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Characteristics of foams produced with viscous shear thinning fluids using microchannels at high throughput

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ABSTRACT

Microchannels are used to produce food foams with the aim of obtaining void fractions and flow rates that are in accordance with food industry targets. Whey protein isolate is used as foaming agent and xanthan gum as thickening agent. At the high throughputs implemented, the shear thinning property of the fluid avoids excessive pressure drops. The tested microsystems allow mastering the foams structural properties, especially the bubble size. Stable foams are produced, even with void fraction of 0.55. Thanks to their particular structure, foams maintain their characteristics of rigidity at volume fractions lower than the maximum compactness. This outcome is also enhanced by the effect of salt on whey proteins interfacial film. The results are compared to data previously obtained with static mixers. Microchannels can be used as a continuous foaming process suitable for the food industry as well as a versatile tool for research and development in the scope of industrial expansion.

1. Introduction

Formulation of "food foams" is a dynamic area of food engineering. Foams are largely found in food industry (dairy foams, ice creams …). Foam is defined as a uniform dispersion of gas in a continuous aqueous phase (fizzy drinks, for example) or emulsion (milk froth, for example). Food foams are popular because they offer a wide range of tastes, textures, or nutrition claims (Campbell and Mougeot, 1999). In particular, including bubbles in food products is often targeted as it contributes to improve their texture (Buckman and Viney, 2002). Another field of application concerns healthy food products characterized by low calorie density, as stated by Ahmad et al. (2012).

The foaming operation consists in the inclusion of gas bubbles in a liquid matrix. In the food industry, the dispersion of gas is traditionally carried out in batches, through whipping mixers or also in continuous rotor-stator systems, like "Mondomix™". However, these traditional methods present the disadvantage of being energetically costly and are unable to control the rate of incorporation of air into the foam. One of the challenges is then to develop more efficient foaming processes that guarantee the mean size as well as the size distribution of bubbles. Many alternative methods are or have been investigated such as the use of membranes (Charcosset et al., 2004), ultrasounds (Cho et al., 2005), static mixers (Talansier et al., 2013), narrow gap unit (NAGU) (Souidi et al., 2012) or microfluidics devices (Skurtys and Aguilera, 2008).

The use of membranes could appear to be promising considering the production of monodispersed bubbles, but it encounters several drawbacks such as low treated gas fluxes, high induced process costs and a delicate maintenance. Using ultrasounds allows reducing considerably the size of bubbles (<1 μm) but it is associated with a risk of denaturing fragile food constituents, as multi bubble cavitation leads to locally increased temperatures. Static mixers have been shown to be an interesting alternative to traditional whipping mixers. They can be used as a continuous process and allow to control the rate of gas included in the liquid phase.

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They are low energy consumers. Their disadvantage is the difficulty to elaborate stable food foams with a gas fraction lower than 0.7. Their main drawback is that the gas incorporation is constrained by two limits: a minimum gas fraction to ensure the foam stability, and a maximum one linked with the viscosity and the process parameters (Laporte et al., 2013), so that the fluid viscosity must be tuned to target the food industry requirement in the range 0.55–0.8 (Campbell and Mougeot, 1999).

Microfluidics devices are largely studied since about two decades as they offer many advantages. Miniaturization provides large surface to volume ratios which are in favor of mass transfer, while special arrangements of inlets tubes enhance mixing. In this field, gas–liquid applications are still less developed than liquid–liquid ones. However, microfluidics devices have the capacity to generate quite perfectly mono-dispersed size distribution of bubbles (Ahmad et al., 2012; Skurtys and Aguilera, 2008). Simple and easily handled systems have been proposed, like T-junction which allows producing mono-size microbubbles. Dollet et al. (2008) use the "pinch off" effect to obtain bubbles in an aqueous solution of surfactant. They notice that the polydispersity is about 0.1%. Simple scaling laws are proposed by several authors for different capillary flow focusing systems. These laws allow predicting the bubble diameter or length from parameters like the ratio of fluids flow rates, or from geometrical characteristics of the microchannel device (Ganan-Calvo, 2004). It may be emphasized that most of the works characterize the bubbles shape, size and size distribution in the outlet channel of the microfluidics devices. Some contributions deal with the characterization of regimes of diphasic flow in micro channels. Few contributions investigate the formation of foam in the microchannel but most of the literature deals with bubble train formation. Physical characterization of the foam at the outlet is rarely investigated. Among other advantages, the microfluidics devices are generally cheap and low energy consumers. The main drawback is that mono sized microbubbles and narrow size distribution of bubbles are obtained under flow conditions that do not meet the industrial flow rate requirements. At this stage of the knowledge, obtaining mono sized bubbles is conditioned by the use of capillary restrictions and very low flow rates (~μL/min).

This study aims to investigate the characteristics of food foams produced in microsystems at high throughput. The main idea is to explore the effects of high shear rates that can be achieved at high flow-rates in microsystems, on gas splitting. The viscous friction in such systems can be expected to be prohibitive depending on the nature of the fluid. Therefore, an aqueous solution of whey protein isolates (WPI) as foaming agent and xanthan gum (XG) as thickening agent is used. The shear thinning character of xanthan gum makes it possible to investigate high throughputs while viscous friction is maintained at an acceptable level. In these conditions, two micromixers are tested. They have a cross geometry and consist of two identical channels with square sections equal to 600×600 and 500×500 μm^2, respectively. In the case of liquid–liquid mixing, former works point out that the impact of the fluids generates high shear in the contact area, allowing an intensification of the mixing (Ait Mouheb et al., 2012). In the same conditions, the mixing efficiency is better and pressure drops are lower with crossing channels than with T channels (Ait Mouheb et al., 2012).

In the present work, foams are produced with two different void fractions, respectively 0.55 and 0.72, in accordance with the range of gas fractions generally cited for food foams. This range is complementary to the range of gas fractions (0.72–0.84) obtained with food foams in a previous study dealing with the same liquid solution and using SMX static mixers (Laporte et al., 2015). Obtained foams are characterized by their bubbles size (mean size and size distribution), their rheological properties (yield stress and elasticity) and also by their stability to short time and long time. The effect of the composition of the solution consisting of xanthan and whey proteins, with and without salt, on the foam properties is also investigated. A key parameter for the food industry is the foam stability as the foams need to remain unchanged for weeks before consumption. These results are discussed and compared to the characteristics of foams formerly obtained with SMX static mixers (Laporte et al., 2015).

2. Materials and methods

2.1. WPI-XG solutions

The foams are prepared from aqueous solutions of whey protein isolate (WPI) at different concentrations of xanthan gum (XG) in order to modulate the viscosity. WPI are used for their surfactant properties while XG acts as thickener. WPI powder, Prolacta95, is purchased from Lactalis Ingredients (Bourgbarré, France). The xanthan gum (Cargill, Baupte, France) provides high viscosities at low concentrations, with a strong shear thinning behavior (Laporte et al., 2015). Two solutions were prepared with 3 wt% WPI and 0.35wt% XG. The effect of salt addition is tested with one solution, encoded X035NaCl.The solution without salt is encoded X035. For these concentrations, both biopolymers do not interact and are soluble in water (Benichou et al., 2007). The salt is expected to lower the viscosity of the xanthan solution by screening the electrostatic repulsion between the negatively-charged molecules and hence their hydrodynamic volume in the concentration range employed (Sworn, 2011). Whey proteins are also negatively charged at neutral pH; it limits their interfacial concentration at the bubble surface. Screening protein charges allows getting a denser and compact interface that favors bubble stability against coalescence and ripening. In the concentration tested, salt is supposed to improve the functional properties of both constituents (Mott et al., 1999). The solutions are prepared by dispersing the powders in batches of 20 L in a cylindrical mixing vessel (Guedu, Lavergne, France) at a controlled temperature (40 °C) under low speed stirring (50 rpm) during 5 h. The pH is adjusted to 7, by addition of 0.1 M NaOH solution, for better protein solubilization (Guimarães Pelegrine and de Moraes Santos Gomes, 2008). The batches are then kept at 4 °C over night to ensure complete hydration of the polymers.

The viscosity of the WPI-XG mixtures is determined for each batch using the AR-1000N rheometer (TA Instruments, USA) with a cone-plate geometry (60 mm diameter, 4° cone angle) at 20 °C. Shear rate $\dot{\gamma}$ ranged between 0.3 s^{-1} and 700 s^{-1}. These solutions exhibit a shear thinning behavior that can be fitted with a power law between 0.3 and 700 s^{-1}.

$$\tau = K\,\dot{\gamma}^{n} \tag{1}$$

Where τ is the shear stress, K the flow consistency and n the flow index. The composition and properties of the solutions are summarized in Table 1. The viscosity of the solutions is affected by the

Table 1
Composition and properties of the liquid solutions, 20 °C.

Liquid solution	WPI (wt%)	XG (wt%)	NaCl 0.2 M (wt%)	ρ_L ($kg.m^{-3}$) ± 3%	K ($Pa.s^n$) ± 6%	n (−) ± 5%	σ ($N.m^{-1}$) ± 3%
X035	3	0.35	0	1034	3.1	0.20	0.044
X035NaCl	3	0.35	1.2	1046	2.2	0.24	0.044