Mechanical Inhibition of Foam Formation via a Rotating Nozzle

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We recently discovered that bubble formation can be substantially prevented when an aqueous solution is sprayed into a bath of the same solution provided that any two consecutive drops impacting the same surface location do so with a time interval greater than the capillary relaxation time. Building on this observation, here we report a mechanical means of preventing foam formation during liquid addition: the nozzle delivering the liquid is rotated sufficiently rapidly so that no two successive drops impact the interface at the same location. Foam formation is reduced by as much as 95% without any chemical anti-foaming agents. [DOI: 10.1115/1.4003987]

1 Introduction

Many industrial processes involve a step where two or more liquid streams are combined in one vessel. If one of the liquids is poured, sprayed, or dripped into liquid already in the vessel, then often times air is entrained upon impact, and the consequent bubbles form a foamy layer. Generally these foams are an unintended and unwanted byproduct of the process because they may interfere with unit operations, decrease process efficiency, increase process time, and lead to additional process defects [1]. Consequently, a great number of commercial chemical additives have been developed to minimize the impact of foams [2]. Anti-foaming agents are added to prevent foam formation, while defoaming agents are designed to increase the speed of foam drainage. Unfortunately, these additive chemicals have several drawbacks: they may contaminate the final product, pose environmental disposal problems, and increase the overall process cost and complexity [3]. Non-chemical strategies are thus desirable. Although some work has suggested that mechanical or ultrasonic vibrations help disrupt foams after they form [3,4], to date there has been no demonstration of a non-chemical technique that prevents foam formation in the first place.

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In this Technical Brief, we describe a simple mechanical apparatus that, for appropriate flow rates, significantly reduces the amount of foam generated when a liquid is sprayed into a container. Specifically, we demonstrate a technique to substantially prevent bubble entrainment due to what we refer to as "multidrop" impacts. First reported by Franz [5], multidrop bubble entrainment occurs when two successive drops impact a liquid-air interface within a critical time interval. We recently performed systematic experiments [6] that demonstrated the critical time interval is commensurate with the time required for an impact crater formed by the first drop to close by capillarity (approximately 5 ms for millimeter scale water droplets). Note that the multidrop regime is distinct from the "regular" or "irregular" entrainment regimes [7] exhibited by single droplets impacting at sufficiently high velocities; see Fig. 2 of Ref. [6] for a detailed overview. The key implication here is that bubble formation, and hence foam formation, can be minimized in the multidrop regime simply by ensuring that no two droplets impact the air-liquid interface at the same location within the critical time interval. Building on this observation, here we report a design for a rotating nozzle that prevents successive collocated impacts, thereby minimizing bubble entrainment. We demonstrate that a lab-scale prototype can reduce the volume of foam formed by as much as 95% for a given flow-rate, provided the angular velocity of the nozzle is sufficiently high.

2 Methods

The prototype apparatus is shown in Fig. 1. Two plastic circular gears (hub diameter = 7.3 cm, McMaster-Carr, Elmhurst, IL) were placed together, one of which contained the nozzle for fluid delivery while the other was attached to a rotating shaft powered by a motor. The nozzle was mounted through a hole drilled a distance $d_{noz} = 2.4$ cm from the gear center. When the motor was activated, the nozzle thus traced out a circular trajectory with a 4.8 cm diameter. The liquids were 2% wt/wt solutions of either Dawn dish soap (Proctor Gamble, Cincinnati, OH) or sodium dodecyl sulfate (Sigma-Aldrich, St. Louis, MO) in Milli-Q deionized water (Millipore, Billerica, MA). The liquid was pumped through the 0.75 mm diameter nozzle (Vita Needle, Needham, MA) by a syringe pump (Harvard Apparatus, Holliston, MA) with a 30 or 60 ml syringe (BD Biosciences, Franklin Lakes, NJ) at a specified flow rate until a predefined volume was delivered (typically 30 ml). Note that the flow rates used here ($q \gg 1$ ml/min) caused the fluid to exit the nozzle as a jet with velocity on the order 0.1 m/s; the jet rapidly broke up via the Rayleigh-Plateau instability into discrete droplets. Although rotation of the nozzle imparted some angular momentum to the droplets, the large vertical component of the velocity ensured that the droplets impacted the bottom surface rather than the container walls.

In each trial, the fluid was pumped into an initially dry and empty beaker (VWR, West Chester, PA). Each experimental trial was recorded with two CCD cameras (Dino-Lite, Torrance, CA) at 15 frame/s, and the resulting movies were analyzed using standard image analysis procedures in Matlab. One camera was mounted parallel to the beaker wall to image the foam height while the other camera was mounted from above (i.e., a birds-eye view) to image the area covered by the foam. Foam volume was estimated by multiplying the height of the foam by the area covered, and the volumes were then normalized to the maximum amount of foam formed for zero angular velocity at a given flow rate. We emphasize that the generated foam was not static but rather was draining slowly over the time course of the experiment even as additional foam was generated by the addition of new liquid; the foam volume at any given time thus represents the dynamic imbalance between foam generation and foam drainage.

3 Results

The foam-suppressing effect for a sufficiently high angular velocity is demonstrated qualitatively in Fig. 2. Dawn dish soap was chosen as a trial fluid because of its well known foamability, and as

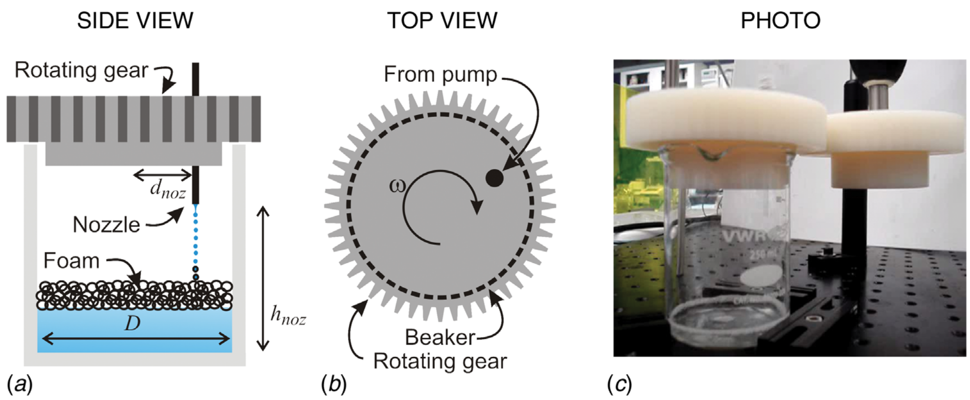

Fig. 1 The experimental apparatus. (*a*) Side-view schematic (not to scale). The tip of the nozzle $h_{noz}=7.5$ cm above the beaker bottom and $d_{noz}=2.4$ cm from the gear center. The beaker diameter is $D=6.7$ cm. (*b*) Top-view schematic. The gear and nozzle rotate with angular velocity ω. (*c*) Photo of the apparatus. The white objects are the gears; the gear on right is connected to a rotating shaft.

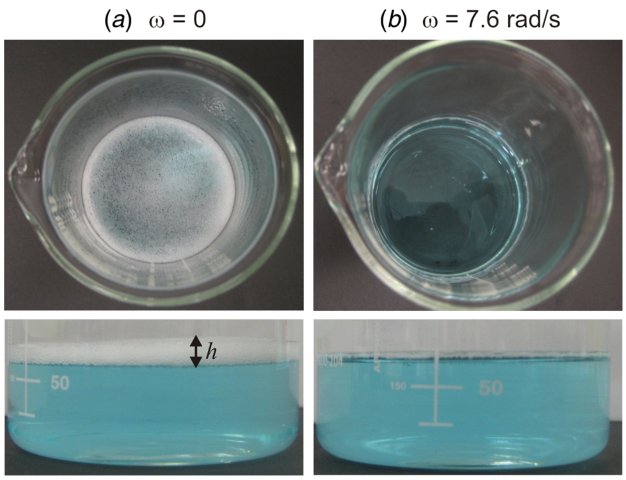

Fig. 2 Top and side views of the amount of foam formed by pumping a 2% solution of Dawn dish soap at 4.7 ml/min for 15 min into a 250 ml beaker for two different angular velocities. In each case, the images were captured immediately after dispensing was complete. (*a*) Stationary nozzle. (*b*) Nozzle rotating at 7.6 rad/s. Note that almost no foam is generated with the rotating nozzle.

expected, a significant volume of foam was generated for a stationary nozzle [Fig. 2(*a*)]. In contrast, almost no foam was generated when the nozzle rotated at $\omega=7.6$ rad/s [Fig. 2(*b*)]. We emphasize that both the chemical composition of the fluid and the volumetric flow rate were identical in each trial; the only difference was in the angular velocity of the nozzle. This result demonstrates that rotating the nozzle during fluid addition can suppress the formation of foam.

To quantify the transition between these two limits, we systematically varied the rotation rate of the nozzle for two different flow rates and measured the approximate volume of foam formed after dispensing 30 ml of 2% SDS solution. The normalized foam volumes are plotted versus time for different angular velocities and flow rates in Fig. 3. Several features of the data are noteworthy. First, for zero angular velocity (i.e., a stationary nozzle), the foam is formed at an approximately constant rate and collects at the top of the container. Qualitatively different behavior occurs for nonzero angular velocities, with the dynamics highly sensitive to the magnitude of the angular velocity. For a very slow angular velocity, the rate of foam generation actually increased [Fig. 3(*b*), $\omega=1.9$ rad/s]. In this case, the rotating nozzle served to more rapidly distribute the foam across the entire liquid/area interface; in contrast, foam was generated by the stationary nozzle in only one location and hence filled the entire area more slowly. At a slightly larger angular velocity, however, the amount of foam generated decreased compared to the stationary nozzle [Fig. 3(*a*), $\omega=3.2$ rad/s]. Note that the slight oscillations apparent in the curve stem from transient

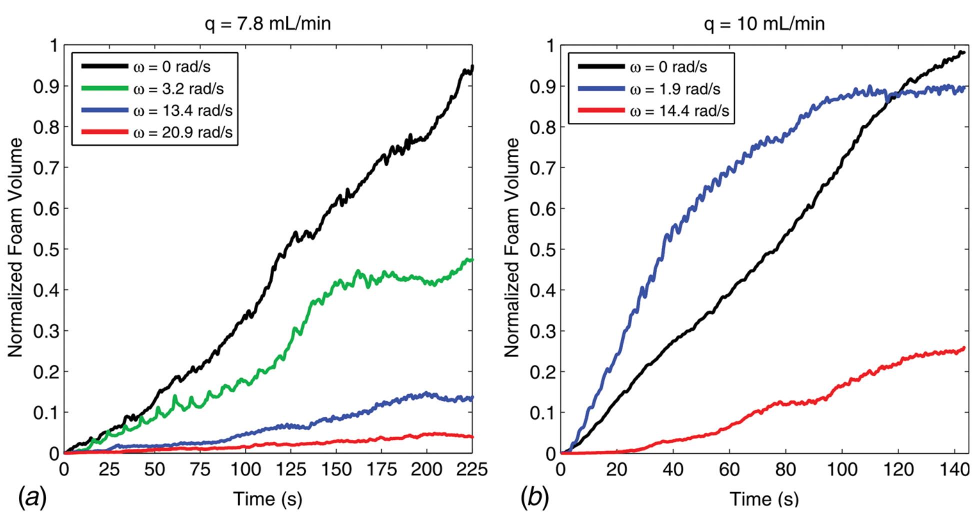

Fig. 3 The normalized volume of foam produced by 2% SDS solutions as a function of time for different angular velocities and flow rates. (*a*) Flow rate = 7.8 ml/min. (*b*) Flow rate = 10 ml/min.

capillary waves that “sloshed” the foam around, resulting in artifactual deviations in the foam volume as obtained via image analysis. The main result, however, is that the total amount of foam formed at a fixed flow rate was reduced by 50% compared to the stationary nozzle even at the slow angular velocity of 3.2 rad/s.

Even more dramatic reductions in the foam volume were observed at higher angular velocities: a 75% reduction was observed for $\omega = 14.3$ rad/s at a flow rate of 10 ml/min. Likewise, at 7.8 ml/min, an 85% reduction was observed for $\omega = 13.4$ rad/s, while a 95% reduction was observed at $\omega = 20.9$ rad/s. We note that the distinct increase in foam suppression at higher angular velocity is consistent with our previous findings [6] because successive drops dispensed from a nozzle moving less than 3 rad/s have increased likelihood of interacting with the craters formed by previously impacting drops, while a nozzle moving at 13 rad/s is less likely to do so.

These results highlight that under some circumstances chemical agents may be replaced in a process simply by incorporating a rotating nozzle with a controlled angular velocity. By minimizing the interaction of successive drops, foam formation is minimized—even for fluids with high foamability. These lab-scale findings motivate larger scale models and may enable the reduction or elimination of anti-foaming and defoaming additives in some industrial processes.

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