Spontaneous Capillarity-Driven Droplet Deployment

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Abstract

Precision deployment of liquid drops is the hallmark of the inkjet printing industry. There are a variety of different driver technologies, with the two most common being either piezo or bubblejet. In this work we present a novel passive driving method that exploits only the fluid properties and conduit geometry. An enormous range of droplet volumes produced is demonstrated. The method is already being used as a tool to enhance the capability of other experiments to study drop dynamics including droplet impacts, adhesions, and rebounds and the method may also be exploited for specific purposes in the design and testing of capillary fluidics applications such as ink jet printing. It may also be directly applicable to sensor systems such as in the precise delivery of microscopic amounts of fluids in Lab-On-Chip applications and for liquid management aboard spacecraft.

Introduction

Capillarity-driven flows in tubes halt when the advancing meniscus reaches the end of the tube. In 1961, NASA Lewis Research Center scientist Robert Siegel conducted the first low gravity capillary rise experiments using a drop tower as a method to study fluid behavior in a weightless environment [1]. Similar to terrestrial microfluidics systems, when the forces of gravity are weak surface tension forces dominate the flow in ways that are not always intuitive. Siegel's experiments confirmed that although capillary forces pump the liquid along the tube, it is these same forces that reverse direction and resist the flow at the tube end. A capillary pressure argument by de Gennes et al. [2] proved that the driving capillary force is insufficient to overcome itself when the tube end is reached, never leading to 'auto-ejection'. We repeat Siegel's tests using a 2.1 s drop tower at Portland State University [3]. Fig. 1 shows the halted meniscus of 0.65 cS PDMS liquid, similar to Siegel's results, before being drawn back into the tube end.

However, we find that if the tube end is a contracting nozzle the liquid can accelerate with ample inertia to overpower surface tension and auto-eject the liquid [4]. We demonstrate this phenomenon in a terrestrial lab, in drop tower tests, and aboard the International Space Station (ISS) for single drop ejections as shown in Fig. 2. Droplets ejected in a weightless environment can be up to 10^6 times larger than their normal gravity counterparts.

Analysis

A scale analysis is adapted to identify a modified Weber Number $We^+ \equiv \rho R V^2/\sigma\alpha^3$ as the primary parameter predicting the ejection phenomena. For these flows We^+ measures the strength of liquid momentum $\rho V^2/2r$ compared to the maximum resisting capillary pressure gradient $2\sigma/r^2$ for liquid density ρ, surface tension σ, characteristic velocity V, tube radius R, nozzle radius r, and nozzle contraction ratio $\alpha \equiv r/R$. We estimate that when $We^+ > 12$ auto-ejection is highly likely, whereas when $We^+ < 9$ it is highly unlikely. Figure 3 presents data mapping the transition between the ejecting and non-ejecting conditions. The anticipated We^+ limits identified are provided on the figure for comparison. Further details may be found in [4].

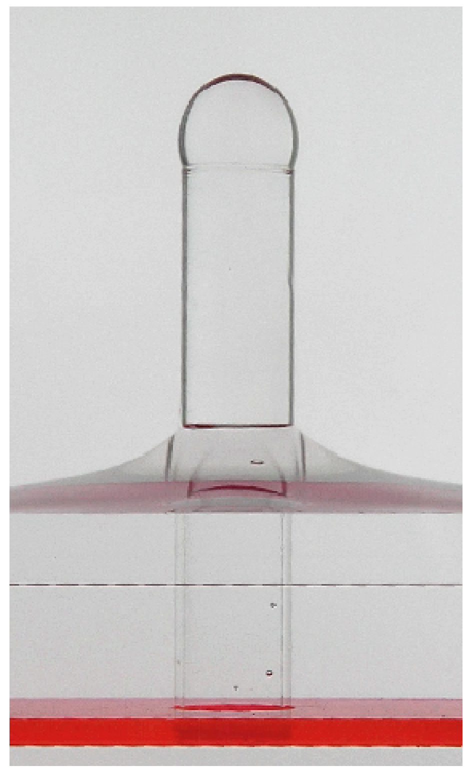

***Figure 1**. Ebbing capillary rise of 0.65 cS PDMS liquid in a 60 mm long, 10 mm diameter right circular cylinder.*

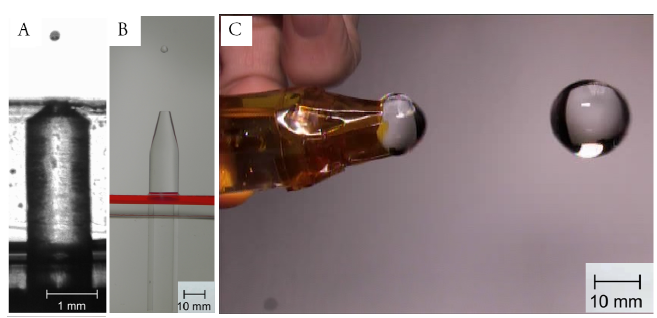

***Figure 2.** Select images of auto-ejection following spontaneous capillary rise in circular tubes. A. Terrestrial test: a 0.009 µl droplet ejection (perfectly wetting 0.65 cs PDMS). B. Drop tower: a 400 µl droplet ejection (perfectly wetting 0.65 cs PDMS). C. ISS: a 3000 µl droplet ejection (partially wetting water).*

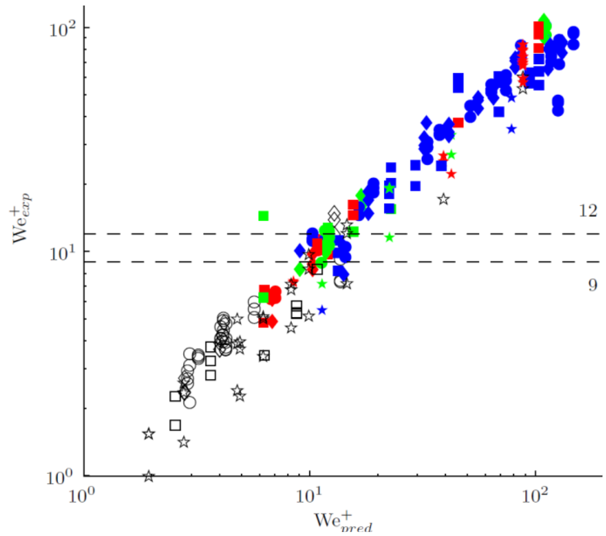

***Figure 3**. Auto-ejection regime map where solid symbols identify conditions for ejection: values of $We^+ > 12$ are expected to eject while $We^+ < 9$ are not. Values $9 < We^+ < 12$ are highly sensitive to specific nozzle geometry and capillary wave dynamics.*

Experiments

The time scales of the large droplets generated in low-gravity are much greater than those of terrestrial microscale droplets and the former may be studied effectively using unmagnified HD video imaging at as low as 60 fps—mitigating in part the need for stroboscopic methods and/or high speed photography. Thus, the effects of aperture shape and irregularity on droplet size, modes, and stability can be readily studied at wildly different time scales. This approach enables the systematic study of such themes as ejection asymmetry due to manufacturing defects. A sample study is provided herein as a demonstration.

The passive droplet deployment method is highly repeatable as shown in Fig. 4 and may also be used to study fundamental capillary fluidic jetting dynamics including impacts, adhesions, and rebounds. By varying tube and nozzle dimensions and fluid properties we demonstrate a variety of auto-ejections from single drop ejections to transient jets as shown in the drop tower test in Fig. 5. Nozzle geometries similar to inkjet applications reveal a hierarchy of droplet diameters and precursor, intermediate, and primary drops are shown in the drop tower auto-ejection in Fig. 6.

Drop encapsulations, bubble ingestions, and droplet swarms using nozzle arrays are also produced by this method of droplet deployment as demonstrated in Fig. 7. Impacts of such swarms are of interest to observe at such scales, and examples of impacts on thin films as well as on macro-porous surfaces are shown in Fig. 8.

Figure 9 provides a sense of scale for the droplets produced by the passive ejection method in the various environments of the terrestrial lab, a drop tower, and an orbiting spacecraft (i.e., the International Space Station).

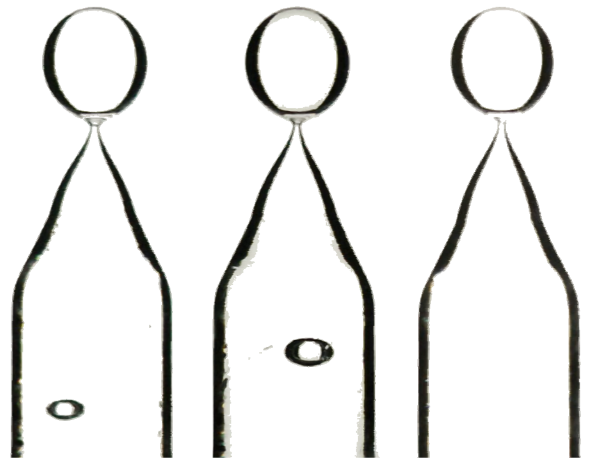

***Figure 4**. Three typifying drop tower tests illustrating repeatability of passive droplet ejection at bubble pinch-off point. The bubbles in the flow have no*

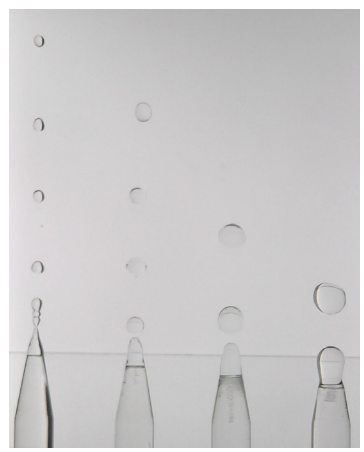

***Figure 5**. Varieties of auto-ejection in a 2.1 s drop tower test due solely to nozzle dimensions.*

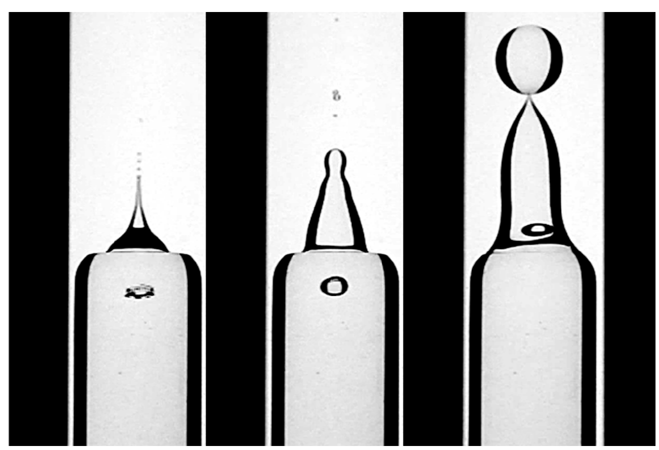

***Figure 6**. Hierarchy of drops in an aperture-type nozzle: from left to right: precursor, intermediate, and primary drops ejected during a single ejection event.*

***Figure 7**. Approximately 300 0.32 µL 1 cS PDMS liquid droplets passively ejected from a 10 by 10 array of tubes.*

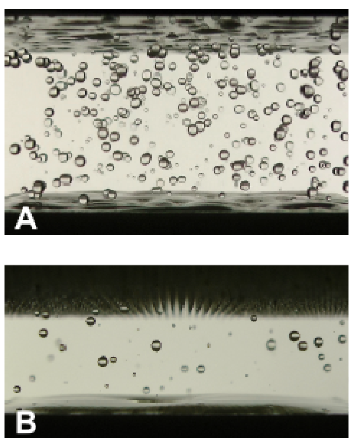

***Figure 8**. Tests demonstrating swarms of drops produced by the passive ejection method: A) impacts on wettable surface with developing thin film and numerous rebounds and B) swarm impacts on macro-textured surfaces providing nearly 100% impacting drop absorption.*

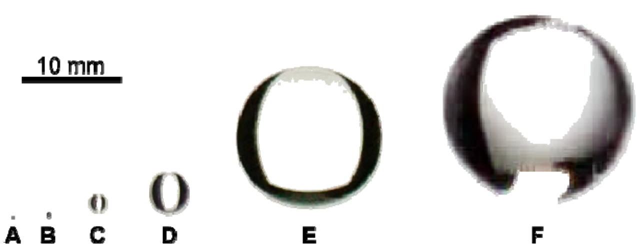

***Figure 9**. Typical range of auto-ejected droplets in A)-B) in normal gravity, C)-E) in a drop tower, and F) low earth orbit. Droplet volumes vary from A) 0.02, B) 0.06, C) 4, D) 36, E) 1480, and F) 3544 µL.*

***Figure 10.** Variations in drop-jet topologies as a function of nozzle geometry: A) standard drop, B) drop with encapsulated bubble, and C) long thin jet.*

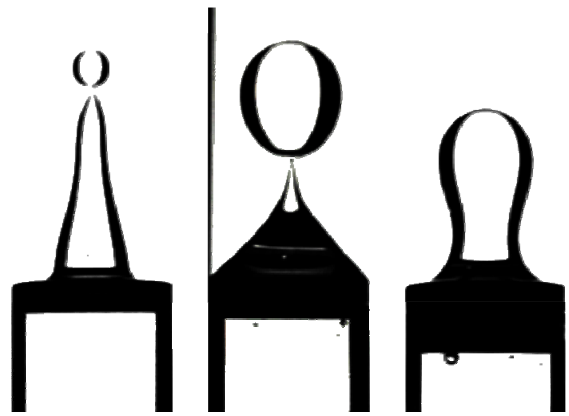

***Figure 11.** Droplet ejections for 2 cS PDMS from orifice-type nozzles of varying thickness: A) a 6 mm thick nozzle with 26 µL droplet, B) a 9 mm thick nozzle with a 612 µL droplet, and a C) 15 mm thick non-auto-ejecting nozzle.*

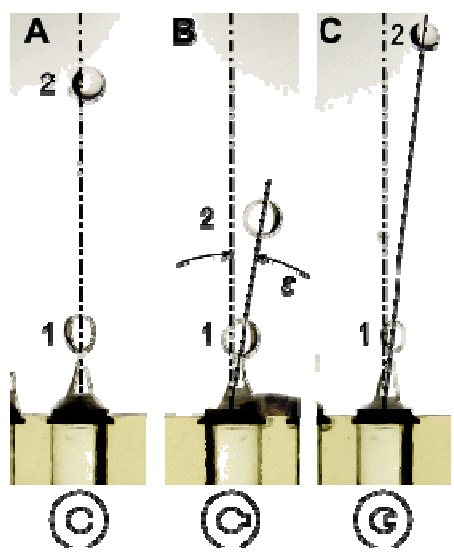

***Figure 12.** Droplet ejection tests simulating the effects of nozzle defects for 2 cS PDMS. Droplets shown 1) just before pinch off and 2) 0.5 s later: A) 5 mm nozzle with no defect (162 µL). A 2 µL primary satellite drop can be seen just to the left of the main drop at position 2. B) 5 mm nozzle with a 2 x 2 mm enlarging defect (236 µL). C) 5 mm nozzle with a 2 x 2 mm constricting defect (96 µL). B)-C) are off axis by approximately 8º.*

Sample Study of Nozzle Design and Imperfection

The nozzle style plays a significant role in the auto-ejection process. The wide variety is only lightly represented in Fig. 10 where a single drop, a drop-gas bubble encapsulate, and a thin jet are displayed resulting from different style nozzles.

For abrupt nozzles where the tube essentially ends with a lid possessing an 'aperture', the aperture thickness is an important parameter as illustrated in Fig. 11 where small, large, or absent drops result from thickness such as 6, 9, and 15 mm.

Droplet ejection tests simulating the effects of nozzle defects are shown in Fig. 12. The drop tower provides an ideal platform to study the nature of the resulting asymmetries due to the fine control of the large devices and because the devices can be constructed of transparent materials allowing the developing interfaces to be viewed at normal frame rates at all locations within the nozzle and beyond. In Fig. 12A, 'symmetric' drop ejection from a 'symmetric' nozzle is shown. In Figs. 12B and C however, examples from systematically varying nozzle aperture-types are provided from which highly quantitative data may be obtained. The cross sections of these aperture-type nozzles are provided in the figure below each image. It is interesting to note how additive (faster, smaller) and subtractive (slower, larger) defects draw the jetted droplet in the same direction as the defect as observed in Figs. 12B and C. The resulting drops in these cases are off-target by approximately 8º compared to the 'symmetric' nozzle.

Directions

A wide variety of droplet ejections are readily observed using the passive auto-ejection approach. Many observations may be explored providing insight into jetting unit operations. For example, deliberate selection of nozzle geometry allows for the ejection of large droplets with nearly zero residual velocity for studies in combustion or with other capillary interests such as thermo-, acousto-, electro-, magneto-, and soluto-capillary droplet phenomena. Large droplet solidification or evaporation can be visualized independent of the complicating effects of gravity requiring microscale imaging and fabrication. Further, the passive mechanism for such highly controlled droplet ejections inspires concepts for microfluidic 'print' applications including Lab-On-Chip concepts where precision deployment of small samples is required, such as in biotech applications where the ability to passively control the position, volume, and dosage timing of microfluidic quantities is critical. For example, by selecting the appropriate system geometry, the simple 'touch' of an assay cartridge to a small biofluid sample would spontaneously eject any number and variety of specific drop volumes into the cartridge. The drops could be accurately directed toward targets within the 'chip' where tuned reactions take place for further inquiry, screening, or diagnosis. Technologies developed by the inkjet community relevant to jetting are directly applicable to this and other advanced applications.

References

[1] R. Siegel, Transient capillary rise in reduced and zero gravity fields, J. Appl. Mech., 83, 165-170 (1961).

[2] P.G. de Gennes, F. Brochard-Wyar, D. Quéré, Capillarity and wetting phenomena: drops, bubbles, pearls, waves. Springer-Verlag, NewYork, pp 52-53 (2004).

[3] Wollman, A., Weislogel, M., New Investigations in capillary fluidics using a drop tower, Experiments in Fluids, Vol. 54, Issue 4, p 1499, April 2013.

[4] A. Wollman, T. Snyder, D. Pettit, M. Weislogel, Spontaneous Capillarity-Driven Droplet Ejection, Gallery of Fluid Motion fluid dynamics video entry and article Sept. 18, 2012, 1 video, 9 pages, 6 figures: http://arxiv.org/abs/1209.3999

[5] A. Wollman, MSME Thesis, Portland State University, 2012, Permanent Link: http://archives.pdx.edu/ds/psu/8243.

Author Biography

Andrew Wollman received his BSME from John Brown University and his MSME from Portland State University, where he is currently a PhD student. Along with Prof. M.M. Weislogel he conducts research aboard the International Space Station and in PSU's Dryden Drop Tower to develop design tools for fluids management aboard spacecraft. Dr. T. Snyder is a Principal Scientist for Xerox in Wilsonville Oregon. He also has significant background in microgravity and drop tower related research which applies at many levels in the inkjet printing industry. D. Pettit is a NASA Astronaut with a variety of unique space flight experiences including numerous fluidics experiments aboard the International Space Station.

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