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Flow process conditions to control the void fraction of food foams in static mixers

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ABSTRACT

Previous studies have shown the feasibility of food foam production in a SMX10 static mixer. Nevertheless the void fraction, α, obtained was high (>0.85) compared to the target range in food industry (0.5–0.7). This work aims to reduce α by using a smaller hydraulic diameter of the static mixer (SMX+6) and higher liquid base viscosities. The hydrodynamic study exhibits slight differences in the pressure drop and process shear constants. The foams are processed with a liquid base of whey protein isolates (3%) and xanthan gum (0.35% or 0.6%). The boundaries between "slug flow" and "bubble flow" are determined for the two SMX and represented in a flow pattern map. Only the latter flow regime is suitable as α (0.73–0.96) can directly be controlled from the flow-rates. Working with a SMX+6 mm offers a substantial enlargement of the convenient velocity range that allows attaining lower void fractions compared to the SMX10.

1. Introduction

Food foams such as foams based on proteins are in constant development, as they are appreciated by the consumers and offer a wide range of possibilities to suit a variety of tastes, textures, or nutritional allegations (Campbell and Mougeot, 1999). In most cases for food foams, the foaming processes are carried out in batch in table top mixers. According to Campbell and Mougeot (1999), the void fraction of foams usually ranges from 0.5 for chocolate foams or ice creams to 0.7 for whipped creams (Chantilly). Yet, continuous processes bring significant benefits: high productivity, homogeneous shearing, small size of the equipment, energy saving and easy-to-monitor systems (Thakur et al., 2003a. Al Taweel and Chen, 1996; Al Taweel et al., 2007). However, continuous foaming is relatively poorly understood and the current knowledge is mostly empirical.

There are two types of continuous foaming processes. The first type is "dynamic mixers", such as rotor–stator systems (Mondomix™, for one of the most widespread use in the industry), scraped-surface heat exchanger, or even the foaming column developed by Djelveh et al. (1998) and Souidi et al. (2012). The second one is "static mixers", consisting of inserts in the flow section, namely "elements", generating complex flow structure to create the mixing. There are different shapes of static mixers but the cross designed ones, of SMX type, outperform the others, especially in the laminar regime (Meijer et al., 2012. Fradette et al., 2006). Static mixers are usually used for liquid–liquid extraction, liquid–gas absorption, heterogeneous chemical reactions, suspensions, emulsification or solid–liquid mixing (Paglianti, 2008). In the suitable foaming conditions, the main asset of static mixers is that the gas incorporated in the foam can directly be controlled from the flow-rates (Talansier, 2009), which is not the case in most of the other foaming processes. For example, the amount of gas incorporated with the Mondomix™ is only 30–80%, which makes it impossible to master the amount of overrun (Thakur et al., 2003b, 2005).

In a previous study displaying the opportunity to produce food foams with a static mixer, it has been shown that foams from egg white proteins can be produced in a SMX10 static mixer for void fractions (i.e. gas volume fractions) above 0.85, i.e. corresponding to dry foams (Talansier et al., 2013). However, as mentioned above, food foams are usually liquid foams with void fractions lower than 0.8. Actually, a key parameter for industrial foams is the stability, whereby smaller bubbles as well as higher void fractions improve the foam stability (Talansier et al., 2013). The challenge of overrun reduction (less than 0.85, compared with the previous runs in the SMX10 with egg white proteins), appears at first sight to be delicate, as it will affect the structural and textural characteristics of a foam with a negative effect on the stability. Literature reports that it is necessary to increase either the shear rates or/and the

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liquid viscosity to compensate for it (Hanselmann and Windhab, 1999; Mary, 2011; den Engelsen et al., 2002).

The determination of the conditions that are required to achieve the gas mixing in the main liquid flow, i.e., the flow pattern, is crucial in the industrial process control for both dynamic and static mixers. In a biphasic gas/liquid flow, the two phases distribute themselves into several distinct flow patterns depending upon their flow-rates, properties and pipe geometry (Kleinstreuer, 2003). These are referred to as flow regimes, mainly the annular, slug/plug and bubble regimes that are recognized by visual inspection. There have been several experimental works on the gas–liquid flow patterns in horizontal pipes (Baker, 1954. Mandhane et al., 1974; Wong and Yau, 1997). However, the frontiers between the different regimes cannot be expressed by the same dimensionless numbers, despite the different attempts to establish universal maps (Schicht, 1969; Taitel and Dukler, 1976; Barnea et al., 1980; Spedding and Chen, 1981; Lin and Hanratty, 1987). Different studies oriented toward fluid properties have been published; nevertheless, very few investigations were conducted on the effect of the fluid viscosity in the case of flow through horizontal pipes. Studies concerning high fluids viscosity came up with contradictory conclusions: Matsubara and Naito (2011) stated that the regimes are affected by the viscosity, whereas Weisman et al. (1979) reported only minor changes induced by this parameter. A decrease in the surface tension shifts the frontiers to lower gas velocity (Spedding and Hand, 1997. Wilkens et al., 2006) but this effect vanishes at high gas velocities (Tzotzi et al., 2011)). Therefore, additional work is required for the understanding of the flow pattern maps, especially in a complex geometry such as the SMX, generating elongational effects that are not present in empty plain tubes (Bone, 2005).

In this study, we propose to investigate the effect of the flow conditions and of the liquid base properties in two SMX static mixers characterized by different hydraulic diameters. The experiments are designed to determine the flow process conditions in SMX static mixers enabling formation of foams at lower void fractions. Firstly, a hydrodynamic study is performed through the determination of the respective characteristic constants: K_p, the power constant, and Ks, the shear rate constant evaluated by the Metzner–Otto method (Metzner and Otto, 1957). The hydrodynamic conditions allowing complete and homogeneous gas incorporation and corresponding to the bubble regime are experimentally determined, by varying the gas and liquid flow-rates for each tested solution. Foams are made of whey protein isolates (WPI) as foaming agent and xanthan gum (XG) at different concentrations to modulate the liquid viscosities, elucidating the effect of liquid base viscosities on the flow pattern.

2. Experimental facility and methods

2.1. SMX static mixers

The foams are elaborated by gas injection in a continuous flow of liquid using the static mixers SMX™ or SMX+™ (Sulzer, Winterthur, Switzerland). They have a respective inside diameter of 10 and 6 mm in diameter. One element of SMX consists of stainless steel crossed bars at angles of 45° over flow direction with ratios of length to diameter equal to one. Each element is rotated 90° prior to the previous element. Characteristics of the static mixers geometry are given in Table 1.

2.2. Hydraulic loop

The elements of static mixers are included in the hydraulic loop shown in Fig. 1. A gas injection device has been designed to feed the static mixer section with air. It is located immediately upstream the first element of static mixer. Its specific geometry ensures that the gas is well dispersed all around the pipe diameter: the gas is introduced in the liquid by an annular dispenser with 12 tubular holes symmetrically located around the section. The injection holes are 0.5 mm in diameter for SMX10 and 0.3 mm in diameter for SMX+6.

The experimental loop includes a screw pump (Lenze™) to feed the static mixer with the liquid, as well as a liquid flow-meter and a gas mass flow-meter (Proline Promag 50 and Promass 80 from Endress + Hausser™). Two pressure sensors, Ceraphant T and Deltabar S (Endress + Hausser™), with adjusted measuring range until 3 bars, are located at the gas inlet and at the bounds of the static mixer to measure the pressure drop across the mixer. Thermocouples (Type K, Omega®) are used to record the temperatures of liquid and foam.

2.3. Fluids: whey protein – xanthan gum solutions

2.3.1. Composition and preparation

The liquid phase consists of Whey Protein Isolate (WPI) (Lactalis Ingredients, Bourbarré, France) with 95 wt% protein as surface-active agent and Xanthan Gum (XG) (Cargill, Baupte, France) acting as a thickener. Two WPI-XG solutions are prepared from 3 wt% WPI, and 0.35 and 0.6 wt% xanthan gum, referred to as WPI3XG35 and WPI3XG06 respectively. A third solution is obtained by adding NaCl (0.2 M) to WPI3XG035 to test the eventual effect of the ionic strength on the conformation of the protein and/or xanthan gum. These concentrations correspond to the ones used in the milk industry (Fox and McSweeney, 2003; Simon, 2001). For these concentrations, the two biopolymers are non-interacting and mutually soluble in the water (Benichou et al., 2007).

Dispersions are obtained using the following procedure. Batches of 20 L are prepared in a cylindrical mixing vessel (Guedu, Lavergne, France). Powders of WPI and xanthan are dispersed in water, at a controlled temperature (40 °C) and at pH 7, by the addition of 0.1 M NaOH solution, for better protein solubilization (Guimarães Pelegrine and De Moraes Santos Gomes, 2008). Stirring is carried out at low speed (50 rpm) to prevent formation of foam, during five hours, and then the batches are kept at 4 °C to ensure complete hydration of the polymers

2.3.2. Viscosity and surface tension

The viscosity of the WPI-XG mixtures is determined for each batch using the AR-1000N rheometer (TA Instruments, USA) with cone-plate geometry (60 mm diameter, 4° cone angle) at 25 °C. Shear rate $\dot{\gamma}$ ranged between 0.2 s^{-1} and 2800 s^{-1}. The viscosity of the solutions is affected by the XG concentration, and the addition of sodium chloride decreases the viscosity. These solutions exhibit a shear thinning behavior as seen in Fig. 2 and can be fitted with a power law for shear rates between 0.3 and 700 s^{-1}.

$$\mu = K\dot{\gamma}^{n-1} \tag{1}$$

where τ is the shear stress, K is the flow consistency index and n the structure index.

The interfacial tension σ of the test solutions (3 wt% WPI) was measured with a K12 tensiometer (Krüss GmbH, Germany) using the Wilhelmy's plate method at 20 °C during 3 h. With a constant WPI concentration, the interfacial tension is 43 ± 1 mN m^{-1} at long time (equilibrium value) for all the solutions. Neither xanthan gum nor sodium chloride changes the interfacial tension. The composition and properties of the solutions are gathered in Table 2.