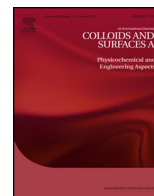




Contents lists available at SciVerse ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa



Influence of surface properties and bulk viscosity on bubble size prediction during foaming operation

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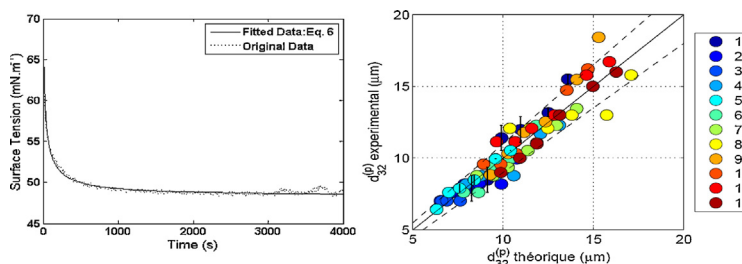
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HIGHLIGHTS

- Effect of processing parameters, bulk viscosity and surface tension on foam formation.
- The modelling of foaming operation by dimensional analysis.
- Viscosity, rotation speed and surface tension are the most influent parameters on foam formation.
- The bubble size in the foams was found to decrease in line with increasing mixing speed.
- Sauter diameter decreases with increasing viscosity and increasing concentration of surfactant.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 30 November 2012
Received in revised form 4 May 2013
Accepted 6 May 2013
Available online xxx

Keywords:

Surface tension
Whey protein
Surfactant
Dimensional analysis
Bubble size
Foam

ABSTRACT

The aim of the present studies was to follow in detail and understand how the surfaces properties, viscosity of the continuous phase according to process conditions (whipping rotation speed, pressure, and flow rates) were related to the micro-structure of the foam (bubble size).

Newtonian model foods containing glucose syrup and foaming agents (WPI or sucrose fatty ester) were prepared and characterized using rheometry and tensiometry. The effect of surfactant type, surfactant concentration and bulk viscosity on interface properties were evaluated using a drop tensiometer. Foams were generated by an instrumented industrial rotor–stator mixer. Bubble size distributions were determined by image analysis.

A dimensional approach allowed us to determine the correlation between the Sauter diameter and some interfacial properties, bulk viscosity and process variables. The bubble size in the foams was found to decrease in line with increasing mixing speed, increasing viscosity and increasing concentration of surfactant. Dynamic surface properties appeared to be relevant and should be included in the prediction.

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1. Introduction

Foams are complicated systems and frequently encountered in the everyday life, as well as in most industries, including the food industry. An understanding of the mechanisms underlying their formation is essential to the production of such high-quality products in a reproducible way. The foaming operation consists in the

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Nomenclature

Symbols

a_1 – a_6	exponent (dimensionless)
C	concentration
Ca	Capillary number
$d_{32}^{(p)}$	Sauter mean drop diameter (i.e. at atmospheric pressure) (m)
D	rotor diameter (m)
g	gravitational acceleration (m/s^2)
K_d	diffusion rate
N	rotor speed ($rev\ s^{-1}$)
Q_L	liquid flow rate (m^3/s)
Q_G	gas flow rate (m^3/s)
P, p	pressure (bar)
R^2	linear regression correlation coefficient (dimensionless)
t_r	time required for the reorganization (s)
T	temperature
We	Weber number (dimensionless)

Greek symbols

σ	surface tension (N/m)
σ_{eq}	surface tension at equilibrium (N/m)
η	apparent viscosity of continuous phase (Pa s)
ρ	continuous phase density (kg/m^3)
η_G	gas viscosity (Pa s)
ρ_G	dispersed phase density (kg/m^3)
γ	shear rate (s^{-1})

inclusion of gas bubbles in a continuous matrix and results from two sub-processes: air entrapment and bubble break-up [1]. In the case of liquid continuous phases, and because aerated liquids (liquid foams) are thermodynamically unstable, bubbles must be stabilized at the air–liquid interface. This stabilization is usually achieved through an increase in the viscosity of the liquid phase and the addition of surface-active agents such as proteins and molecular weight surfactants [2,3]. Both types of molecules tend to adsorb at interfaces and lower the surface tension. As they have very different chemical structures the mechanism by which they stabilize bubbles differs. The composition and structure of these adsorbed layers determine the behaviour of foams. In particular, these interfacial films should also be able to diminish external disturbances that prevent the film from rupturing [4]. During foam formation, new interfaces develop continuously and a rapid adsorption of the surfactant is desirable. The rate of adsorption of a surfactant during foaming processes is critical to foam stability and depends on conditions such as surfactant concentration and adsorption kinetics, as well as the rate of dispersion.

A variety of methods (bubbling, steam injection, and mechanical whipping) are possible to produce wet foam [5,6]. In industrial settings rotor–stator mixers are used. In such devices, the gas is injected directly into the mixing head, where high shearing gaps ensures dispersion of the two phases [7–10]. The incorporated air is then broken down into smaller bubbles, either by kinetic energy or by the high speed motion of an impeller which generates shear and turbulence movements in the mixture [11]. The generated mixing flows are very complex and are still poorly characterized [7,12,13]. The operating parameters are: rotational speed, fluid flow rate, gas flow rate, the pressure and the temperature of the mixture. Foam formation using these devices has been achieved successfully by many authors [7,14–22].

While the role of surfactants and the influence of physicochemical parameters on creation of an interface have been well

documented [23–26], few authors have studied the influence of this process on foam structure. The aforementioned studies focused on industrial products with complex compositions and complex rheological properties [16,27,28] in which it was difficult to take account of viscosity and rheological behaviour. In other studies, the influence of rheology was studied using Newtonian model fluids [26] or simplified (fat-free) shear thinning model fluids [17]. In most studies, the influence of process or product parameters on foam structure has been characterized by measuring a mean bubble diameter using a microscopic image analysis procedure [8,15,16,29].

The bubble size is one of the important factors governing the properties of foam: its control is crucial and this is a major challenge that has not yet been met in industrial food processing. To model the bubble size of their system, reference is often made to the so-called Weber number, We . This dimensionless number stems from the Capillary number Ca , defined by Taylor in the small deformations range and at infinite dilutions [30]. It reflects the balance between the viscous forces that tend to deform the bubbles and the interfacial forces that tend to maintain the spherical shape.

$$We_{cr} = \frac{\eta \cdot \dot{\gamma} \cdot d_{3,2}}{\alpha \cdot \sigma} \quad (1)$$

In Eq. (1) $d_{3,2}$ is the Sauter diameter defined as a volume surface mean diameter, σ is the gas/liquid surface tension at equilibrium, η is the continuous phase viscosity and $\dot{\gamma}$ is the shear rate. As the Weber number was originally defined at a local scale, this expression is usually corrected as a function of the used equipment and the product under study. Some work has focused on the effect of surface tension kinetics on foam generated at a laboratory scale [31–33]. As bubbles are generated for periods in the order of milliseconds, short-term surface tension may be more relevant to explain the foam structure.

This paper focuses on the continuous dispersion of a gas phase in a rotor–stator unit. The objective was to use dimensional analysis to correlate the Sauter diameter with bulk viscosity, surface tension and operating conditions for foams generated at a pilot scale. Model systems with controlled bulk viscosity and surface properties were formulated. Newtonian fluids at different levels of viscosity and two foaming agents were studied: whey protein isolate and a low molecular weight surfactant, which generated different surface tensions at equilibrium. The foams were processed in a complex industrial device under laminar flow conditions at several different mixing speeds.

We also investigated the effect of surfactant adsorption on mean bubble size; supplementary experiments involved changing the concentration of surface-active molecules in the continuous phase.

2. Materials and methods

2.1. Materials

The continuous phase of the model food consisted of commercial glucose syrup (Roquette, France; dry matter content of 80%) at different concentrations. Using this glucose syrup at different concentrations allowed us to change the viscosity level of the solution. All the solutions presented a Newtonian behaviour. Two surface-active agents were used: Whey Protein Isolate (Prolacta90; 52.3% β -lactoglobulin, 15.3% α -lactalbumin for 90% total nitrogen) was purchased from Lactalis (France). Sucrose fatty acid ester (E473; saccharose esterified with stearic and palmitic acids (70/30), 70% mono-esterified; HLB = 15) was obtained from Stearinerie Dubois (France). These two ingredients are widely used as foaming agents in the food industry.

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