The impact of external electrostatic fields on gas–liquid bubbling dynamics

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Abstract

The effect of an applied electric potential on the dynamics of gas bubble formation from a single nozzle in glycerol was studied experimentally. Dry nitrogen was bubbled into glycerol through a nozzle having an electrified tip while pressure measurements were made upstream of the nozzle. As the applied electric potential was increased from zero, bubble size reduced, bubble shape became more spherical, and bubbling frequency increased. At constant gas flow, bubble-formation exhibited a classic period-doubling route to chaos with increasing potential. We defined an electric Bond number assuming that both the liquid and gas phases are conducting. This is in contrast to previous studies where one phase was considered a perfect conductor and the other one a perfect nonconductor or insulator. Although electric potential and gas flow appear to have similar effects on the period-doubling bifurcation process for this system, the relative impact of electrostatic forces, as measured in terms of electric Bond number for conducting liquid and gas phases, is smaller. However, the relative impact of electrostatic forces for the case of insulating liquid and conducting gas phases is comparable to flow forces. Further data collection is required for different nozzle geometries and liquid column heights in order to verify the relative impacts of electrostatic and flow forces, and would allow us to ascertain if electrostatic potential is a feasible manipulated variable for controlling this system.

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1. Introduction

Although gas–liquid bubbling can seem to be a simple phenomenon, it actually involves complex dynamical interactions. Such bubbling is a major component of a wide range of chemical and environmental processes. Typically, one expects that the most efficient gas–liquid processes have small bubbles, since greater interfacial area increases inter-phase heat and mass transfer. One might also expect that bubbles are of uniform size which will simplify control and predictability. However, in reality, gas–liquid bubbles generally have broad size distributions and complex property variations over time (e.g., Kikuchi et al., 1997; Fémat et al., 1998; Luewisuthichat et al., 1997).

Bubble formation has been the subject of numerous studies (e.g., Tsuge, 1986; Deshpande et al., 1991; Longuet-Higgins et al., 1991; Drahoš et al., 1992; Terasaka and Tsuge, 1993). One key finding from those studies is that bubble-to-bubble interactions create instabilities leading to bifurcations and chaos. At low gas flow rates, bubbling is regular and periodic, but it becomes increasingly irregular with increasing flow. In their classic paper, Davidson and Schüler (1960) were among the first to use high-speed photography to study the interaction and coalescence between leading and trailing bubbles. More recently Leighton et al. (1991) illustrated the complicated hydrodynamic phenomena present in bubbling through high-speed imaging and acoustic signatures. Other investigators identified different regimes of bubbling, defined by dimensionless groups and characterized by different amounts of interactions between forming bubbles (Miyahara et al., 1984; Tsuge, 1986). Predictive models have been developed based on a simple
description of the interaction between a primary bubble and subsequent bubbles at higher gas flow rates (Deshpande et al., 1991; Ruzicka et al., 1997; Ruzicka, 2000).

With the availability of better experimental measurements and improved nonlinear dynamics analysis tools, additional progress has been made in understanding the nature of bubbling instabilities. Deterministic chaos in bubbling was first reported by Tritton and Egdell (1993), who studied air injected from a single submerged orifice in water–glycerol mixtures. In these studies, Tritton and Egdell reported a period-doubling bifurcation with increasing air flow. Mittoni et al. (1995) subsequently reported deterministic chaos in a similar system under a range of conditions by varying chamber volume, injection nozzle diameter, liquid viscosity and gas flow rate. Nguyen et al. (1996) further identified the spatio-temporal aspect of chaotic bubbling; noting that bubble-to-bubble interactions propagate long distances. This research clearly observed period-8 behavior. A simple model was also used that gave a good representation of the attractor behavior. Such spatial interactions reduce the directness of the analogy between bubbling and the classical dripping faucet.

In other studies, the effects of external perturbations, such as flow and acoustic pulsations, have been examined (e.g., Fawkner et al., 1990; Cheng, 1996). In some cases such perturbations have led to control schemes. Most notably, Tufaile and Sartorelli (2000, 2001) reported the capability to transform a chaotic bubbling state to a periodic state by the application of a synchronized sound wave. Zaky and Nossier (1977) first reported the effect of an electric field on bubbling, noting a decrease in bubble size and an increase in pressure with increasing voltage for bubbling of air into transformer oil and \( n \)-heptane through an electrified needle. Further studies by Ogata et al. (1979, 1985), Sato et al. (1979) and Sato (1980) showed that by the application of a few kilovolts, bubble size can be reduced from a few mm to less than 100 \( \mu \)m in many liquids, including nonpolar fluids like cyclohexane and polar compounds such as ethanol and distilled water. Sato et al. (1993) reported similar results for liquid–liquid systems in which the time scale of electrical charge relaxation (i.e., permittivity/conductivity) of the injected fluid is greater than that of the continuous fluid. This type of dispersion has been termed inverse electrostatic spraying (Tsouris et al., 1998) to differentiate it from the well-studied normal electrostatic spraying (Grace and Marijnissen, 1994). Several practical applications have been suggested for this type of spraying, including generating fine bubbles for flow tracers (Sato et al., 1979), enhancing gas–liquid reactions (Tsouris et al., 1995), and producing uniform microcapsules (Sato et al., 1996).

Two main contributing phenomena have been identified for bubble formation in the presence of electric fields, electric stress and electrohydrodynamic flow. Electric stress acts directly at the gas–liquid interface of growing bubbles and is directed inward (Tsouris et al., 1994). This force is manifested by an increase in nozzle pressure with an increase in applied voltage. Above a critical voltage (that depends on nozzle geometry and fluid properties), electrohydrodynamic flows are induced in the bulk fluid (Sato et al., 1979, 1993, 1997). These flows have a toroidal shape with a high magnitude near the injection nozzle and move outward from the points of highest field gradient. Under conditions of electrohydrodynamic flow, a significant decrease in nozzle pressure is exhibited with increasing voltage (Tsouris et al., 1998). The dynamics of electrified bubbling are complicated by the interactions of these mechanisms. Sato et al. (1979) described three regimes of bubbling: periodic bubbling, dispersed bubble production, and a high-voltage region characterized by sparking and larger bubble production. Similarly, Shin et al. (1997) outlined three bubbling modes—dripping, an erratic mixed mode, and a spraying mode.

To date, no detailed study of the dynamics of electrified bubbling has been conducted. For example, it has not been verified that the regimes characterized as periodic are truly periodic, nor are there any detailed analyses and/or means of prediction of the transitions from periodic bubbling. Beyond its intrinsic scientific value, such information would be highly valuable in guiding the development of methods for controlling bubbles size distribution.

In the present study, the effects of an applied electrostatic potential on bubbling dynamics were determined experimentally. Bubbles were formed in a viscous liquid (glycerol) such that electrohydrodynamic flows were negligible and the main electrostatic mechanism affecting bubbling was the electric stress at the gas–liquid interfaces of the forming bubbles. To keep the analysis reasonably straightforward, bubble formation from only one submerged nozzle was examined. The dynamics were characterized using pressure measurements upstream from the injection nozzle. The combined effects of gas flow and applied voltage were evaluated.

In the following section we describe the experimental setup. Subsequently, we show results from the data analysis and discuss their implications. Finally we offer conclusions and propose future directions for research.

2. Experimental setup

A schematic of the experimental apparatus (Sarnobat, 2000) is shown in Fig. 1. The apparatus consisted of a glass bubbling column, a gas metering system, a pressure transducer for monitoring the response of the system, a high-voltage, direct-current power supply for maintaining a potential difference between the nozzle and a ground electrode immersed in the liquid, and a data acquisition system.

The experiments were conducted in a square glass column (4 cm × 4 cm in cross-section, 27 cm in height) into which gas was injected through a central vertical nozzle having an electrified metal tip. The column was filled with
99.98% pure glycerol to a level 21.6 cm above the tip of the nozzle which protruded 3.5 cm from the column base. Dry nitrogen from a compressed gas cylinder formed the bubbles. The column was operated at atmospheric conditions, and the gauge pressure measured in the tubing immediately upstream of the nozzle served to characterize the bubbling.

The gas train used in the experiments was similar to those used in previous studies (Nguyen et al., 1996). It consisted of two pressure regulators, a rotameter with a stainless-steel float (Shor-Rate II, tube number R-2-15-D, Brooks Instruments), piezo-electric valve (MaxTek MV-112), flow sensor (Cole-Parmer 8168), high-speed pressure transducer (Setra Systems 228), a Nupro double cross metering valve (with a maximum $C_v$ of 0.004 for flow control), and a ball valve connected in series. This system supplied measured gas flow rates covering a range of 10–500 cc/min. The tubing volume from the piezo-electric valve to the nozzle was minimized to reduce the dynamics of gas compression.

Details of the nozzle design are shown in Fig. 2. The nozzle was constructed from 6.35-cm-o.d. Lucite tubing. A 6.35-cm-o.d., 1.0-mm thick brass orifice plate was secured at the end of the nozzle. This plate could be electrified by a 22-gauge, uninsulated copper wire passing through the nozzle to a connector on the gas inlet line.

An orifice diameter of 0.75 mm was used to avoid indistinct return maps that have been obtained with larger orifice diameters (Mittoni et al., 1995). Preliminary experiments with applied electrostatic potential conducted in this study using a 1.0-mm orifice obtained results with irregular spikes and peaks in the pressure time series. Three design features allowed the system to be operated such that liquid that may have weeped through the orifice during setup could not adversely affect the results by causing intermittent bubbling. These were the relatively large inside diameter of the nozzle tube, a tee-bend in the gas inlet, and a drain valve.

A high-voltage, direct current power supply (model 225-50R, Bertan High Voltage Corp.) was connected to the nozzle tip with positive polarity. A 3.2-mm-diameter stainless steel rod immersed 2.5 cm into the upper surface of the glycerol served as the counter electrode and was connected to electrical ground. The electrode was not inserted farther into the liquid in order to minimize the electrode surface area in contact with the liquid. With this configuration, a potential of approximately 13 kV could be attained at the nozzle tip before the 0.3-mA current safety limit of the power supply was reached.

A capacitive transducer (model 228, Setra Systems Inc.) having a range from 0 to 1 psig was used to measure the pressure in the gas line upstream of the nozzle. The output from the pressure transducer was a 0–5 V DC analog signal, which was fed through a signal conditioning card signal amplifier to a data acquisition board (models SC-2043-SG and PCI-MIO-16E-50, National Instrument) in a 300-MHz Pentium II™-based personal computer. National Instruments Labview™ 5.1 was used as the data acquisition software.

For consistent experimental results, a fresh batch of glycerol was used for each run. Each run consisted of data collected at a specific flow rate and changing the applied voltage in increments of 1 kV from 0 V to 10 kV. Time intervals of 300 s were provided between successive readings. The pressure data were collected for 50 s at 2000 or 5000 Hz at each set of experimental conditions.
3. Data analysis

The following data analysis techniques were used for the characterization of nonlinear bubble-formation dynamics.

*Power spectra*: The classical linear method of Fourier analysis was used to transform the time-series information into the frequency domain, which has been shown to be sensitive to changes in periodicity (Fémat et al., 1998). Although not definitive for nonlinear time series, the power spectra yield useful information for continuous physical systems as a pointer to the relevant time scales and the choice of parameters in nonlinear time-series analysis.

*Delay embedding*: We used the delay embedding (Takens, 1981) of pressure measurements to characterize the attractor. Given the set of measurements \( \{x_i| i = 1, \ldots, n\} \), the sequence of vectors formed as \( x_j = [x_j, x_{j+1}, x_{j+2}, \ldots, x_{j+(m-1)\tau}]^T \) (where \( j \) is a time index) can be used to reconstruct the dynamic trajectory of the system. Takens (1981) proved that if some \( m \) is sufficiently large, the embedding vectors preserve the geometrical properties and invariants of the system. Our observations indicated that typically an embedding dimension of 5 and delay of 35 are appropriate embedding parameters for resolving the injected bubble patterns. We also apply local principal component analysis (PCA) to the embedded data to allow the resulted to be projected into two or three dimensions for easier viewing.

*Period-doubling bifurcation and route to chaos*: Bifurcation plots have been widely used (e.g., Nguyen et al., 1996; Tufaile et al., 1999; Tufaile and Sartorelli, 2001) to illustrate the onset of complex dynamics as a result of variation in some process input variable. For the bubbling process, the changes were quantified in terms of the period of formation of the bubble. In the context of this experiment, a plot of bubbling rate (or period of bubble formation) against the gas flow rate or the electrostatic potential is a bifurcation diagram. We also generated three-dimensional bifurcation plots involving both system variables—gas flow rate and electrostatic potential—to illustrate the simultaneous effect of electrostatic potential and flow rate on bubble formation.

*Time return maps*: Time return maps (Moon, 1992) were used to condense the information of time series and to help determine the periodicity of the system. Period-of-formation intervals were generated by measuring the peak-to-peak time intervals of the pressure time-series data. A peak in the pressure trace corresponds to the beginning of bubble growth at the nozzle, and the peak-to-peak time-interval corresponds to the bubble formation time.

4. Results and discussion

Previous experimental work (e.g., Mittoni et al., 1995; Tritton and Egdell, 1993; Nguyen et al., 1996; Tufaile and Sartorelli, 2000) has shown that as gas flow is increased, bubble formation undergoes a bifurcation process that is readily detected by observing variations in bubble size and speed. At low flow, it is observed that a regular train of identical bubbles is produced. In addition to being of equal size,
the bubbles are formed and released in equal time intervals. In our apparatus, the sequence of identical bubbles produces a train of identical pressure peaks in the nozzle (Fig. 3a). Increasing gas flow increases the frequency of bubbling and leads to interaction between bubbles (Fig. 3b). Specifically, trailing bubbles are accelerated by the wakes of preceding bubbles. At the nozzle, this gives rise to the formation of two alternating size bubbles (period-2), and the pressure pulses contain two distinct alternating peaks (Fig. 3c). With still greater gas flow, the system enters a state in which four distinct bubble types are formed (period-4). This period-doubling process continues progressively with increasing flow rate, finally leading to deterministic chaos.

Fig. 4 shows examples of pressure time-series data for four different flow rates that resulted in periods 1, 2, 4 and chaos. Subplots 4(a)–(d) contain 2-s pressure traces. As the flow rate is increased, the bubbling frequency increases, and the number of distinct peaks appearing in the pressure trace increase. In 4(d), the number of distinct peaks has become effectively infinite due to the onset of deterministic chaos. Under these conditions, there are never two bubbles produced with exactly the same characteristics. Figs. 4(e)–(h) show the three-dimensional delay embedding formed with the time-series segments shown in Figs. 4(a)–(d), with embedding delay of 35. The single band in Fig. 4(e), gives way to two distinct bands in 4(f)—leading from period-1 to period-2 behavior. Fig. 4(g) has four distinct bands, indicating period-4, and Fig. 4(h) has many bands with fractal structure—a sign of chaotic dynamics.

When an electrostatic potential is applied to the injection nozzle, electric stresses cause a “pinching” action on the bubbles during formation (Tsouris et al., 1994). The visual effects of applied voltage in our experiments are illustrated in Fig. 5, which compares the images of bubbles formed at a fixed flow rate under applied potentials of 0 and 12.5 kV. The images shown are at a point in time 4 ms before the bubbles detached from the nozzle. It is seen that the bubble formed with an applied voltage is smaller and more spherical. Increasing electrostatic potential hastens the detachment of bubbles, which leads to greater and more significant interactions between bubbles. These results demonstrated how increasing gas flow affects the bubbling dynamics. Now we examine the impact of increasing the electrostatic potential at a given flow rate.

Fig. 6 shows pressure traces collected at 2 kHz for bubbling at constant gas flow of 335 cc/min and multiple applied potentials of 1–9 kV (increments of 1 kV). A subtle variation can be observed in the time series in terms of an increase in the number of peaks observed, a decrease in the peak heights, and increasing irregularity in the peak heights with increasing potential. On average, the bubbling frequency also increases with increasing potential. The system is chaotic in subplots (h) and (i). Fig. 7 shows the local principal component scores for the time series in Fig. 6. Note that with increasing electrostatic potential, the banding in the plots becomes more complex and the system is chaotic for potentials of 8 and 9 kV. Fig. 8 shows the spectral densities for the time series shown in Fig. 6. The distribution becomes broader with increasing potential.

Fig. 9 illustrates an alternative approach for observing the dynamic changes induced by the electric potential in terms of the characteristic intervals between bubbles. In this figure, successive time interval values between bubbles are plotted as two-dimensional ‘return maps’ for the same conditions in Fig. 6. Initially (at low potential) we observe four distinct points corresponding to the four different bubble periods—thus the system is exhibiting period-4 behavior. As the potential increases, we observe the four points merge into a curve, representing the chaotic state. It should be noted that this curve is actually a trace of the dynamic ‘map’ of this system. In fact, a function fit through this map can provide an approximate model of the bubbling dynamics. The bubble formation interval continues to wander along this line due to the continuous state of instability driving the deterministic chaos. Although not obvious, the average inter-bubble
interval decreases from 0.11 to 0.08 s as the voltage transition is made, indicating that the bubbles produced in the chaotic state are smaller.

Fig. 10 is a bifurcation plot in which bubble formation intervals are plotted as a function of applied potential. In these experiments, gas flow was held constant, and voltage was gradually increased in steps of 1 kV. At low values of the applied potential, the system exhibits period-4 behavior as indicated by the four distinct bands of observed intervals. With increasing voltage, the period of formation of bubbles decreases and bubble size distribution becomes broader. At applied voltages between 7 and 8 kV, the bubbling becomes chaotic and there is almost a continuous range of values along a wide band. Fig. 11 shows a similar bifurcation diagram obtained at a lower gas flow. Note that although the same general trends are apparent at the two flows, the details of the bifurcations with applied potential are different.

To illustrate the combined effects of electrostatic potential and gas flow, data collected from experimental runs at different flow rates and different applied potentials were plotted on the same graph to generate a co-dimension bifurcation plot. Fig. 12 illustrates such a plot showing bubble interval as a function of the applied voltage and flow rate.

Perhaps a more useful way of mapping the two-dimensional bifurcations is to use the appropriate dimensionless flow and potentials. Tsuge’s flow number represents a ratio of the combined mechanical disruptive forces— inertia and buoyancy—to surface tension, and is defined as (Tsuge, 1986)

\[ N_w = Bo Fr^{0.5} \]  

where

\[ Bo = \frac{d_i^2 \rho g}{\sigma} \quad \text{and} \quad Fr = \frac{u^2}{d_i g} \]
Fig. 6. Pressure traces for various potentials at a fixed gas flow rate. Subplots (a)–(i) refer to potentials of 1–9 kV in increments of 1 kV. The gas flow rate was 335 cc/min.

Fig. 7. Principal component scores for various potentials at a fixed gas flow rates. Subplots (a)–(i) refer to potentials of 1–9 kV in increments of 1 kV. The gas flow rate was 335 cc/min.
Fig. 8. Power spectral density for various potentials at a fixed gas flow rate. Subplots (a) through (i) refer to potentials of 1–9 kV in increments of 1 kV. The gas flow rate was 335 cc/min.

Fig. 9. Bubbling interval return maps for various potentials at a fixed gas flow rate. Subplots (a)–(i) refer to potentials of 1–9 kV in increments of 1 kV. The gas flow rate was 335 cc/min.

and \( d \) is the inside diameter of the nozzle orifice, \( \rho \) is the liquid density, \( g \) is the gravitational acceleration constant, \( \sigma \) is the liquid surface tension, and \( u \) is the gas velocity through the orifice. \( Bo \) and \( Fr \) refer to Bond and Froude numbers, respectively. However, electric forces are also acting on the bubbles, and should be taken into account.

Now we consider the electric stress tensors, assuming the fluids are linearly polarizable (Landau and Lifshitz, 1960). If \( E_a \) is the electric field though the ambient liquid and \( E_g \) is the electric field across the gas phase, we have

\[
E_a \varepsilon_a = E_g \varepsilon_g,
\]  

(3)
where \( \varepsilon_g \) is the permittivity of the gas and where \( \varepsilon_a \) is the permittivity of ambient phase. Since

\[
E_a = \frac{V}{d_a} \quad \text{and} \quad E_g = \frac{V_i}{d_i}
\] (4)

where \( V_i \) is the potential at the interface. Eliminating \( V_i \) from Eqs. (3) and (4), we obtain

\[
E_g = \frac{V}{d_i \left[ \frac{1}{\varepsilon_a / \varepsilon_g} + \frac{1}{d_a / d_i} \right]} \quad \text{and} \quad E_a = \frac{V}{d_i \left[ \frac{1}{\varepsilon_a / \varepsilon_g} + \frac{1}{d_a / d_i} \right]},
\] (5)

where \( d_a \) is the distance from the submerged electrode tip to the nozzle and \( \varepsilon_L \) is the permittivity of glycerin. Assuming \( \varepsilon_g \equiv \varepsilon_0 \) where \( \varepsilon_0 \) is the permittivity of air, Eq. (5) reduces to

\[
E_g = \frac{V}{d_i \left[ 1 + (d_a / d_i) / K \right]} \quad \text{and} \quad E_a = \frac{V}{d_i K \left[ 1 + (d_a / d_i) / K \right]},
\] (6)

where \( K = \varepsilon_g / \varepsilon_a \simeq \varepsilon_g / \varepsilon_0 \) is the dielectric constant of the ambient phase.

If the ambient (liquid) phase is a perfect conductor, i.e., \( K \approx \infty \), and the electric field in the liquid will be zero and the liquid would be isopotential. In that limiting case, Eq. (6) becomes

\[
E'_g = \lim_{K \to \infty} \frac{V}{d_i} \left[ 1 + (d_a / d_i) / K \right] = \frac{V}{d_i} \quad \text{and} \quad E'_a = \lim_{K \to \infty} \frac{V}{d_i} = 0.
\] (6a)

The jump in the electric stress tensor at the interface would be

\[
T_e = \frac{1}{2} \left( \frac{\varepsilon_g E_g^2}{\varepsilon_a E_a^2} \right) = \frac{V^2}{2d_i^2} \left[ \frac{\varepsilon_g - \varepsilon_a / K^2}{1 + (d_a / d_i) / K} \right]
\]

\[
= \frac{V^2 \varepsilon_g}{2d_i^2} \left[ 1 - \frac{\varepsilon_a / \varepsilon_g}{1 + (d_a / d_i) / K} \right].
\] (7)

Note that if \( \varepsilon_a \gg \varepsilon_g \) and \( K \gg 1 \), Eq. (6) reduces to

\[
T'_e = \lim_{\varepsilon_a \ll \varepsilon_g, K \to \infty} T_e = \frac{V^2 \varepsilon_g}{2d_i^2}
\]

\[
= \frac{1}{2} \frac{\varepsilon_g}{d_i^2} \left( \frac{V}{d_i} \right)^2 \approx 1 \frac{\varepsilon_g E_g^2}{\varepsilon_a E_a^2}.
\] (7a)

A ratio of this stress to the stress caused by surface tension forces can be constituted as

\[
B_e = \frac{2T_e}{\sigma / d_i} = \frac{V^2 \varepsilon_g}{\sigma d_i} \left[ 1 + (d_a / d_i) / K \right],
\] (8)

which is the electric Bond number for this setup.

In the limiting case of the liquid being a perfect conductor, Eq. (8) reduces to

\[
B'_e = \lim_{\varepsilon_a \ll \varepsilon_g, K \to \infty} B_e = \frac{V^2 \varepsilon_g}{\sigma d_i} \frac{d_i}{d_a} \left( \frac{V}{d_i} \right)^2.
\] (8a)

The difference in Eqs. (8) and (8a) (or in Eqs. (6) and (6a)) is a factor for given values of \( K, d_i \) and \( d_a \). However, the definition in Eq. (8) allows us to compare the impact of electric stress as compared to surface tension for all nozzles. For low to moderately conducting liquids, placing the ground electrode closer to the nozzle (decreasing \( d_a \) would allow one to achieve higher electric stresses given the same potential difference.
Note that in this derivation, we have assumed that the electric field is normal to the interface, and the tangential components have been omitted. Regardless of the polarity, the electric field is normal to the interface and is directed inward towards the gas phase. Ideally, we should have conducted the experiment with a very small $d_a$ so that the gas phase would be the dominating resistance. However, that could not be performed as our intention was to reduce the electrode area in contact with the liquid. We also ignored the aspect ratio, as the field is normal to the interface, and the shortest path through the gas phase is the nozzle i.d.

Fig. 13 presents the bifurcation plot as a stability map in terms of dimensionless variables; specifically, the Tsuge flow number and the electric Bond number. Since both dimensionless groups are scaled against surface-tension forces, they allow comparison of the relative effect of forces caused by gas flow and those caused by the applied electric field. We note that for chaotic dynamics, the Tsuge number was 16.4 and the electric Bond number was greater than 0.2. This may indicate that electrostatic forces have greater impact on bubbling dynamics than flow forces; however, further data obtained at larger electric Bond numbers and smaller Tsuge flow numbers would be necessary to verify this assertion.

It would be desirable to define a system variable incorporating the effects of both applied voltage and flow rate that could be used as a predictor of bubbling regime. In order to capture the collective effect of electrostatic and inertial forces on bubble formation from an electrified nozzle, Shin et al. (1997) suggested a modified Weber number that is the ratio of the sum of the electrostatic and inertia forces to surface tension forces. That modified Weber number (simply the sum of electrical Bond number and Weber number) is defined as

$$W_{es} = \frac{d_1 \rho_a E^2 + u^2 d_1 \rho_a}{\sigma},$$

where $\rho_a$ is the gas density. Fig. 14 replots Fig. 13 with modified Weber number replacing the electric Bond number as the ordinate. The derivation in Eqs. (7) and (8) is a very important correction in estimating electric stresses at the interface. If we had assumed the liquid phase to be perfectly conducting, the electric Bond numbers would have reached up to 20, compared to the maximum value of 0.33 in Fig. 13. Fig. 15 replots Fig. 13 but replaces the electric Bond number with a modified Weber number.
number defined in Eq. (8) by that defined in Eq. (8a). Under this scaling, it is apparent that electrostatic forces have much lower impact on bubbling dynamics than flow-related forces.

5. Conclusions and recommendations

Our results demonstrate that, at constant flow rate, bubble formation dynamics from an electrified nozzle exhibits the classic signs of a period-doubling bifurcation to chaos with increasing applied potential. With increasing voltage, the bubble frequency increases and the bubbling undergoes period-doubling bifurcations to become chaotic, similar to that for increasing flow rate. Similar behavior has been observed in liquid–liquid systems under electrostatic spraying (Tsouris et al., 1994). Although the basic type of bifurcation is similar for applied voltage and flow, voltage has a proportionally smaller effect than flow. Application of voltage also reduces bubble size, apparently by promoting early bubble release. The smaller bubbles have higher interfacial surface area for heat and mass transfer, and this might have beneficial applications in gas–liquid contacting devices.

Use of applied electrical potential for bubble size control should be further investigated because it would be possible to manipulate this variable very quickly and thus provide very fast feedback perturbations (e.g., much faster than can be obtained with gas flow perturbations). A possible limitation is the relatively large voltage amplitude needed to achieve significant effects. This study is the first one to consider the case where both the ambient and gas phases were conducting. Other studies have assumed both of these to be either perfect conductors or perfect nonconductors. An expression for electric Bond number was derived for the current apparatus, and it was shown that it reduces to the expression for other, limiting cases studied in the literature.

In the present study, the effects of electro-hydrodynamic (EHD) flows were assumed to be negligible and were not studied. Future studies should include EHD flows induced with different shapes of nozzles, various chamber sizes and changing the nozzle diameter. The particular liquid used is another important parameter, and consideration should be given to similar studies in immiscible liquid–liquid systems.

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