

HOW ORDERLY IS ULTRASONIC ATOMIZATION?

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ABSTRACT

In the formation of a spray from a liquid film on a vibrating surface it is received opinion in the literature that droplets are formed periodically from the apexes of standing capillary waves with a wavelength related to vibration frequency by stability analysis. It is described how this assumption may be incorrect in that, after droplet formation commences, the orderliness of a standing wave pattern that occurs prior to droplet formation, is lost due to one or more secondary instability phenomena. These phenomena are investigated by using high speed imaging techniques and by using a low frequency vibrating film to model the high frequency case, which is necessary because of the difficulty of penetrating clouds of very small droplets in the latter case. Different modes of droplet formation are identified and the flow patterns responsible for these modes are discussed. Application of CFD using a VOF model provides conformation of a growth of disorder.

NOTATION

a	amplitude	σ	surface tension
f	frequency (Hz)	μ_L	viscosity of liquid
h	depth (average) of film	ρ_L	density of liquid
λ	wavelength		

INTRODUCTION

Although droplet formation from trays of water vibrated mechanically at low frequency has been known for centuries, the phenomenon was first described in 1927 [1] as a practical means for producing sprays using frequencies equal to or greater than 20kHz. Now 20-100 kHz devices are common and use piezoelectric crystals driving a metal velocity transformer "horn" on the end-face of which the liquid is introduced. The basic performances

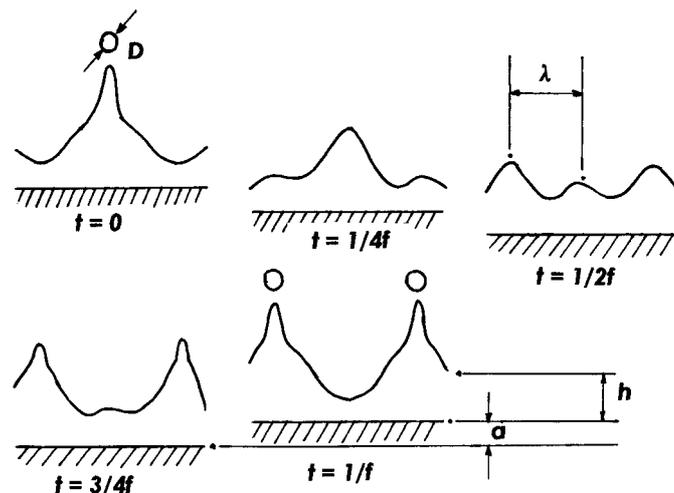


Figure 1. Generally assumed drop formation process.

of such devices have been studied experimentally, [2,3,4,5]. Analytical studies [2,6] assume that drops are formed from the crests of standing capillary waves as shown in fig 1., and have addressed the wavelength and critical vibration amplitudes for the formation of these waves. However, the literature contains no description of the drop formation process and has not addressed the drop detachment stage and the flow inside the film following detachment. It is noted that the frequency of oscillation of the surface wave should

be one half of the applied frequency f . Most analyses assumed two-dimensional “cylindrical” waves whilst, in the real case, vibration-driven capillary waves (at amplitudes less than that for droplet formation) exhibit a range of surface patterns, [7]. According to Kelvin, see [8],

$$\lambda = (8\pi\sigma/\rho_L f^2)^{1/3} \quad (1)$$

Mean droplet size is generally proportional to the most likely surface wavelength λ so that, for example[2],

$$D_{32} \approx 0.34 \lambda \quad (2)$$

In general the breadths of size distributions are too wide to be consistent with the droplet formation process in Fig 1. Furthermore, when atomizing metal such as solder, the possibility of cavitation should be negligible, so that this cannot be used to explain the observed increase in size distribution breadth with increase in flow rate that the authors and others have found. This research has the aim of investigating the mechanisms by which a range of droplet sizes are produced. The initial work investigated atomizers used for solder powder production, ($f=39.5\text{kHz}$ and higher). It was very difficult to see the droplet formation process or standing wave patterns, apart from at extremely low flow rates, and the investigation moved to studying physically scaled-up atomizers for which droplet formation could be seen more clearly. Numerical modelling of wave formation and break-up has also been carried out.

The authors made the hypothesis that a regular organised standing wave pattern with drops always forming from wave crests, might not exist during atomization and the literature on the subject was examined to ascertain how conclusive the evidence was for standing wave atomization. Most literature states or assumes that this is the atomization mechanism (with some adding that cavitation may also be important) without providing evidence. Publications showing standing wave patterns usually state that these are for pre-atomizing conditions, as exception being Topp [4]. Examination of photographs in [4], which are obtained at amplitudes which gave atomization inception, is inconclusive. For regions where standing waves can be seen, no droplets are visible, and when intervening droplets occur between the camera and the surface, the film surface is not visible. A close-up photograph of the liquid film in [9], is given as proof of atomization from standing capillary waves, but the images show lack of order in the process, compared with Fig 1.

EXPERIMENTAL APPARATUS AND PROCEDURE

Experiments used a large-scale vibrating film atomization apparatus which consisted of a 200W “public address” loudspeaker coil-magnet assembly that was used to vibrate either a square cross-sectioned or a cylindrical tray. The coil was air cooled so that sufficient power could be input to produce droplet formation at frequencies up to 500Hz. The internal dimensions of the cylindrical tray were 72mm (diameter) and 15mm (height) with wall thickness 3mm. Tray vibrational modes were very much higher frequencies than those applied in the experiments. Three video systems were used, and the principal images shown here used a Hadland Imacon 468 ultra-high speed camera, that could use a frame rate up to 1MHz. This camera stored only 8 frames, but provided a suitable image resolution. In order to scale-up the ultrasonic atomization process it is necessary to maintain the important dimensionless groups to be similar for the small-scale, high frequency, and the large scale, low frequency cases. These are, $We=\rho_L U^2 h / \sigma$, $Re=\rho_L U h / \mu$, $Fr=U^2 / gh$, h/a and ρ_L/ρ_g , where the velocity scale is, $U=fa$, which is typically 1m/s. It is not difficult to match Weber and Reynolds numbers for small and large scale cases, by using frequencies, $f=200\text{Hz}$ or higher, and with film thickness, h , of the order 2mm. Matching Froude number cannot be achieved but Fr can be kept to high enough values for gravitational effects to be ignored.

RESULTS AND DISCUSSION

Still images of the vibrating tray were obtained for variation of amplitude, in the range 0.1 to 0.4mm, and applied frequency, in the range 80Hz to 900Hz, and with average film thickness between 1 and 3 mm. As reported in previous work, various standing wave patterns were produced before inception of atomization. At low amplitude, near the critical amplitude for wave formation, concentric waves were produced and increasing amplitude gave orthogonal waves and for higher frequencies hexagonal wave cells, were observed. Figure 2, shows a view of the cylindrical tray with a frequency 300Hz and with an amplitude just prior to atomization inception. After atomization inception patches of the standing wave pattern could not be observed, and the higher magnification images, described below, were obtained to understand the process occurring. The vibration amplitude for inception of atomization decreased with frequency, for example at 80Hz the inception amplitude was 0.15mm and at 200Hz it was 0.10mm. This agrees reasonably with [9], that the atomization inception amplitude is between 3 and 6 times the critical amplitude a_c for wave formation,

$$a_c = 2(\mu_L/\rho_L)(\rho_L/\pi\sigma f)^{1/3} \quad (3)$$

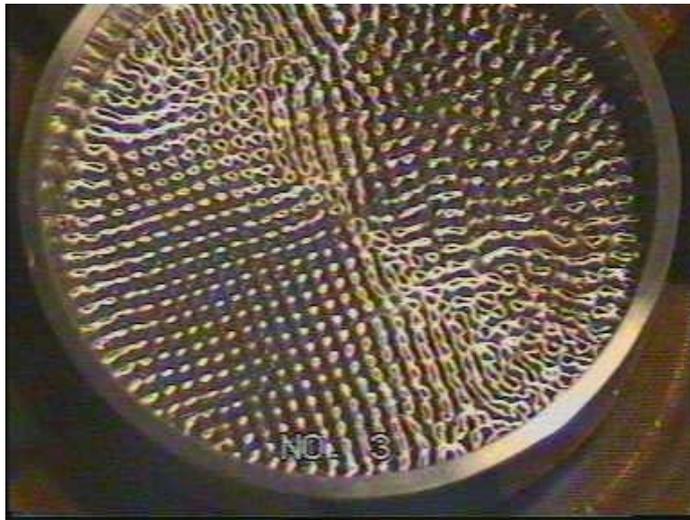


Figure 2. Standing wave patterns just prior to atomization.

It was observed that there was a maximum amplitude for good atomization, above which sections of film were flung from the tray floor, rather than individual droplets. This reduced from 150% above the inception amplitude, at 80Hz, to approximately 15% above inception amplitude at 200 Hz and above. Figures 3 and 4 show frame sequences, with time interval 286 μ s, which were taken of the same area with the same magnification and where in all cases $f=150$ Hz, $h=2$ mm and vibration amplitude was 0.13mm, which was 60% larger than that for atomization inception. Although formation of a single droplet from a single wave crest was observed, as in Fig 1, this occurred for a low proportion of vibrations and the sequences are selected to show some of the various other processes commonly involved. Figure 3 shows a drop forming in a manner similar to the classical view of the process, i.e. Fig 1. A ligament protrudes from the wave during the upward movement phase of the wave's oscillation. A droplet forms at the end of the ligament and initially maintains the upward velocity of the wave. However as the wave moves downwards the ligament is stretched to produce a "neck" and surface tension decelerates the droplet.

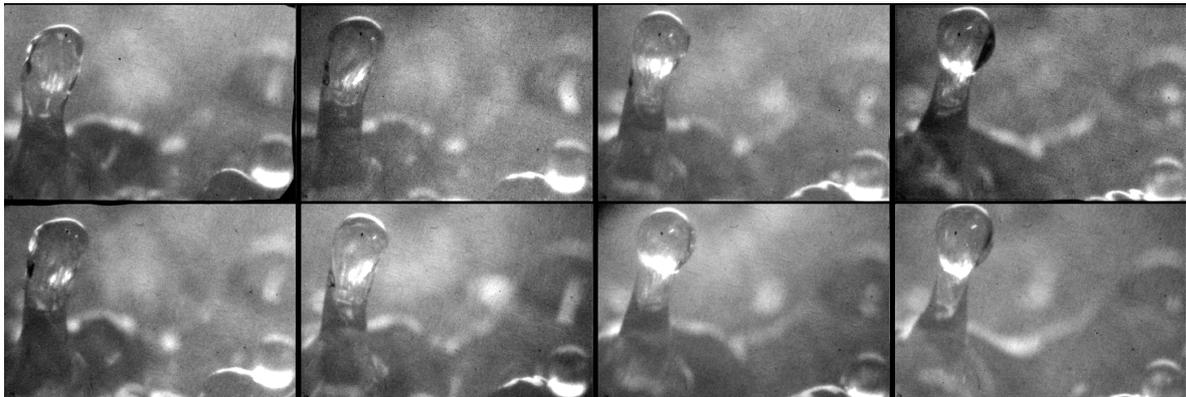


Figure 3. "Normal" drop formation from wave and ligament.

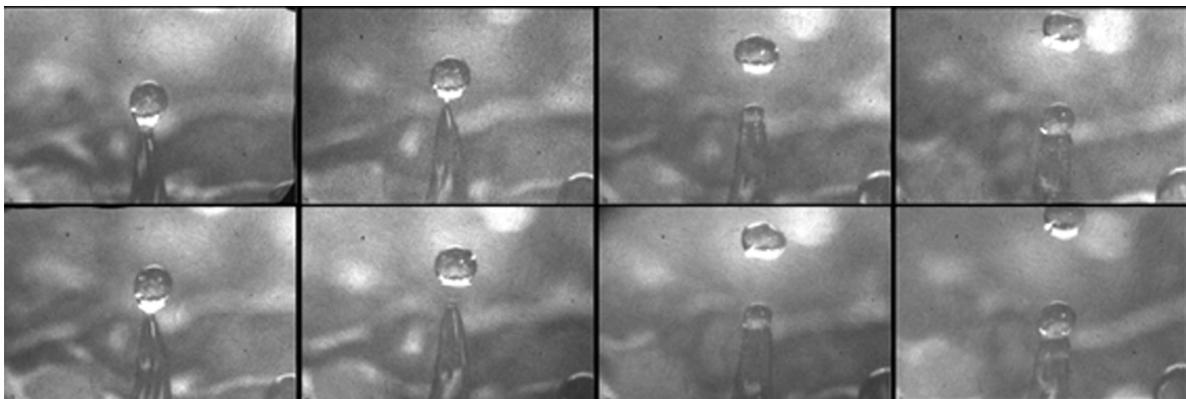


Figure 4. Multiple drops form from one ligament.

Formation of multiple droplets from a single ligament, without return of the ligament to the wave, was commonly observed, with variability in the sizes of droplets. For example Fig. 4 shows a sequence where two droplets, with possibly a third forming in the final frame, appear from the same ligament, the wall

moving upwards throughout most of the sequence. This process appears to be analogous to the Rayleigh varicose instability of a liquid jet.

Figure 5 illustrates an unexpected process that was frequently observed in the visualisations, and which we refer to as the “volcano mode”. This can be seen at the lower right quarter of each frame where a crater is seen in the film surface and a droplet gradually emerges from the crater during the sequence. A second crater undergoes a similar process, slightly out of phase, in the upper quarters of the frames. Also in the final frames the conical ligament at the left of the frames, that remains after droplet separation, is pulled back into the liquid film and small scale irregular surface waves are formed.

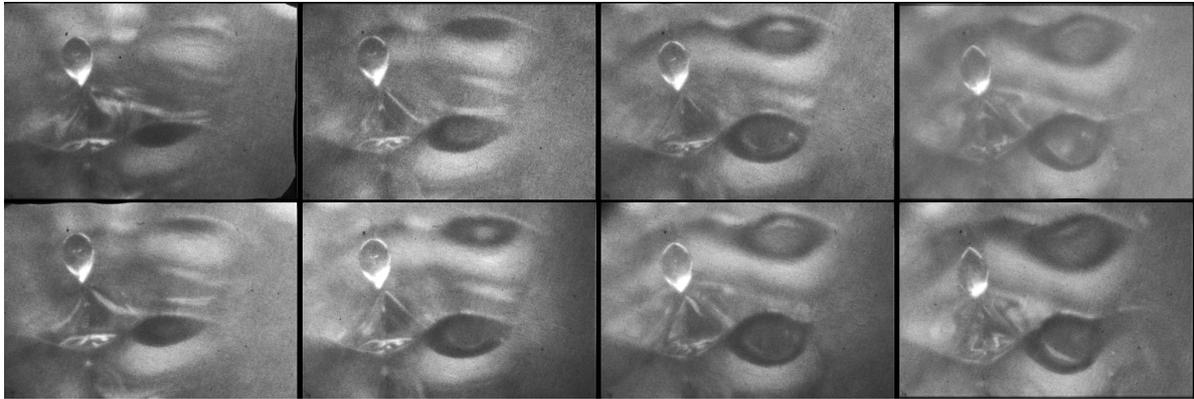


Figure 5. Volcano mode

Droplet images were measured and the relatively wide ranges found were typical of those for ultrasonic atomization but there was overall agreement of mean drop size with that derived from equations (1) and (2). The range of droplet trajectories leaving the film surface have not been reported for ultrasonic atomizers in past work. Measurements of angles of flight for the present scaled-up cases showed approximate Gaussian distribution of angles, with a standard deviation of 15° . This range of angles, which is a direct result of the relative disorder in the droplet formation processes, is likely to lead to some coagulation further downstream. The velocities of droplets after they detached from the film also showed a wide variations, with a 10:1 range of magnitude. The highest velocities were near the maximum wall velocity during its vibration cycle and the faster droplets tended also to have little deflection from the vertical in their angles of flight.

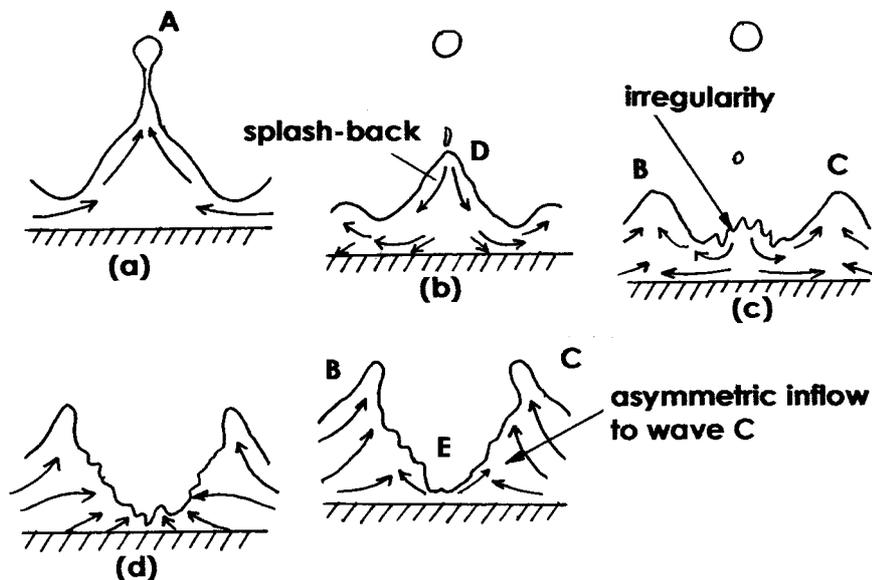


Figure 6. Real effects during drop formation.

Figure 6 indicates some of the “real” effects during one wall vibration cycle, that lead to the observed relative disorder. Thus in (a) the first droplet A is detached as the upwards momentum in the central ligament exceeds that which can be removed by the surface tension in the ligament. The waves B and C are cross-sections of two of the four surrounding wave cells (for an orthogonal pattern) and they are at the lower point of their cycles. At stage (b), in Fig. 6, the back-flow of the remainder of the ligament and the central wave, is strengthened by the acceleration downwards of the central region due to the conservation of the surface

energy, in the stretched ligament D , into kinetic energy. As was observed in the video sequences, this “splashback”, in stage (c), is sufficient to cause surface ripples in stage (d) and may give vortex instabilities at the upper surface of the impinging wall jet that is formed. There is an analogy with the breaking of gravitational surface waves. During stages (b), (c) and (d), in Fig. 6, the adjacent waves B and C move upwards and liquid is entering these waves from both the central wave cell, that which produced the first droplet, and from the surrounding wave cells. However, there are now two phenomena that may prevent an orderly cyclic formation of droplets proceeding from waves B and C , at stage (e) in Fig. 6. One is the irregularity in the central backflow, that may lead to unequal volumes of liquid entering waves B and C (stage (e)), and the other is the depletion of liquid in the central region of the film caused by the droplet formation. The latter phenomenon should lead to less liquid entering waves B and C , than that which entered wave A at stage (a). This may explain the observation, in the video recordings, that when inception of atomization occurred at a wave, atomization from the immediately surrounding waves was not observed for several wall vibration cycles. The irregular backflow would increase the chances of subsequent atomization occurring from one particular wave and, also, for steady atomization conditions, it would lead to differences in drop sizes, and ligament length at drop formation, for different waves. Furthermore the asymmetry of inflow to waves that are adjacent to a wave from which a drop has been formed, is likely to lead to subsequent ligament and droplet formation at angles deviating from the vertical.

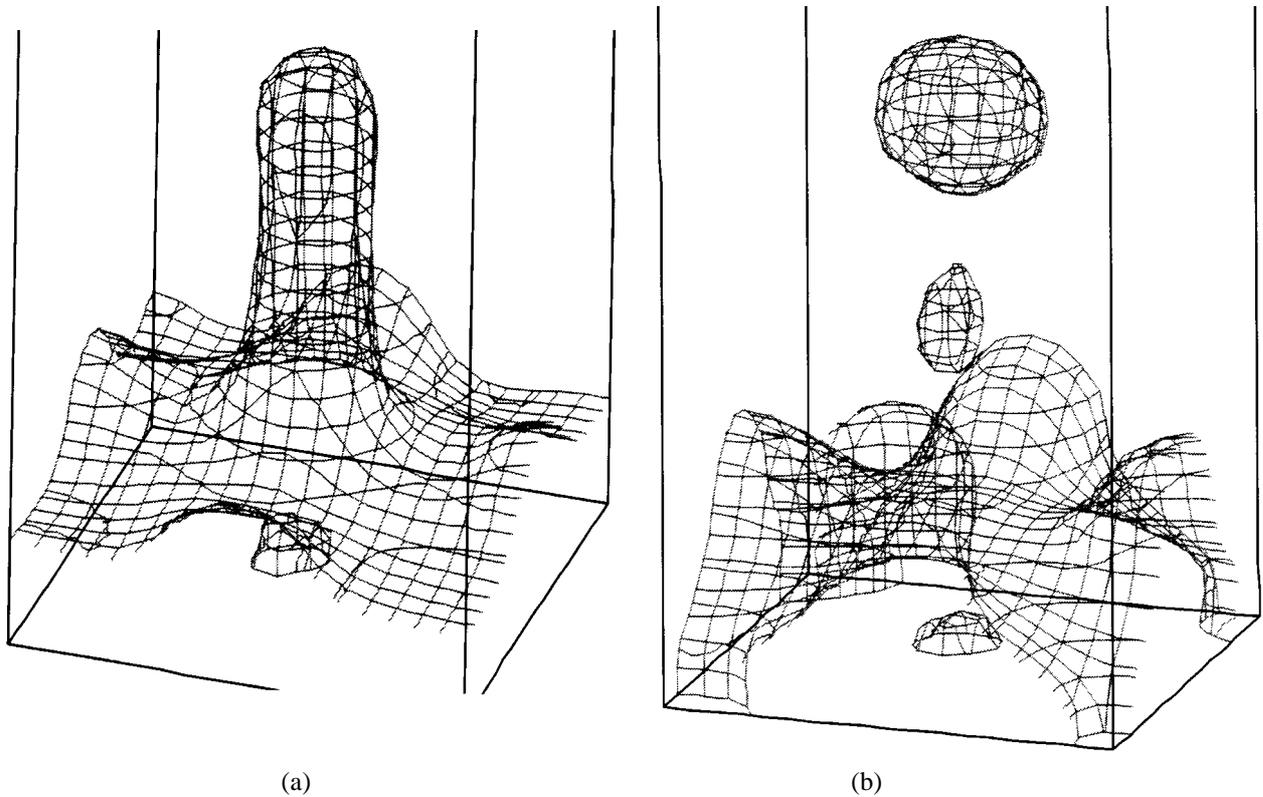


Figure 7 a and b. 3D VOF simulation of a drop formation.

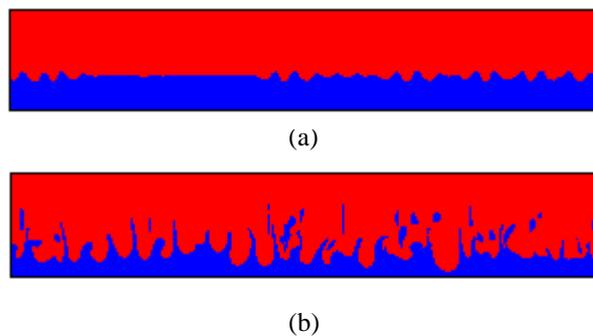


Figure 8 a and b. 2D CFD simulation of 20 wavelengths before and after atomization.

A VOF CFD model has been used to predict droplet formation from one wave cell and Fig 7, shows the situation at two times. The calculations provided support to the arguments made above. Furthermore 2D

calculations of atomization from a large array of waves, such as that shown in Fig 8, showed a rapid growth of relative disorder, qualitatively similar to what has been observed.

CONCLUSION

The droplet formation processes from a film on a vibrating wall has been examined and droplets are formed from capillary waves, however the organised, generally orthogonal, standing wave pattern found prior to atomization inception, becomes disorganised during atomization. Variability of the droplet formation process is observed, which leads to the range of droplet sizes, velocities and angles of flight typically found for ultrasonic atomization. Individual wave cells eject droplets intermittently, with a variable number of cycles between ejections. It is proposed, and confirmed by CFD, that reasons for this disorder are irregularity caused during the rapid backflow of wave crests from which droplets have formed, asymmetry of inflow into wave cells, during ligament formation, when surrounding waves have formed droplets in a previous cycle, and depletion of liquid from wave cells due to droplet formation.

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