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Effect of formulation and processing factors on the properties of liquid food foams

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Abstract

The aim of this work was to determine the phenomena affecting bubble size, according to process conditions (pressure, flow rates, whipping rotation speed) and formulation properties. Model fluids were formulated in order to get simple and well-defined rheology. An instrumented foaming pilot-scale line was built and allowed us to monitor the process and to characterise bubble size under pressure, at the exit of the mixer.

Viscosity and rotation speed of the whipping head are the most influent parameters on foam morphology: interaction between these factors have been highlighted. Experimental measurements obtained were consistent with the critical Weber number since a corrected fluid viscosity is used. It seems indeed that the fluid viscosity is reduced in the whipping head, due to the presence of local heating. These temperature variations consequent to the shear of viscous fluids in a narrow-gap geometry were quantified and modelled as a function of shear rate and fluid viscosity.

Keywords: Foam; Processing; Bubble diameter; Weber number; Viscous dissipations

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1. Introduction

Foams are the subject of a strong interest in a large number of industries, including textile, building trade, oil industry, personal care, etc... In the food industry, foams are also present in a variety of applications, from dairy products to ice creams, soft doughs, confectionery or meat. Indeed, a number of food products show a porous structure that is created either by chemical (e.g. raising powders in biscuits), biological (yeasts in bread) or mechanical (dairy foams) means. These porous food materials are often referred to as "solid" or "liquid foams", depending on the mechanical properties of the continuous phase. Liquid foams here refer to suspensions of gas bubbles in a liquid, with moderate volume fractions (up to 50%), such as typically encountered in food products. Within this class of products, bubble size is of major importance for the foam properties, as it influences the texture, the mouth-feel and the stability of the aerated product.

To predict the bubble size resulting from a mechanical treatment, it is usually referred 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 (Taylor, 1932). It reflects the balance between the viscous forces tending to deform the bubbles over the interfacial forces that tend to maintain the spherical shape

$$We_{\mathrm{cr}} = \frac{\eta \cdot \dot{\gamma} \cdot D_{3.2}}{\alpha \cdot \sigma} \tag{1}$$

In Eq. (1), $D_{3.2}$ is the Sauter diameter defined as a volume surface mean diameter, σ is the gas/liquid interfacial tension, η is the continuous phase viscosity and $\dot{\gamma}$ the shear

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rate. α is a coefficient which vary depending on authors: it can be equal to 1 (De Lorgeril, Cuvelier, Vaslin, & Launay, 2000; Djelveh, Cornet, & Gros, 1999; Kroezen & Groot Wassink, 1987) 2 or 4 (Hanselmann & Windhab, 1999). As most of the numerical values published were calculated using $\alpha = 1$, this value was kept in this study in order to allow a comparison between data.

When We becomes larger than a critical value We_{cr}, bubble break-up is expected to occur: knowing the critical Weber number allows to determine the maximum bubble size that can exist in a dispersion process. Literature gives values of Weber numbers around 0.3–0.5 for foaming applications (De Lorgeril et al., 2000; Djelveh et al., 1999; Djelveh & Gros, 1995; Kroezen & Groot Wassink, 1987; Thakur, Vial, & Djelveh, 2003).

Using this approach, bubble size was estimated in a number of studies and compared with actual measurements. The results are usually in good qualitative agreement with experimental measurements (Djelveh et al., 1999; Hanselmann & Windhab, 1999). Thus, the use of Weber number would seem to be a robust and convenient way to predict bubble size in a continuous foaming process. However, at least three limitations to this approach can be underlined.

First, most studies in the literature have been using complex formulations such as ice-creams, emulsions or dairy deserts. These formulations may have several phases before foaming (water, fat, possibly crystals or solid particles) and exhibit a complex rheological and interfacial behaviour. It is hence difficult to define the apparent viscosity under the processing conditions, since it depends on shear and time.

The second limitation is that most studies are performed in process conditions that are not representative of pilot or industrial ones. Indeed, foam literature is mainly focused on two topics: the impact of ingredients, notably those with surface-active properties (Bos & Van Vliet, 2001; Murray, 2002; Rodríguez Patino & Rosario Rodríguez Niño, 1999; Walstra & De Roos, 1993), and the physical mechanisms involved in foam formation and stability (Dickinson, 1999; Graham & Phillips, 1976; Langevin, 2000; Rouimi, Schorsch, Valentini, & Vaslin, 2005; Walstra, 1987; Wilde, 2000). In most cases, foaming was carried out at the laboratory scale by simple whipping in batch conditions and at atmospheric pressure (Bee, Clement, & Prins, 1987; Lau & Dickinson, 2004). Foams are described at "a local scale" (i.e. the bubble) and in small deformation conditions which differ from those encountered in industrial whipping processes. Only a few studies used a continuous process to produce foam, either using laboratory geometries consisting in a rotor with blades and a smooth cylindrical stator (De Lorgeril et al., 2000; Djelveh et al., 1999; Djelveh & Gros, 1995; Thakur et al., 2003) or with pilot-scale devices, with cogged rotor–stator units (Hanselmann & Windhab, 1999; Kroezen & Groot Wassink, 1987; Kroezen, Groot Wassink, & Bertlein, 1988). In these studies, the influence of some processing parameters such as rotation speed of the whipping head is studied and estimations of average shear rate, residence time, and flow conditions are usually given. However, the impact of pressure in the foam formation was found to be scarcely described, which initiated some of the work discussed in the present paper.

The third limitation of existing literature is that foam is usually characterised at rest, after depositing. Only two teams report in-line measurement (Kroezen & Groot Wassink, 1987; Thakur et al., 2003), using microscopy, which requires a limited flow across a thin transparent observation cell and cannot be done under pressure.

As a sum up, most of the literature on food foams is generated using a lab-scale batch process at atmospheric pressure, which cannot directly be extrapolated to actual processing situations. There are only a few works that study foam formation at the pilot scale, but the continuous phase is often rheologically complex and/or the characterisation of the foam in done off-line. This has motivated the present study, in which:

- model (or at least well-characterised) fluids have been formulated,
- a pilot-scale continuous process under pressure has been used and
- on-line monitoring of the foam at different stages of the process has been performed.

These choices were motivated by the following objective: to identify the relative effect of the formulation (i.e. rheological and interfacial behaviour) and of the processing conditions (rotation speed, flow rate,...) in the formation of liquid foams that are characterised by their bubble size.

2. Material and methods

2.1. Model fluids

- The continuous phase consists in a commercial glucose syrup (HM5080, Syral, France), with a dry substance of 80%, a high maltose content (about 51%) and a dextrose equivalent DE of 50. Diluting the syrup allows to cover a wide range of viscosity (two decades), while keeping a Newtonian behaviour. The rheology of these glucose syrup solutions was also measured for several dilutions and at different temperatures, using a MCR300 rheometer (Physica, Germany). The Newtonian viscosity of the continuous phase increases exponentially with increasing syrup concentration and with decreasing temperature. This can be described by a single equation, relating viscosity to fluid dry substance and temperature:

$$\log \eta = 41.5 - 95 \cdot \mathrm{DS} + 236 \cdot \exp(5 \cdot \mathrm{DS}) \cdot \frac{1}{T} \tag{2}$$

  In Eq. (2), DS is the fluid dry substance (in % w/w) and T is the temperature in K.