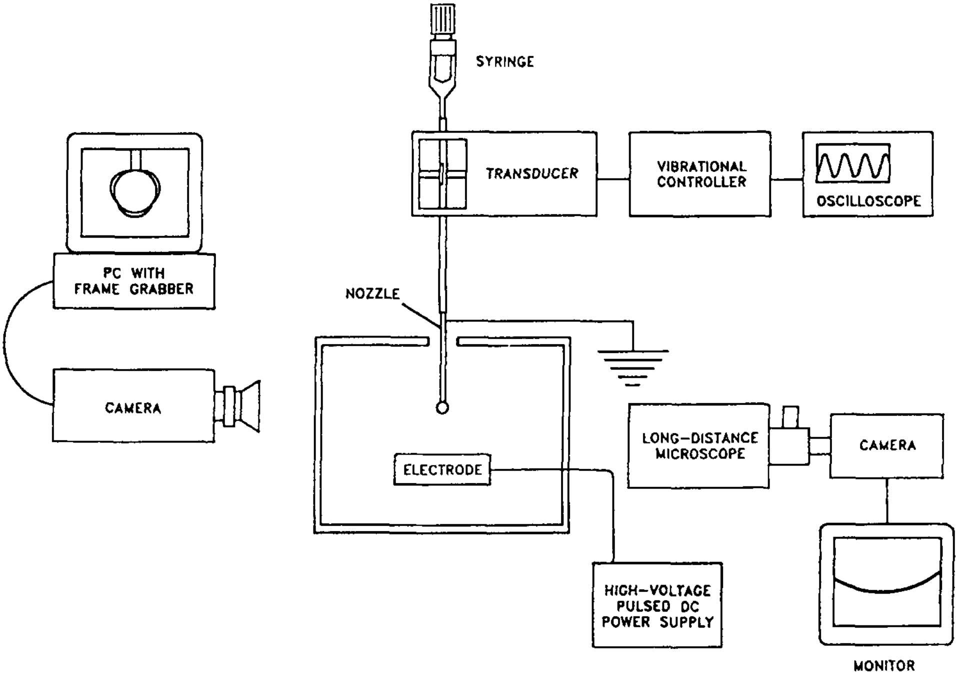

Figure 2. Experimental apparatus for study of pendant drop oscillations driven by electrical and mechanical means.

processed using a calibration of vertical and horizontal pixel values to yield the volume of the axisymmetric drop. The motion of the bottom tip of the drop was detected using the image obtained by a long-distance microscope (Questar, model QM-100) with a field of view of less than 1 mm. Thus, very low amplitude oscillations could be detected.

Experiments were conducted by metering a drop at the tip of the nozzle using the syringe. Care was taken to remove bubbles present in the tubing. An image of the drop was collected for size measurement prior to oscillation; then the power supply for either the electrical or mechanical excitation was activated at low amplitude. The frequency and amplitude of excitation were adjusted until motion of the interface was detected. The amplitude was decreased until motion was barely detectable, then the frequencies at which motion of the interface was maximized were recorded. An image of the drop was collected after oscillation for size measurement.

Theory

The details of the dynamic behavior of forced pendant drop oscillations are modeled here by means of finite-element computations. The solution strategy used in modeling oscillations forced by means of electrical and flow perturbation is summarized in Figure 3. In each case, the nonlinear Navier-Stokes system is solved for viscous flow within the liquid drop and a finite section of nozzle. The surrounding fluid in each case is a gas of negligible density and viscosity.

When the external forcing comes from a periodically applied electric field, the problem is modeled as a drop held on a nozzle attached to the top plate of a parallel plate capacitor. The top electrode and nozzle are grounded, while a sinusoidally varying voltage $V(t)$ is applied to the lower electrode,

$$V(t) = V_o \sin(2\pi F t) \tag{1}$$

where V_o is the peak voltage, t is time, and F is the frequency of the applied voltage in Hz. This problem is solved by tessellating regions both inside and outside the drop into a set of quadrilateral elements. With finite-element basis functions and Galerkin's method of weighted residuals, spatial variations of field variables are discretized. Thus, the original nonlinear partial differential equations of the Navier-Stokes system, governing the flow field inside the drop, and the Laplace system, governing the electric field outside the drop, are transformed into a set of nonlinear differential-algebraic equations. Following the procedure known as the method of lines, the time derivatives are approximated by finite differences and the differential-algebraic system becomes a set of nonlinear algebraic equations that can be solved iteratively using an advanced workstation or large mainframe computer.

When the external forcing comes from a periodic flow up and down the nozzle, the system is simplified somewhat to include only the volume bounded by the nozzle and the free liquid surface. The forcing function is expressed as a flow velocity field applied at a location upstream of the nozzle outlet,

$$v_z(x,t) = v_o(1 - x^2)\sin(2\pi F t) \tag{2}$$

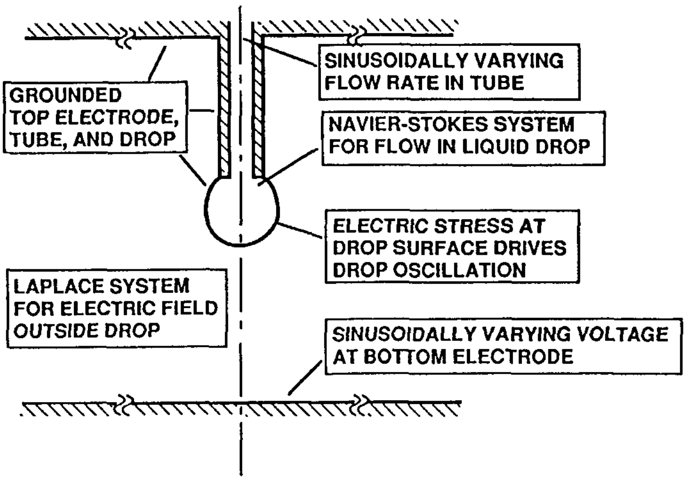

Figure 3. Physical principles for numerical modeling of driven pendant drop oscillations.

where $v_z(x,t)$ is the vertical velocity of the fluid at radial position x within the nozzle at time t, v_o is the maximum velocity, and F is the forcing frequency. The solution procedure for this case is similar to that for the electrical excitation, without the complication caused by coupling of the electrical field, the flow field, and the drop shape.

RESULTS AND DISCUSSION

Figure 4 presents photographs of pendant water droplets undergoing forced oscillations in air. The upper images were collected by an unshuttered video camera during flow-induced oscillations, showing the maximum extents of drop deformation. The left "single-lobed" oscillation is from the lowest frequency resonance mode, while the right "two-lobed" oscillation is from the second-lowest resonance mode. These general shapes of the first two modes of oscillation are similar to those calculated for the system of Strani and Sabetta (11). The lower images are consecutive frames of a small water drop at a 1-ms interval, collected by a Kodak Ektapro EM Motion Analyzer during

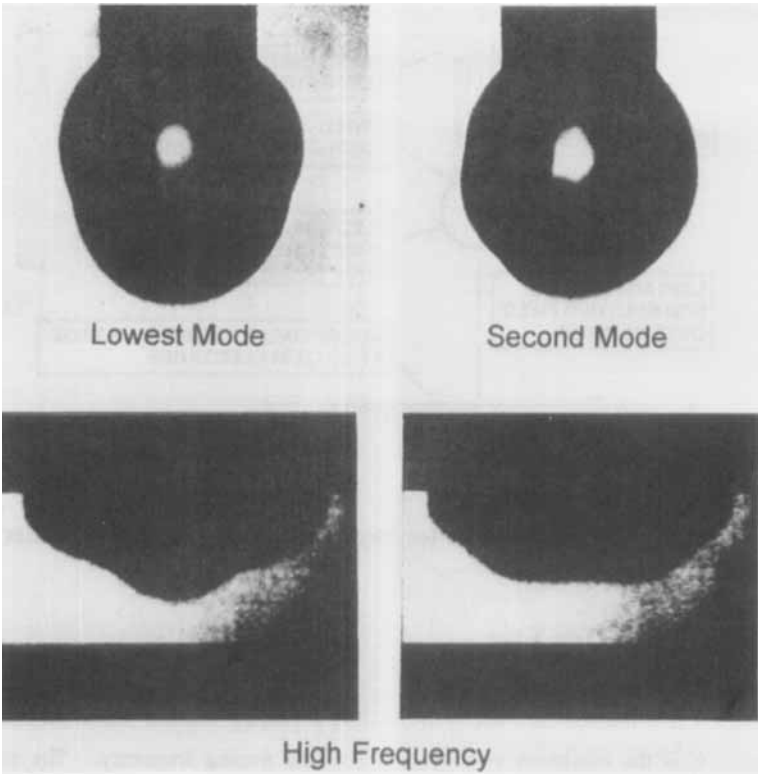

Figure 4. Photographs of pendant water drops undergoing forced oscillations.

high-frequency, high-amplitude electrical excitation. These frames show the more complex shapes that may arise in nonlinear oscillations. At higher electrical field strengths, droplets are ejected from the "nipple" (cf., 14) shown in the left frame.

Figure 5 presents results of forced oscillation experiments conducted with drops of a mixture of 70% glycerine and 30% water held on a 0.159-cm-outside diameter, 0.0508-cm-inside diameter nozzle so that Re=9 and G=0.11. The plot presents dimensionless frequency of the lowest mode of oscillation as a function of the drop-size parameter. Oscillation frequency is shown to be a strong function of drop size, with larger drops exhibiting lower resonance frequency. The frequency/size relationship for electrical excitation is indistinguishable from that for mechanical excitation, despite the different

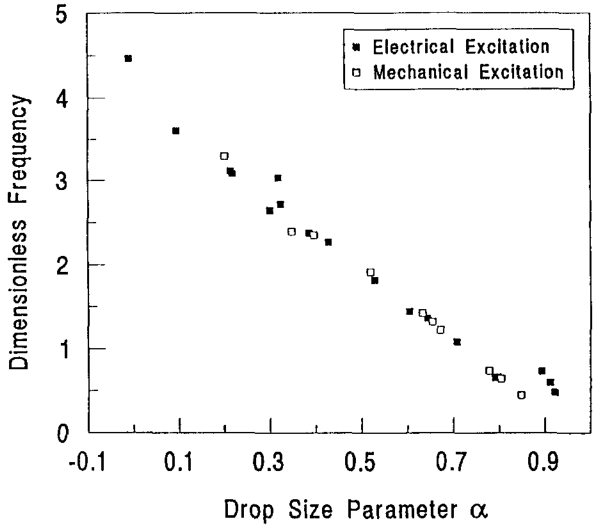

Figure 5. Experimental results showing effect of drop size upon the resonance frequency of the lowest mode of oscillation of pendant drops subjected to electrical and mechanical excitation; Re=9, G=0.11.

means by which the forces induce drop motion. This agreement indicates that the resonance frequency is a function of the fluid properties and geometry and is not greatly affected by the physical character of the low-amplitude perturbation. Of interest for further experimentation to test this agreement are higher amplitude oscillations and variation of the electrical Bond number (indicating the relative importance of electrical forces and surface tension).

When a voltage is applied at the bottom electrode, while the top electrode, nozzle, and drop are all connected to electrical ground, an electric field is generated around the conducting drop. As shown in Figure 6, calculated equipotential contours are not distributed uniformly along the pendant drop surface. Hence, the drop may be deformed and forced to oscillate by the electric field. Computations of electric field distribution such as shown in Figure 6 may lead to improved nozzle/electrode designs (14,15).

Figure 7 shows the results of finite element computations for flow fields inside a pendant drop at various stages within an oscillation cycle when driven by a sinusoidally

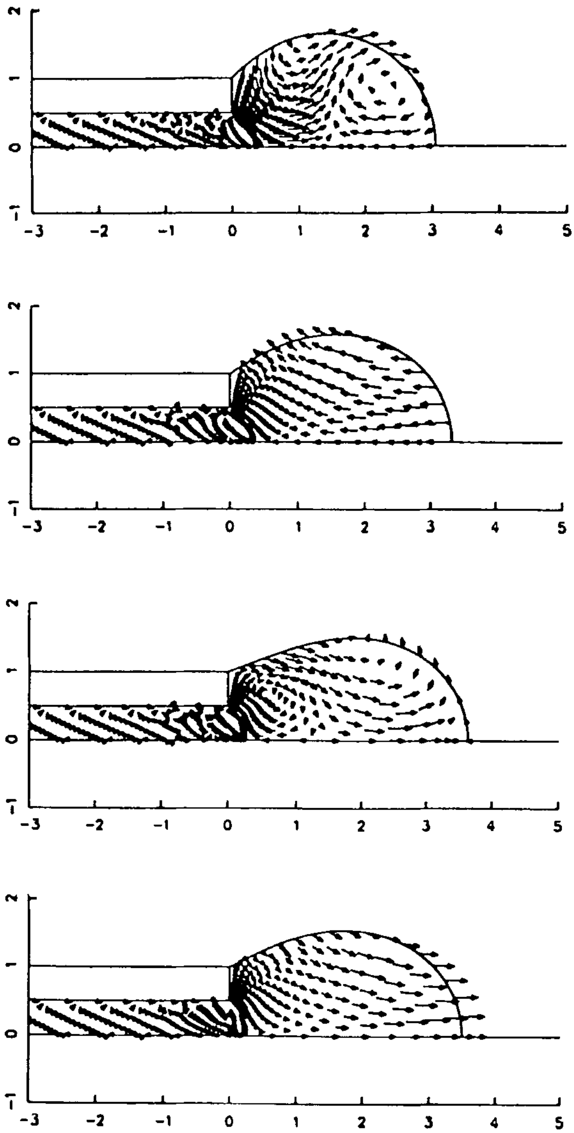

Figure 6. Calculated electric potential distribution surrounding a pendant drop during electrical excitation.

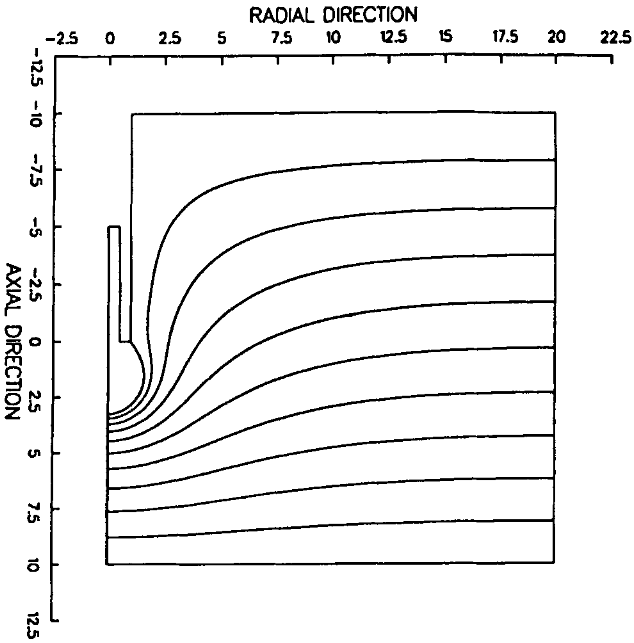

Figure 7. Flow fields within a pendant drop during electrically driven oscillations. Results are shown for dimensionless times of 37.621, 39.121, 41.621, and 43.421.

varying voltage. The parameters for this simulation are Re=10, G=0.1, and $\alpha=0.8$, with a dimensionless driving frequency of 0.75. The first frame shows the drop at a point in time when it is nearing maximum extension. The velocity vectors are uniformly directed in bulk motion. The second frame shows the velocity field at a slightly later time as the drop has passed through its point of maximum extension. Viscous and inertial effects in the drop prevent it from uniformly reversing the direction of flow, and a pair of vortices are formed. The next frame indicates a later point at which the entire flow field is directed upward. The final frame shows that as the drop passes through the point of minimum extension, a pair of vortices are again formed. The vortices lead to mixing within the drop and would not be predicted were the flow approximated as inviscid (cf., 11).

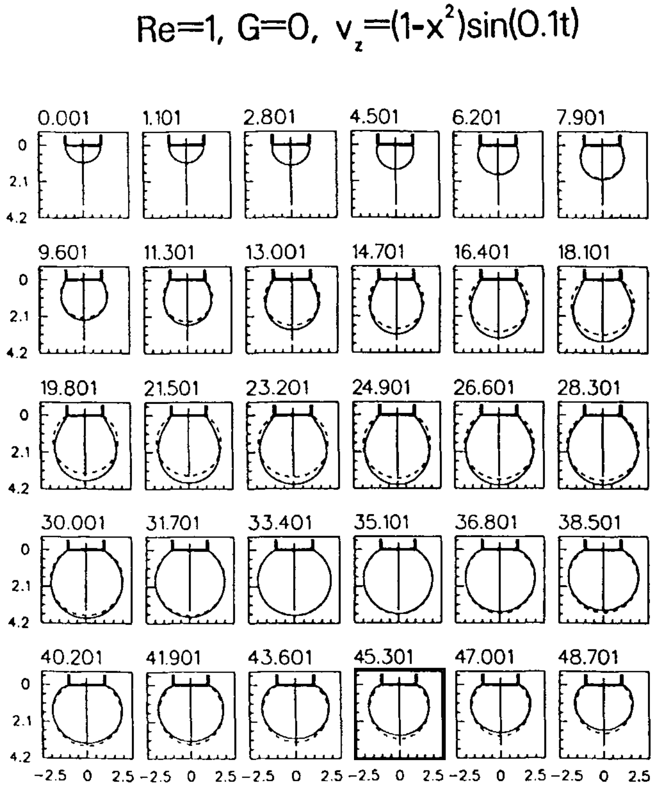

Figure 8. Calculated drop shapes of a pendant drop during large-amplitude flow perturbation. The solid line in each frame is the drop surface, while the dotted line represents the shape of a spherical section having the same volume as the drop.

Figure 8 presents a time series of droplet shapes for a case of high viscous forces (Re= 1), no gravitational forces (G=0), and high-amplitude flow perturbation. The drop shape deviates from the equilibrium shape due to the flow, with the drop extended farther than equilibrium during drop growth and extended less during drop shrinkage. These plots for a greatly exaggerated flow perturbation clearly indicate the driving force for oscillation by this technique; in experiments, amplitude is maintained at a low level such that motion of the interface is not detectable except at resonance conditions.

CONCLUSIONS

Techniques have been developed for the study of forced oscillation of pendant drops on nozzles. Experiments indicate that the relationship of low-amplitude resonance frequency to drop size is independent of the physical means of excitation. Computational capabilities have been developed to match experimental conditions. These computational tools will provide means for probing details of oscillations that are difficult to determine experimentally, such as internal flow fields, and they will be useful for prediction of pendant drop response for any fluid properties.

Present work involves detailed comparison of experiments and theory for validation of the computational methods. Future work will be aimed at the dynamics in liquid-liquid systems, and upon mass transfer. Experiments will also be aimed at relating resonance frequencies of pendant drops to breakup. Such information will be useful in design and operation of future multiphase contacting equipment.

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