



Rheology of colloidal gas aphrons (microfoams)

Sophie Larmignat, Damien Vanderpool, Heung Kei Lai, Laurent Pilon*

University of California, Los Angeles, Mechanical and Aerospace Engineering Department, 420 Westwood Plaza, Los Angeles, CA 90095-1597, United States

ARTICLE INFO

Article history:

Received 21 November 2007

Received in revised form 25 February 2008

Accepted 6 March 2008

Available online 15 March 2008

Keywords:

Microfoams
Remediation
Separation
Bioreactors
Oil recovery
Aqueous foam
Foam rheology
Pipe flow

ABSTRACT

This paper reports on the effect of surfactant concentration and pipe shape and size on the rheological properties of colloidal gas aphrons (CGAs) or microfoams. CGA consists of closely packed spherical gas bubbles with diameter ranging from 10 to 100 μm surrounded by a surfactant shell. It is produced by stirring an aqueous surfactant solution at high speed in a baffled beaker. Pipe flow experiments were performed in cylindrical pipes with diameter ranging from 1.0 to 3.0 mm under adiabatic laminar flow conditions. The porosity, bubble size distribution, surface tension, and pH were systematically measured. First, it is established that there was no slip velocity at the wall and CGA did not change morphology and porosity between the inlet and outlet of the pipes less than 2 mm in diameter. Compressibility effects were accounted for through the volume equalization approach. Then, pipe shape and diameter have no effect on the CGA rheology. Finally, CGA can be considered as a shear-thinning fluid. The dimensionless volume equalized shear stress τ^* is proportional to $(Ca^*)^m$ where Ca^* is the Capillary number and $m = 0.65 \pm 0.06$. The results are in good agreement with theoretical models suggesting $\tau^* = C(x)(Ca^*)^{2/3}$ where $C(x)$ is determined experimentally. It is established that $C(x)$ increases with surfactant mass fraction x . The Fanning friction factor f for CGA under laminar flow conditions follows the standard relationship $f = 16/Re_D$ where Reynolds number is determined using the CGA effective viscosity given by $\mu_e = \mu_1 C(x) Ca^{-1/3}$.

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1. Introduction

Colloidal gas aphrons (CGAs), also called microfoams, consist of closely packed spherical bubbles between 10 and 100 μm in diameter and porosity around 0.7 [1]. They are produced by stirring an aqueous surfactant solution contained in a fully baffled beaker via a spinning disk driven at high speed by an electric motor [1].

Colloidal gas aphrons have found numerous applications including (1) protein or bacteria separation [2,3], (2) soil remediation [4,5], (3) remediation of contaminated water [6,7], (4) fermentation and bioreactors [8], and (5) material synthesis [9–11]. These applications take advantage of (i) their large interfacial area, (ii) the adsorption of particles at the microbubble interfaces, and (iii) their stability for enhanced mass transfer [12]. They could also be used in oil recovery and fire fighting. In most of these applications, CGA is pumped through columns, pipes, and fittings. Thus, it is of practical interest to investigate the rheology of CGA to enable optimum process design. It is also of fundamental interest in the field of soft-matter physics where aqueous foams have been a subject of intense studies. There, the objectives are to model and measure the foam morphology and the different physical phenomena taking

place in foams as well as to predict their effect on the mechanical and rheological properties [13,14].

Colloidal gas aphrons differ from regular foams in terms of bubble morphology. Foams consist of gas bubbles covered by a monolayer of surfactant molecules immersed in the solution which may contain micelles. On the other hand, the most widely accepted structure of CGA bubbles, suggested by Sebba [1], speculates that bubbles are encapsulated in a multilayered shell consisting of surfactant and liquid. The main supporting arguments were (i) the absence of bubble coalescence, (ii) the fact that hydrophobic globules attach to the surface of the bubbles, and (iii) that when the CGA is created in dyed water and the generated bubbles are transferred into clear water, the bubbles contained some dyed water in their shell. Finally, Sebba [1] did not elaborate on the thickness of the speculative soapy shell. Amiri and Woodburn [16] estimated the thickness of the soapy shell to be 750 nm for cationic surfactant CTAB. They studied the liquid drainage rate in CGA dispersion and the bubble rise velocity. Bredwell and Worden [12] estimated the shell thickness to be 200–300 nm for non-ionic surfactant Tween 20, based on the study of gas diffusion from the CGA bubble to the liquid bulk, assuming that the mass transfer is limited by the rate of diffusion across the shell. More recently, Jauregi et al. [15] employed freeze fracture with TEM and X-ray diffraction to study the structure of the soapy shell. They imaged and measured the thickness of a surfactant shell to be 96 nm. They argued that the shell does

* Corresponding author. Tel.: +1 310 206 5598; fax: +1 310 206 2302.

E-mail address: pilon@seas.ucla.edu (L. Pilon).

Nomenclature

a	parameter for minor losses, Eq. (12)
$B(x)$	empirical function in $\tau^* = B(x)(Ca^*)^m$, Eq. (18)
$C(x)$	empirical function in $\tau^* = C(x)(Ca^*)^{2/3}$, Eq. (19)
Ca	Capillary number, $Ca = \mu_1 r_{32} \dot{\gamma}_a / \sigma$
Ca^*	volume equalized Capillary number, $Ca^* = \mu_1 r_{32} \dot{\gamma}_a / \varepsilon \sigma$
d	bubble diameter (m)
D_h	hydraulic diameter based on the wetted perimeter (m)
D_i	Lexan rod inner diameter (m)
K_B, K_{HB}, K_P, K_{VE}	flow consistency for various models
K_{L1}, K_{L2}	minor loss coefficients
L	distance between pressure sensors (m)
L_e	entry length (m)
m	empirical constant in $\tau^* = B(x)(Ca^*)^m$
\dot{m}	mass flow rate (kg/s)
M	mass (kg)
n, n', n''	flow behavior indices
ΔP	pressure drop (Pa)
\dot{Q}	volumetric flow rate (m ³ /s)
r_{32}	Sauter mean bubble radius (m)
Re_D	Reynolds number
t	time (s)
u_f	average fluid velocity in a channel (m/s)
u_s	wall slip velocity (m/s)
V	volume (m ³)
x	surfactant mass fraction (wt.%)

Greek symbols

α	empirical constant, $u_s = \alpha \tau_w$
β	empirical constant, Eq. (9)
$\dot{\gamma}_a$	apparent shear rate (s ⁻¹)
$\dot{\gamma}_{a-s}$	apparent shear rate corrected for slip velocity (s ⁻¹)
$\dot{\gamma}_w$	true wall shear rate (s ⁻¹)
ε	specific expansion ratio, ρ_l / ρ_{CGA}
μ	dynamic viscosity (Pa s)
ρ	density (kg/m ³)
σ	surface tension (N/m)
τ_w	wall shear stress (Pa)
τ_0	yield shear stress (Pa)
ϕ	volume fraction of air in CGA or porosity, V_g / V_{CGA}

Subscripts

CGA	refers to CGA
e	effective property
exp	refers to measured data
f	refers to working fluid in general (water or CGA)
g	refers to gas in CGA
l	refers to the liquid-phase or single-phase water
w	refers to the wall

2. Background

2.1. Foam rheology

Liquid foams are known to be non-Newtonian fluids. Different rheological models have been proposed to predict the evolution of the wall shear stress τ_w as a function of the apparent shear rate $\dot{\gamma}_a$ [14,17,18]. In brief, the pseudo-plastic power-law model has been widely used [19–24] after correcting for possible wall slip velocity. Then, the wall shear stress τ_w , the true wall shear rate $\dot{\gamma}_w$, and the apparent shear rate $\dot{\gamma}_a$ are related by the power law:

$$\tau_w = K_P \dot{\gamma}_w^n = K_P' \dot{\gamma}_a^n = \mu_e \dot{\gamma}_a \quad (1)$$

where K_P and n are the so-called flow consistency and flow behavior, respectively. The apparent shear rate $\dot{\gamma}_a$ corresponds to what the wall shear rate would be if the fluid were Newtonian. The true wall shear rate $\dot{\gamma}_w$ can be derived from $\dot{\gamma}_a$ through the Rabinowitsch–Mooney relationship [25]:

$$\dot{\gamma}_w = \left(\frac{3n+1}{4} \right) \dot{\gamma}_a \quad \text{and} \quad K_P' = K_P \left[\frac{3n+1}{4n} \right]^n \quad (2)$$

On the other hand, Khan et al. [26] found experimentally that polymer–surfactant-based aqueous foams with porosity larger than 0.9 and bubble diameter around 65 μm behave as a Bingham fluid for which the shear stress is expressed as

$$\tau_w = \tau_0 + K_B \dot{\gamma}_w \quad (3)$$

where τ_0 is the yield stress and K_B is an empirical constant.

The Herschel–Bulkley model encompasses the previous models. It has been used successfully for macrofoams made of aqueous polymer solutions [14,27] and is given by

$$\tau_w = \tau_0 + K_{HB} \dot{\gamma}_w^{n'} \quad (4)$$

where τ_0 is the yield stress, K_{HB} is the consistency, and n' is the power-law index.

The above models are typically used for incompressible fluids. However, foams and CGA are compressible fluids which can be analyzed using the volume equalization method proposed by Economides and co-workers [19–21] and successfully applied to flow of polymer foams under high pressure. Their model relates the volume equalized shear stress to the volume equalized shear rate according to the power law:

$$\frac{\tau_w}{\varepsilon} = K_{VE} \left(\frac{\dot{\gamma}_w}{\varepsilon} \right)^{n''} \quad (5)$$

where K_{VE} and n'' are empirical constant while ε is the specific expansion ratio defined as the ratio of the densities of the liquid phase and foams or CGA, i.e., $\varepsilon = \rho_l / \rho_{CGA} = 1 / (1 - \phi)$ where ϕ is the gas volume fraction or porosity.

Moreover, mechanistic models have been developed to overcome the limitations of empirical correlations in predicting the rheology of foams made from surfactant solutions different from those for which they were developed. Earlier models considered two-dimensional foams with large gas volume fraction (porosity) and perfectly ordered and monodispersed bubbles. First, Khan and Armstrong [28] and Kraynick and Hansen [29] focused on the liquid film separating the bubbles as the source of viscous dissipation. Based on their model, they concluded that foams behave as a Bingham fluid (Eq. (1)). This result was confirmed experimentally by Khan et al. [26] but contradicts numerous other experimental evidences for both foams [19–24] and emulsions [30].

Alternatively, Schwartz and Princen [31] focused on the Plateau border where the liquid was assumed to be confined. The authors expanded Bretherton's model [32] for pressure drop along a single bubble flowing in capillary tubes. They solved the Navier–Stokes

not provide room for finite inner water phase as proposed by Sebba [1]. Thanks to X-ray diffraction, they showed that the soapy shell consisted of more than one layer of surfactant molecules. However, they noticed a large uncertainty on the exact number of layers. It remains unclear, however, if and how rheological properties of CGA differ from that of foams.

The present study aims at experimentally investigating the rheology of CGA flowing in cylindrical pipes with various diameters and different concentrations of the non-ionic surfactant Tween 20. It also compares the experimental results with theoretical models proposed in the literature for regular foams.

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