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Bubble pinch-off in Newtonian and non-Newtonian fluids

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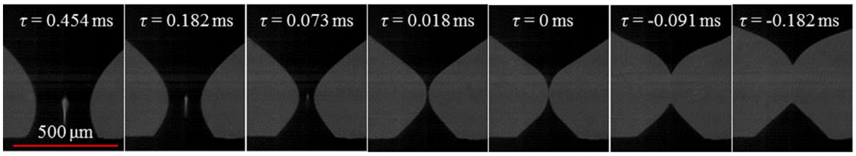
HIGHLIGHTS

- Air bubble pinch-off in Newtonian and non-Newtonian fluids was investigated.
- Scaling law exponent ranges from 0.5 to 1 in Newtonian fluids.
- Scaling law exponent is between 0.5 and 1 for lowly shear-thinning fluids.
- Non-universal scaling was observed in highly shear-thinning fluids.
- Experimental data were validated by the numerical simulation.

GRAPHICAL ABSTRACT

Air bubble pinch-off sequences in 0.50% PAAm solution ($Q = 0.5$ mL/min).



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ABSTRACT

Bubble pinch-off is a rapid process and until now is not well-understood especially for the final stage near the breakup point. In this work, we aim at investigating the air bubble pinch-off at a submerged nozzle in various fluids, including Newtonian and non-Newtonian fluids. Different fluids exert different effects on the pinch-off dynamics as well as shape evolution immediately after pinch-off. A scaling law was applied to describe the bubble pinch-off in Newtonian fluids and the exponents: $b = 0.5$ for low viscosity fluids and $b = 1$ for high viscosity fluids, are in a good agreement with the conventional values predicted by the numerical simulation. For bubbles in non-Newtonian fluids, the pinch-off dynamics is mainly governed by the fluid rheology. The universal scaling exponent exists between 0.5 and 1 for low shear-thinning fluids while a non-universal character occurs for bubble pinch-off in high shear-thinning fluids. Our experimental results were confirmed by the numerical simulation.

1. Introduction

Bubbles from boiling water, carbonated beverage, soap, foam, diving and agitation, are always encountered in our daily life. However, bubble formation plays also a main role in gas-liquid contacting and reaction processes which are widely used in chemical industry, petrochemical industry, biotechnology and mineral processing, etc. In operations such as distillation, absorption, flotation, spray and drying, bubble behaviors especially the bubble size and velocity, determine the contact area and residence time which directly affect the mass and heat transfer and mixing efficiency. Taking the flotation as an example, the small bubbles rise through the suspension and capture particles as they ascend to the surface (Chen et al., 2015).

When a bubble grows from a nozzle with a constant gas flowrate, the increasing bubble volume definitely leads to the increasing buoyancy. Once the buoyancy and inertia overcome the surface

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tension and viscous drag, a gas neck occurs and continuously thins to be a thread. Eventually, the thread pinches off into two parts due to the Kelvin-Helmholtz instability. A lot of previous studies (Simmons et al., 2015; Yang et al., 2007; Yuan et al., 2014) have been devoted to the global characteristics of bubble formation such as the bubble shape, size, rising velocity and frequency, considering the fluid parameters (density, viscosity and surface tension), design parameters (nozzle diameter, geometry and wettability) and operating parameters (flowrate and pressure). More comprehensive information about bubble formation could be seen in a review by Kulkarni and Joshi (2005). However, as the neck approaching to the detachment, the local dynamics is not yet well-understood and well-documented due to the very fast phenomena as well as quite small scales involved.

Pinch-off is a singularity point where the pressure and velocity all diverge to infinity. By assuming a power-law relationship, $h_{\min} = a\tau^b$, where $h_{\min}$ is the minimum neck diameter and τ is the time-to-pinch-off ($\tau = t_0 - t$, here t_0 is breakup time and t is real time), bubble pinch-off can be studied in terms of the universal self-similarity. The early studies of Longuet-Higgins et al. (1991) and Oguz and Prosperetti (1993) have proved that air bubble detaches from an underwater nozzle with an exponent of $b = 0.5$. Burton et al. (2005) experimentally studied the nitrogen bubble pinch-off in liquids like acetone and glycerol solutions and found that when the external liquid viscosity η_{ext} is lower than 10 cP, the exponent b equals 0.5; while η_{ext} is larger than 100 cP, the exponent b remains 1. Gordillo et al. (2005) proposed a modified relationship $h_{\min}(-\log h_{\min})^{1/4} \propto \tau^{1/2}$, and $h_{\min} \propto \tau^{1/3}$ for symmetric and asymmetric air bubble pinch-off in water at high Reynolds numbers. Keim et al. (2006) experimentally demonstrated that air bubble pinch-off in water with an exponent $b = 0.56$. Thoroddsen et al. (2007) conducted a comprehensive experimental study on bubble pinch-off and found that air, helium and SF6 bubbles pinch-off in water all show an exponent in the range of ($b = 0.56$–0.60) which is also a little bit larger than 0.5. Eggers et al. (2007) have used slender body theory to successfully deduce the time-dependent exponent $b = 0.5 + 1/[4\sqrt{-\ln(\tau)}]$. Recently, Ray et al. (2012) investigated the air bubble pinch-off during the liquid drop impacting on liquid pool and demonstrated that *We* number only affect the coefficient a and the exponent b remains as a constant 0.5.

Moreover, bubble pinch-off in confined microchannel has been investigated both in Newtonian and non-Newtonian fluids (Fu et al., 2012; van Hoeve et al., 2011). Despite some experimental analyses and empirical correlations, the mechanism of bubble pinch-off in unconfined systems is far from well-understood, especially in non-Newtonian fluids. Our group has already numerically and experimentally investigated the bubble formation in both Newtonian and non-Newtonian fluids, either in macroscopic columns or microscopic channels (Dietrich et al., 2008, 2013; Fu et al., 2011, 2012; Li, 1999; Li et al., 2002; Lu et al., 2014). As a continuous study to further understand the bubble formation, we here focus on the final and local pinch-off region in an unconfined system and investigate the bubble pinch-off dynamics in the background fluids ranging from Newtonian fluids to non-Newtonian fluids.

2. Experimental

Bubble formation in our experiment was conducted in a cubic PMMA tank (inside three dimensions: 5 × 5 × 6.5 cm) filled with various solutions. Air bubbles were generated through a submerged nozzle (inner diameter $d = 0.5$ mm and outside diameter $d' = 0.81$ mm) which located at the bottom center of the cube in order to avoid the wall effect. The air was injected through a syringe pump (Hamilton, Germany). All experiments were carried out at the same temperature (293.15 K). The sodium dodecyl sulfate (SDS) and glycerol were added into water to change the surface tension and viscosity, respectively. Table 1 gives the basic properties of the investigated Newtonian fluids.

0.25 wt%, 0.50 wt% and 1.00 wt% polyacrylamide (PAAm) (AN 905 SH, SNF Floerger, France) in deionized water were used as non-Newtonian fluids. These PAAm solutions were viscoelastic fluids and exhibited a shear-thinning effect. The rheological properties of PAAm solutions measured by a Rheometer (AR-G2, TA, USA) were shown in Fig. 1 and could be fitted with a power-law model ($\eta = K\dot{\gamma}^{n-1}$), where η is the viscosity, K is the consistency, $\dot{\gamma}$ is the shear rate and n is the flow index. These values together with the density and surface tension of PAAm solutions were given in Table 2.

The bubble behavior was imaged and recorded with a Phantom v7.11 camera (Vision Research, USA). The nozzle diameter was also photographed as a reference length. The visualized speed was 160,000 frames per second (fps) with a field of view 144 × 120 pixels for air bubble pinch-off in Newtonian fluids; While 110,032 fps with a resolution 144 × 176 pixels for bubble pinch-off in non-Newtonian fluids. The exposure time remains as low as 2 µs. This high-intensive local magnification almost reaches the limit of the

Table 1
Properties of Newtonian liquids at 293.15 K.

	Density, $\rho/(\mathrm{kg{\cdot}m^{-3}})$	Viscosity, $\eta/(\mathrm{mPa{\cdot}s})$	Surface tension, $\sigma/(\mathrm{mN{\cdot}m^{-1}})$
Water	996.0	1.0	72.5
0.10% SDS + Water	996.0	1.0	50.3
0.15% SDS + Water	996.0	1.0	40.6
61.23% Glycerol + water	1156.6	13.4	67.6
86.73% Glycerol + water	1227.1	138.7	65.3
100% Glycerol	1261.1	1407.0	63.4

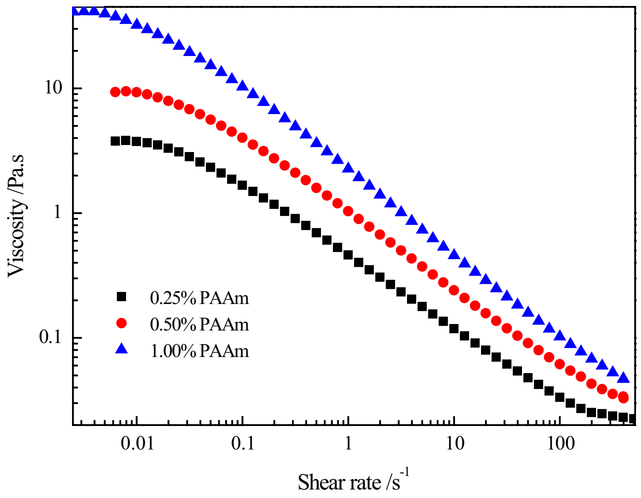

Fig. 1. Rheological properties of PAAm solutions.

Table 2
Properties of PAAm solutions at 293.15 K.

	Density, $\rho/(\mathrm{kg{\cdot}m^{-3}})$	Surface tension, $\sigma/(\mathrm{mN{\cdot}m^{-1}})$	Consistency, $K/(\mathrm{Pa{\cdot}s^n})$	Flow index, n
0.25% PAAm	996.0	70.3	0.461	0.412
0.50% PAAm	996.0	69.6	1.033	0.372
1.00% PAAm	996.0	67.7	3.338	0.317