

Effect of Matrix Elasticity on the Continuous Foaming of Food Models

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Abstract The aim is to understand the effect of matrix elasticity on continuous foaming using food models based on glucose syrup. This was modified by adding polyacrylamide (PAA) with 2% whey protein isolate (WPI) or Tween 80 as foaming agents. Foaming was conducted in a stirred column. Rotation speed N and gas-to-liquid flow ratio (G/L) were varied. Overrun, average bubble size d_{32} , texture and stability were measured using densimetry, image analysis, and rheometry, respectively. Experimental results showed that 0.01% PAA did not modify the viscosity of 2% WPI models, but conferred low elastic behavior. PAA (0.05%) doubled matrix viscosity and drastically increased elasticity. The increase of elasticity became slower for further PAA addition. Foaming experiments demonstrated that theoretical overrun could not be achieved for inelastic WPI models in two cases: for high viscosity and low N , as dispersion effectiveness was reduced; for high G/L and N because of enhanced coalescence. Matrix elasticity was shown to increase overrun at constant viscosity for high G/L by enhancing interface stabilization. However, in elastic models, gas dispersion was more difficult and d_{32} was higher than in inelastic fluids of similar viscosity. Finally, when the limiting step was dispersion, foaming was shown to be negatively affected by matrix elasticity.

Keywords Foamed food · Foaming process · Matrix elasticity · Matrix viscosity

Introduction

Whipping or foaming process denotes a unit operation of food engineering that consists of the dispersion and the stabilization of a gas phase in the form of bubbles into a continuous liquid phase or a semi-solid matrix. Its objective is to confer to a food material an aerated structure similar to that of wet foams. The expression “foaming” is preferred when the operation is carried out continuously under steady state conditions. Foaming and whipping

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correspond to a mechanical treatment that requires gas injection or surface aeration; this is usually applied to food when the gas phase is not produced through chemical (e.g., using sodium bicarbonate) or biochemical ways (yeast dough...). This situation corresponds to many industrial products such as desserts (fruit fools, chocolate mousse, whipped cream, ice cream, meringue...), to mousses based on meat, fish or vegetable, but also to some cakes and biscuits (sponge cake, lady finger batter...) and to some fermented food (spreadable cheeses...). If foaming operation has been devoted to make lighter products, it is also able to modify the visual aspect and to provide a softer texture to food products. Indeed, the presence of a dispersed gas phase confers simultaneously cohesion, scoopability and spreadability, together with a more homogeneous aspect and a more uniform distribution of flavors. As a result, foaming operation has been widely used in the nineties as a flexible tool for developing innovative food products adapted to consumer choice and needs, using air as a zero-cost ingredient [1, 2].

Although foaming is a unit operation used for centuries in food industry, it is however not fully understood yet because it involves a complex interplay between food formulation and process conditions. Indeed, the addition of gas phase modifies drastically the microstructure of the raw material. The end-use properties of the resulting foam depend on its gas content (namely, the overrun) and on the size and the morphology of bubbles, but also on the distribution of the ingredients between the matrix and the gas–liquid interfaces [3]. If the effect of ingredients on whipping, such as proteins, fat or stabilizers (mainly gelatin and polysaccharides) has been studied for a long time, most contributions on ingredients have dealt only with the ability of proteins to form and to stabilize foams in model systems (mainly proteins in water, sometimes with one additive), rather than in complex food [4, 5]. This neglects the possible interactions of proteins with other ingredients and there is still much to understand on the interactions between ingredients during foaming. Similarly, the respective influences of the geometry of the foaming device and of operating conditions have been disregarded up to the early nineties [6, 7] using only kitchen mixers to conduct foaming [8]. The continuous foaming operation in a mechanically stirred foaming device had already been used to carry out foaming on several models and real foods, such as a white sauce [9], an ice cream mix [10], a spreadable cheese [11, 12] and dairy toppings [13]. Although the mechanisms of foaming and emulsification processes look similar (i.e. both require high mechanical stress to achieve dispersion of either a gas or an immiscible liquid phase), gas dispersion and stabilization are more difficult to achieve than emulsification because of the higher density difference between the continuous and the gas phases and also because of the higher interfacial tension of gas–liquid interfaces. As a result, the abundant literature on emulsion preparation cannot be directly applied to foaming operation and there is still much to discover on the technological aspects of foaming operation.

For real food, the attempts to correlate the properties of raw materials to their foaming ability, taking into account operating conditions, has been limited mainly to the respective effects of viscosity and surface tension [2], although food media are complex fluids that often exhibit viscoelastic properties. These result mainly from the presence of biopolymers, such as proteins, thickening and gelling agents, as well as colloidal particles (partially crystallized fat droplets, micelles, ice crystals...) that can interact through complex mechanisms, such as polymer entanglement, thermodynamic (in)compatibility, bridging, depletion... [14]. In particular, the influence of matrix elasticity on foaming of food products has been ignored. Indeed, viscoelastic media present the particularity to behave either as an elastic solid or a fluid as a function of the intensity and the frequency of the mechanical stress applied to them: The fluid behavior prevails for slow deformation and

low shear rate, while elasticity dominates at high deformation and shear rate. This is often accounted for using the dimensionless Deborah number (De) [15]:

$$De = \frac{t_f}{t_p} \quad (1)$$

in which t_f is the relaxation time scale of the fluid and t_p the time scale of the process. A particular manifestation of elasticity is the Weissenberg effect in stirred tanks [16]. This may be quantified using the dimensionless Weissenberg number (Wi) that corresponds to a particular form of De for shear-dominated flows:

$$Wi = \frac{N_1}{2\tau} \quad (2)$$

in which N_1 is the first normal stress difference that measures the anisotropy of the stress tensor due to elasticity, while τ is the viscous shear stress. Elasticity number (El) is often used in place of Wi to measure the anisotropy generated by elasticity under strain:

$$El = \frac{Wi}{Re} \text{ or } El = \frac{De}{Re} \quad (3)$$

In Eq. 3, Re is the dimensionless Reynolds number that corresponds to the ratio of inertial forces to viscous forces.

The main difficulty for investigating the influence of matrix elasticity in foaming operation applied to food products is that these media often exhibit simultaneously viscoelastic and pseudoplastic behaviors. Therefore, the first objective of this work was to define food models exhibiting simultaneously a Newtonian behavior rate in order to overshadow pseudoplasticity, together with measurable “elastic” normal forces. It should be mentioned that “Newtonian behavior” in this work means that the viscosity of the studied fluid does not depend on the shear rate, assuming laminar flow and constant temperature and pressure. Using the previous work of Narchi et al. [17], a Newtonian mixture including glucose syrup and a foaming agent (whey proteins or Tween 80) was selected as an inelastic model. Elasticity was induced by the addition of an elasticity promoter, i.e. polyacrylamide [18]. Then, the second objective of this paper was to better understand the role of matrix elasticity, both on the dispersion and the stabilization of gas phase.

Materials and Methods

Preparation of Food Models

Foaming experiments were carried out using a Newtonian glucose syrup as a food model. The amount of dehydrated glucose syrup (Glucidex IT21, *Roquette Frères*, France) in water was selected to adjust the viscosity of the continuous phase between 1 and 2 Pa s at 25°C, using previous results of Narchi et al. [17]. Two surface active agents were added at 2% (w/w). The first one consisted of whey proteins isolate (WPI) (Prolacta90, *Lactalis*, France) which is often used as a foaming agent in food because it provides abundant and stable foams. This behavior is often attributed in the literature to the formation of cohesive interfacial gels through disulfide bonds, which provides a high surface elasticity to the interface [5]. The second one belongs to the nonionic surfactant class: Tween 80 (*Acros Organics*, Belgium). It is known to form abundant dry foams in water, stabilized through Gibbs–Marangoni effect [19]. Narchi et al. [17] had already demonstrated that such additions neither modified the

Newtonian behavior of the food model, nor provided matrix elasticity. Finally, the synthetic polymer polyacrylamide (PAA) was used as an elasticity promoter because of its high water solubility and its ability to provide high elasticity in water at low concentration [18]. Thus, PAA was added in the syrup alone or together with one of the prior tensioactive agents. In this work, the amount of PAA used to modify the matrix elasticity of food models was varied between 0.01% and 0.1% (w/w) with the constraint to maintain a Newtonian behavior for viscosity in the range of shear that interests foaming process.

The preparation of models was carried out in a kitchen mixer (Stephan UMC 5, Germany) under vacuum at room temperature (about 25°C). The method consisted in adding successively in water: PAA (optional), foaming agents (optional), and finally dehydrated glucose syrup. Models were kept overnight at room temperature for aging. This aging period was necessary for the total hydration of proteins.

Foaming Process

The apparatus used for continuous foaming operation consisted of a three-stage jacketed column. This was mechanically stirred using a cross-blade impeller in each stage of the column. This device was used first by Djelveh and Gros [6] and described in detail in many other papers [9, 20]. The rotation speed of the impeller in the column (N) was varied between 400 and 1,600 rpm using a speed-controlled IK LaborTechnik RE-16 engine (Ika-Werke GmbH, Germany). The torque (T) between the shaft and the impeller was measured using a MR-D1 system (Ika-Werke GmbH, Germany) during foaming process. The liquid flow rate (L) was kept constant at 30 ml/min using a peristaltic pump (Cole-Parmer Instr., IL, USA) and the gas flow rate (G) was adjusted between 10 and 30 ml/min using a thermal mass flowmeter (Brooks Instr., PA, USA). Both phases were introduced co-currently from the bottom of the column. The exit temperature was maintained at 25°C using the circulation of a cooling fluid in the jacket using a WKL-600 cryostat (Lauda GmbH, Germany). The exit stream at the top of the column was divided into two streams, one for collecting foam samples for density and rheological measurements (see “[Methods for Model and Foam Characterization](#)” section), while the other one passed through an online image analysis system described in detail in “[Characterization of Foamed Product Properties](#)” section. Steady state conditions were assumed when the foam density at the outlet and the torque were constant over time for three successive samples.

Methods for Model and Foam Characterization

Characterization of Food Models

Model foods were characterized after aging in terms of density, surface tension and rheological properties. Surface tension (σ) was estimated by the Wilhelmy plate method using a K-12 tensiometer instrument (Krüss GmbH, Germany). Rheological properties were measured using a stress-controlled SR-5 rheometer (Rheometric Scientific, NJ, USA) equipped with a Peltier circulator for temperature control. A parallel plate of 40 mm diameter with a gap of 0.5 mm was used to determine the mechanical response of fluids, both under high and low shear deformation. Rheological properties under steady state conditions were measured using shear rate $\dot{\gamma}$ between 10 and 1,000 s⁻¹: viscosity (η), shear stress ($\tau = \eta \cdot \dot{\gamma}$) and first normal-stress difference (N_1). Weissenberg number, Wi , was deduced from these measurements using Eq. 2. Then, dynamic oscillatory measurements were carried out to determine the low-deformation viscoelastic properties before foaming.

Measurements included strain sweep tests from 0.4% to 100% strain at constant temperature and frequency (1 Hz), as well as frequency spectra from 0.1 to 10 Hz at constant strain (2%) and temperature. These give access, respectively, to the elastic shear modulus (G'), the viscous shear modulus (G''), the complex viscosity (η^*), and tangent loss ($\tan \delta$) defined as the ratio G''/G' .

Characterization of Foamed Product Properties

Foams have been characterized in terms of foaming efficiency and bubble size and distribution. Foaming efficiency, Eff , was determined by comparing the gas fraction in foams ε to the theoretical value ε_T . ε was measured using foam density (ρ_F) and the density of the food model (ρ_L). ε_T was deduced from a mass balance on the gas phase under steady state conditions:

$$\text{Eff} = \frac{\varepsilon}{\varepsilon_T}, \quad \varepsilon = \frac{\rho_L - \rho_F}{\rho_L}, \quad \varepsilon_T = \frac{G}{G+L} \quad (4)$$

For bubble size measurements, a visualization cell placed on one of the exit stream of the foaming device was used, which enabled the on-line acquisition of experimental data. This was placed on an inverted microscope (Axiovert-25, Carl Zeiss Jena GmbH, Germany) equipped with a CCD camera (Kappa Opto-Electronics GmbH, Germany). Further details on this setup can be found in Labbafi et al. [13]. Three images were taken for each set of operating conditions; this corresponded to at least 1,500 bubbles which were analyzed using ImagePro+ 4.01 software (Media Cybernetics, MD, USA), which ensured the statistical significance of bubble size and morphology parameters. As bubbles were always spherical in this work, bubble diameter was used as the only morphology parameter to estimate bubble size distributions. The mean bubble diameter was expressed as the surface average diameter, denoted Sauter diameter (d_{32}) and defined as follows:

$$d_{32} = \frac{\sum_{i=1}^n d_i^3}{\sum_{i=1}^n d_i^2} \quad (5)$$

Stability was measured visually on foam samples stored at room temperature. Long-term stability was quantified using the minimum time at which a drained liquid layer of 1 mm thickness could be observed at the bottom of storage containers.

Weber Number Analysis

For single bubble or drop in shear or elongational flows of inelastic fluids, the equilibrium bubble size can be correlated to the level of viscous forces that promote gas dispersion in laminar flow conditions and to interfacial forces that prevent bubble breakup using a capillary number that is a function of the ratio of the viscosity of the dispersed phase divided by that of the continuous phase [21, 22]. This approach has been extended to concentrated emulsions and foams: When gas dispersion is total, i.e. when no blow-by occurs and $\varepsilon = \varepsilon_T$ (Eq. 4), a dimensionless Weber number (We) has been widely used in the literature as an invariant able to predict the average bubble size in wet foams [5, 9, 17]. These authors have shown that We is independent of operating conditions, equal to a critical dimensionless value noted We_C . It must however be pointed out that We_C depends on the

formulation of food model and even on pH [23]. However, for inelastic models based on glucose syrup, We was already shown to be nearly constant and able to estimating bubble diameter in foams by Narchi et al. [17]. Conversely, there is no information in the literature on the effect of matrix elasticity on the applicability of this relation for foaming operation. Usually, We is defined as:

$$We = \frac{\tau d_{32}}{\sigma} \quad (6)$$

τ is the average shear stress deduced from torque measurements during foaming using the virtual Couette analogy developed by Thakur et al. [20]. This can be summarized by Eq. 7:

$$\tau = \frac{T}{2\pi r_0^2 L_0} \quad (7)$$

where $L_0=0.195$ m and $r_0=0.0162$ m in the present work. We was therefore estimated by combining Eqs. 6 and 7. The average shear rate (γ) and the process viscosity during foaming (μ) were also deduced from the Couette analogy using Eq. 8 with $K_S=51$ [20]:

$$\gamma = K_S N, \mu = \frac{\tau}{\gamma} \quad (8)$$

These expressions can be used to check that model viscosity η is nearly independent of γ in the domain of foaming operation (typically 340–1,360 s⁻¹).

Results and Discussion

Effect of the Addition of PAA on Model Properties

First, the addition of PAA will be studied in models without surface active agents that will be used as a reference. Then, the addition of WPI and Tween 80 will be considered. Preliminary results showed that the addition of 0.01% PAA (w/w) in 1 Pa s glucose syrup increased significantly, up to 20%, the viscosity of the matrix. This remained however Newtonian and reached about 1.2 Pa s (Fig. 1a). The addition of 0.01% PAA in the food model induced low elastic behavior under shear flow with Wi close to 0.11. When 0.05% PAA was added, flow curve remained Newtonian and the viscosity of the food model doubled $\eta \approx 2.0$ Pa s. Moreover, the matrix elasticity was significantly increased with $Wi=10$ (Fig. 1a). For 0.1% PAA added in the matrix, the viscosity η increased up to 2.5 Pa s and the behavior remained Newtonian in the range of shear rate of interest for foaming operation (Fig. 1a). It was noticed that beyond 0.05% PAA, the addition of PAA in the model induced a slower increase of Wi , as the value passed from 10 to 13. In the range 0.01 to 0.1% PAA, matrix viscosity could be fitted by the following power-law as a function of PAA content w_{PAA} expressed in % (w/w):

$$\eta(w_{PAA}) = 5.2 \cdot (w_{PAA})^{0.32} \quad (R^2 = 0.9999) \quad (9)$$

When PAA was added with 2% surface-active agent (WPI or Tween 80) in 1 Pa s glucose syrup. The addition of 0.01% PAA did not modify significantly the Newtonian behavior of the matrix. For models containing 2% WPI, η was 1.35 Pa s and increased up to 1.5 Pa s with the addition of 0.01% PAA, while, for models with 2% Tween 80, η was

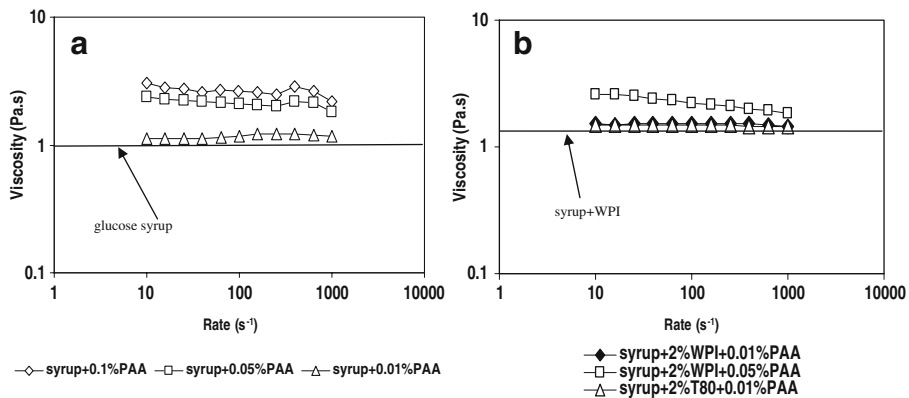


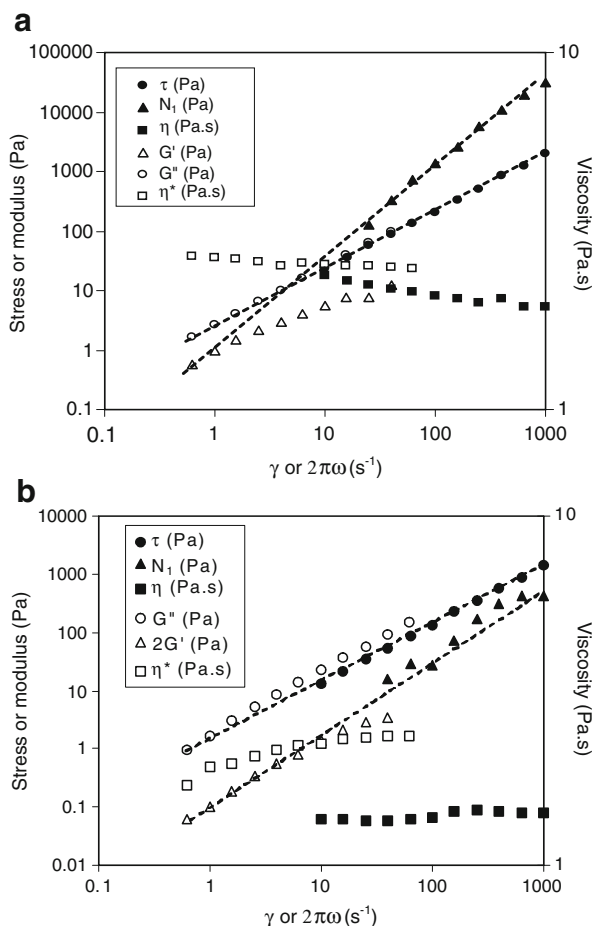
Fig. 1 Effect of the addition of PAA on the rheological properties of **a** 1 Pa s glucose syrup; **b** 1 Pa s glucose syrup with 2% WPI

1.4 Pa s and increased up to 1.5 Pa s (Fig. 1b). However, PAA conferred an elastic behavior for both models with Wi around 0.25 which is slightly higher than in glucose syrup with 0.01% PAA and without surface active agent. Moreover, the addition of 0.05% PAA in glucose syrup with 2% WPI increased the viscosity up to 2.0 Pa s (Fig. 1b). This value was similar to that obtained for the syrup with 0.05% PAA and without WPI, but the food model including WPI exhibited lower matrix elasticity, $Wi=2$, instead of $Wi=10$. It seems that the presence of WPI in glucose syrup solution containing 0.05% PAA decreases dramatically matrix elasticity, probably because proteins (which are polyampholyte biopolymers) prevent polymer entanglements of the non-ionic polyacrylamide macromolecules. Additionally, Fig. 1b shows that food model with 0.05% PAA and 2% WPI exhibited slight shear-thinning trend. This trend increased for a further increase of PAA content. Experimental data showed that a Newtonian behavior could not be maintained for an amount of PAA respectively higher than 0.05% for 2% WPI and 0.01% for Tween 80. In conclusion, the addition of PAA with tensioactive agents is limited to a small range of Wi values for investigating the influence of matrix elasticity on foaming operation, independently from pseudoplasticity. Model properties varied between poorly ($Wi \approx 0.1$) to moderately viscoelastic behavior ($Wi \approx 1$). However, this range of matrix elasticity corresponds typically to the domain of food products.

For fluids that fulfill the condition of constant viscosity as function of shear rate, dynamic oscillatory measurements showed that G'' was always higher than G' and that a fluid behavior always prevailed at low deformation, even up to 10 Hz. For viscoelastic fluids, $\tan \delta$ values were always between 3 and 10. This was in agreement with N_1 values that were usually measurable above 10 s^{-1} and even, in some case above 100 s^{-1} . As a result, the influence of elasticity should appear only at high deformation and high frequency or at high shear rate, which corresponds typically to the conditions of foaming operation. Despite their apparent simplicity in comparison to real food, elastic models did not always verify the Cox–Merz rule that assumes $\eta^*(2\pi\omega) = \eta(\dot{\gamma})$ (Fig. 2). Thus, η^* was often higher than η , which demonstrated the complexity of the interactions between the ingredients. Moreover, Fig. 2 showed that G'' under small amplitude deformation was nearly confounded with τ and N_1 tended to $2G'$ when shear rate tended to 0, although G' and N_1 values were often close to the minimum sensitivity of the measuring methods.

While surface tension of glucose syrup and mixtures including WPI and Tween 80 have already been reported by Narchi et al. [17], the addition of PAA was shown to modify only

Fig. 2 Comparison between small amplitude measurements (G' , G'' , and η^*) and measurements under flow conditions (τ , N_1 , and η) for 1 Pa s and with 0.05% PAA (a) and for 1 Pa s glucose syrup with 2% WPI and 0.01% PAA (b)



slightly σ . As a rough approximation, σ values of mixtures with and without PAA will be confounded in this work. Finally, η and σ values of all the formulations used in this work that maintain nearly a Newtonian behavior in the range of shear rate that interests foaming operation have been summarized in Table 1.

Effect of the Matrix Elasticity on Foaming Efficiency

Experimental results on continuous foaming operation could be interpreted in two ways: first, taking into account the effect of ingredients; then, by accounting for the evolution of physicochemical properties. In 1 Pa s glucose syrup without WPI, 0.01% PAA was shown to improve significantly Eff, as gas dispersion was negligible without PAA. For models with 0.01% PAA, Eff was about 56% at 400 rpm for $G/L=10/30$ with a stability of several hours, but Eff decreased when either G/L or N was increased (Fig. 3). When PAA content was increased up to 0.05%, Eff fell, even though gas dispersion seemed qualitatively easier than without PAA. For 0.1% PAA, only a very small fraction of the gas flow rate was dispersed and large gas plugs could be observed at the outlet of the column. Figure 4

Table 1 Summary of η , σ , and Wi values for food models used in this work.

Glucose syrup	η (Pa s)	σ (N.m ⁻¹)	Wi
1 Pa s	1.00	70	0.00
1 Pa s + 0.01% PAA	1.20	68	0.11
1 Pa s + 0.05% PAA	2.00	68	10.0
1 Pa s+0.1% PAA	2.50	64	13.0
1.0 Pa s+2% WPI	1.35	49	0.00
1.5 Pa s+2% WPI	1.85	49	0.00
2.0 Pa s+2% WPI	2.30	49	0.00
1 Pa s+2% Tween 80	1.50	35	0.00
1.0 Pa s+2% WPI+0.01% PAA	1.50	49	0.25
1.0 Pa s+2% WPI+0.05% PAA	2.10	49	2.00
1 Pa s+2% Tween 80+0.01% PAA	1.55	35	0.25

illustrates these trends by comparing images of bubbles for the three cases described above. It is however difficult to conclude whether this effect is due to either the increase of viscosity η or to the development of a viscoelastic behavior.

In Tween 80-glucose syrup mixtures, Narchi et al. [17] had already demonstrated that the high foaming ability of Tween 80 in water vanished when it was mixed in 1 Pa s glucose syrup for $G/L=10/30$, despite the low σ value reported in Table 1. Complementary data obtained at other G/L and N values confirm this result which could be attributed to the influence of viscosity. In this case, the addition of 0.01% PAA did not allow a total dispersion of the gas phase, but measurable Eff values were achieved, both for $G/L=10/30$ and $G/L=20/30$ (Fig. 3): Eff reached even 88% for $G/L=10/30$ and $N=800$ rpm. This seemed to indicate that matrix elasticity contributed to improve foaming operation, even though Eff decreased when G/L was increased.

When Tween 80 was replaced by 2% WPI with high surface elasticity, Narchi et al. [17] had shown that total gas incorporation with stable foams could be obtained, except in one situation: for high $G/L=30/30$ and rotation speed, probably because high G/L and N values increased simultaneously the collision frequency of bubbles and therefore the probability of bubble coalescence. In this work, foaming using mixtures based on glucose syrup of higher

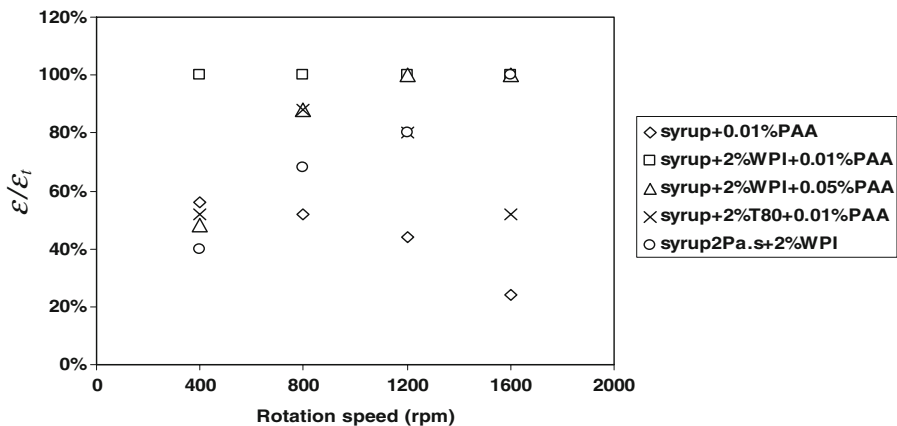
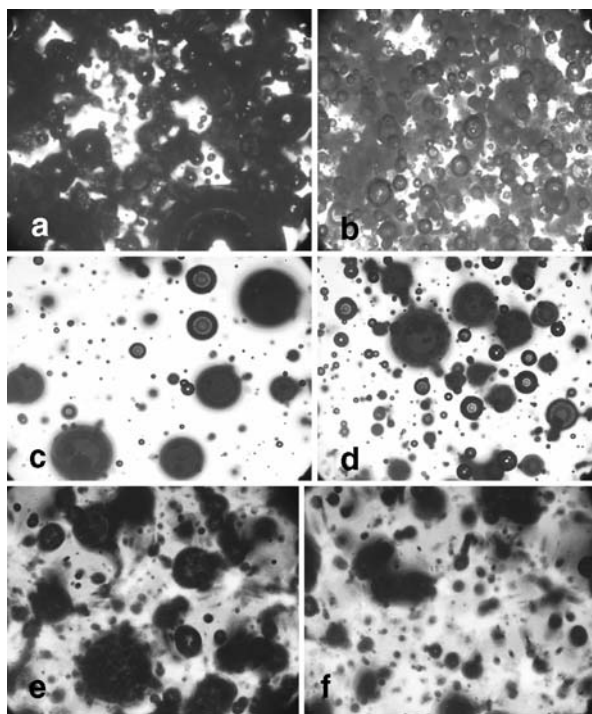
**Fig. 3** Evolution of foaming efficiency as a function of rotation speed for $G/L=10/30$

Fig. 4 Images of the dispersed gas phase in 1 Pa s glucose syrup for $G/L=10/30$ with 0.01% PAA: **a** $N=800$ rpm, **b** $N=1,200$ rpm; with 0.05% PAA: **c** $N=800$ rpm, **d** $N=1,200$; and with 0.1% PAA: **e** $N=800$ rpm, **f** $N=1,200$ rpm



η (up to 2 Pa s) showed that Eff was also limited at higher η for low rotation speed (Fig. 3). This confirms the negative role of high matrix viscosity on foaming. Such a result could stem from the fact that when the viscosity ratio (i.e. the ratio of the viscosity of the dispersed and the continuous phases) increases, bubble break-up is known to become more difficult in shear flows [21, 22]. This effect may be reduced by an increase in viscous forces responsible for gas dispersion when rotation speed is increased. This indicates that increasing η played usually a negative role mainly on foam formation at constant operating conditions. However, when 0.01% PAA was added in a 1 Pa s glucose syrup with 2% WPI, total gas incorporation could be achieved, regardless of N and G/L up to 30/30 (Fig. 3). When the amount of PAA was increased to 0.05%, total incorporation was however more difficult and could not be achieved when N was lower than 1,200 rpm. This looked similar to the effect of viscosity reported above for 2 Pa s glucose syrup with 2% WPI (Table 1). As a conclusion, experimental results revealed that matrix elasticity favored foaming when coalescence was the limiting step of the operation, but that elasticity did not compensate the negative effect of viscosity on dispersion. Consequently, matrix elasticity seemed to act mainly on bubble stabilization, rather than on bubble formation.

To better understand the respective influence of matrix viscosity and elasticity, food models have been prepared to obtain mixtures of similar viscosity exhibiting different elasticity values. For example, 2 Pa s glucose syrup with 2% WPI exhibited a viscosity value close to that of 1 Pa s glucose syrup with 2% WPI and 0.05% PAA; the first one was inelastic, while the second one exhibited $Wi \approx 2$ (Table 1). In all cases, experimental data demonstrated that Eff (Fig. 3) were always higher in the viscoelastic than in the inelastic matrix, always with a long-term stability of nearly 3 days. This confirms that matrix elasticity seems to play a stabilizing role on the interfaces that prevents coalescence and reinforces the interfacial elasticity provided for example by WPI. Indeed, foaming operation

using models based on 1 Pa s glucose syrup, 0.01% PAA and either Tween 80 or WPI presented also rather different performance, although these models exhibit the same Wi and η values. As a result, it can be concluded that the key physicochemical parameters that control successfully foaming operation in viscous media are:

- (1) viscosity that must be lowered to maintain the effectiveness of gas dispersion;
- (2) interfacial elasticity that favors foam stabilization;
- (3) matrix elasticity that enhances interface stability.

Effect of the Matrix Elasticity on Bubble Size Distribution

The influence of matrix elasticity and viscosity on bubble size distribution and average bubble diameter d_{32} was studied on formulations containing WPI because only these allowed to obtain total gas dispersion at the outlet of the foaming device ($\varepsilon=\varepsilon_T$), which is necessary for a consistent comparison. For these models, bubbles were always spherical and bubble size distributions monomodal. In Narchi et al. [17], foaming experiments using an inelastic 1 Pa s glucose syrup with 2% WPI gave d_{32} value around $18\pm 1\ \mu\text{m}$, regardless of rotation speed for G/L . For $G/L=20/30$, d_{32} increased to $23\pm 1\ \mu\text{m}$, but the influence of rotation speed remained as weak as for $G/L=10/30$ (Table 2). For $G/L=30/30$, d_{32} varied with rotation speed, but this resulted mainly from the fact that total gas incorporation was achieved only at low rotation speed (Fig. 3). Therefore, d_{32} could be either higher at low N ($d_{32}\approx 30\ \mu\text{m}$) and lower at high N ($d_{32}\approx 15\ \mu\text{m}$) than for $G/L=20/30$ (Table 2). In the above experiments, it seems that bubble size was mainly imposed by the interfacial properties of whey proteins and the G/L ratio. In this work, the influence of matrix viscosity was studied as above, by varying the viscosity of glucose syrup before the addition of WPI: Recipes based on 1.5 and 2 Pa s glucose syrup with 2% WPI were subjected to foaming operation. In both cases, mean bubble sizes were shown to be nearly independent of rotation speed for $G/L=10/30$, regardless gas incorporation was total or not. However, bubble size decreased continuously when η was increased. This is illustrated by Table 2 that summarizes the evolution of d_{32} values for $G/L=10/30$ as a function of N for each formulation: d_{32} passed from $18\ \mu\text{m}$ ($\eta=1.35\ \text{Pa s}$) to $15\ \mu\text{m}$ ($\eta=1.85\ \text{Pa s}$) and finally to $13\ \mu\text{m}$ ($\eta=2.30\ \text{Pa s}$). This is in agreement with data from the literature obtained with other continuous foaming devices and food models [2, 7]. Such behavior can be attributed to the increase of viscous forces when matrix viscosity increases. Using the results of “Effect of the Matrix Elasticity on Foaming Efficiency” section, one can conclude that high matrix viscosity reduces the amount of gas that can be dispersed, but provides smaller bubbles.

When PAA was added in the WPI models, the evolution of bubble size differed significantly from the behaviors described above. With 0.01% PAA, a significant influence of rotation speed was reported: d_{32} decreased from 35 to $18\ \mu\text{m}$ when N passed from 400 to $1,600\ \text{rpm}$ (Table 2). At the same time, bubble size distributions became narrower, as illustrated by Fig. 5a, conferring a more homogeneous aspect to the gas phase in foams. Figure 6 illustrates the size and morphology of bubbles observed in these foams. When G/L was $20/30$, d_{32} decreased and fell to $15\ \mu\text{m}$ at $800\ \text{rpm}$, but a further increase of rotation speed allowed neither the reduction of bubble diameter nor a decrease in the width of the size distribution (Fig. 5b). Finally, when G/L was increased up to $30/30$, which allowed to obtain 50% gas fraction in foams, the mean bubble diameter increased slightly up to $21\ \mu\text{m}$ at $400\ \text{rpm}$ in comparison to those obtained for $G/L=20/30$, but they remained however definitely lower than d_{32} obtained for $G=10\ \text{ml/min}$ (Table 2). When these results are

Table 2 Evolution of d_{32} as a function of viscosity, G/L and rotation speed N for food models including WPI.

Glucose syrup	N (s^{-1})	G/L (ml/min)	d_{32} (μm)
1 Pa s+2% WPI	400	10/30	19
	800		19
	1,200		17
	1,600		16
	400	20/30	24
	800		22
	1,200		23
	1,600		24
	400	30/30	30
	800		15
	1,200		14
	1,600		16
1.5 Pa s+2% WPI	400	10/30	13
	800		15
	1,200		15
	1,600		15
2 Pa s+2% WPI	400	10/30	12
	800		13
	1,200		12
	1,600		14
1 Pa s + 2% WPI + 0.01% PAA	400	10/30	35
	800		32
	1,200		23
	1,600		18
	400	20/30	18
	800		15
	1,200		15
	1,600		15
	400	30/30	21
	800		18
	1,200		16
	1,600		15
1 Pa s+2% WPI+0.05% PAA	400	10/30	32
	800		24
	1,200		20
	1,600		20

compared to those obtained with a formulation containing 0.05% PAA that exhibits a higher elastic behavior, one can note for example for $G/L=10/30$ that d_{32} and bubble size distribution (Fig. 5c) are not significantly different from those obtained with a formulation containing 0.01% PAA (Fig. 5a) for similar operating conditions. One can finally conclude that the addition of PAA has increased the influence of rotation speed on d_{32} and that opposite effects of G/L on d_{32} have been reported with and without PAA.

The complex trends described above result mainly, as for Eff, from the simultaneous change of viscosity and elasticity when PAA is added. To distinguish the respective influences of each of these physicochemical parameters, we have compared d_{32} and bubble size distributions of food models of similar viscosity with and without PAA, as in “[Effect of the Matrix Elasticity on Foaming Efficiency](#)” section. The results on d_{32} , summarized in

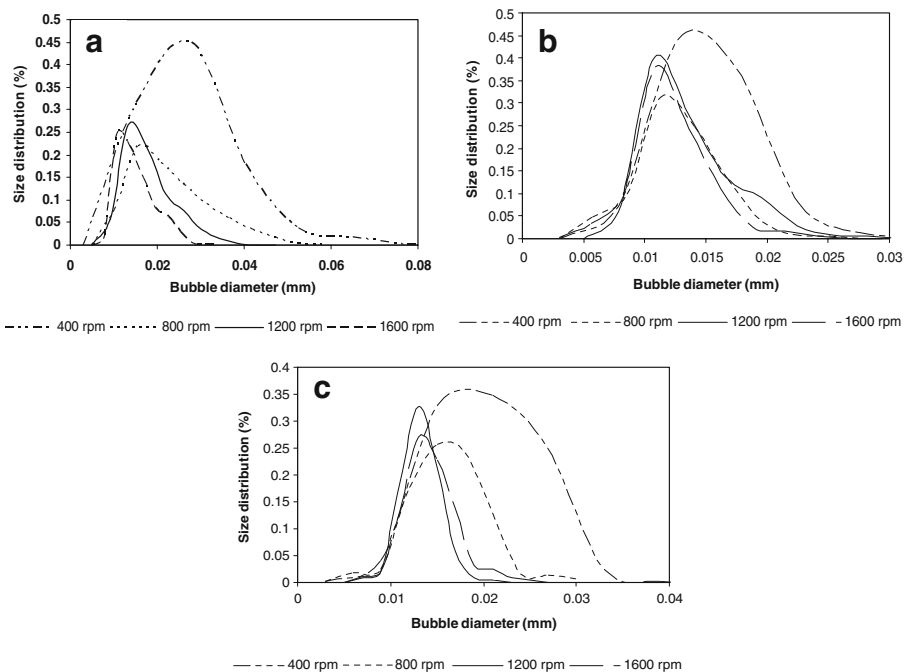


Fig. 5 Bubble size distributions in a glucose syrup with 2% WPI and 0.01% PAA as a function of rotation speed: **a** $G/L=10/30$, **b** $G/L=20/30$, and **c** $G/L=30/30$

Table 2, demonstrated that the mean bubble diameter was lower in foamed product from inelastic fluids. This appeared clearly when experimental data from inelastic formulations based on 1.5 and 2.0 Pa s were compared to that from elastic fluids based on 1 Pa s with 0.01% and 0.05% PAA, respectively. As a conclusion, while viscosity favors bubble division through shear forces, elasticity prevents bubble division and reduces the effect of hydrodynamic forces on bubble break-up. This is in agreement with the results obtained in “[Effect of the Matrix Elasticity on Foaming Efficiency](#)” section: Matrix elasticity seems to favor bubble stabilization, which in turn induces an additional protection against shear. It results that viscoelastic fluids form more stable, but larger bubbles. This has an opposite effect on foam stability because large bubbles are more sensitive to buoyancy forces, whereas elasticity maintains an additional force that opposes to bubble ascension. This explains probably why the stability of foams with PAA formulations was not significantly higher than those without PAA. The influence of ingredients can therefore be explained as

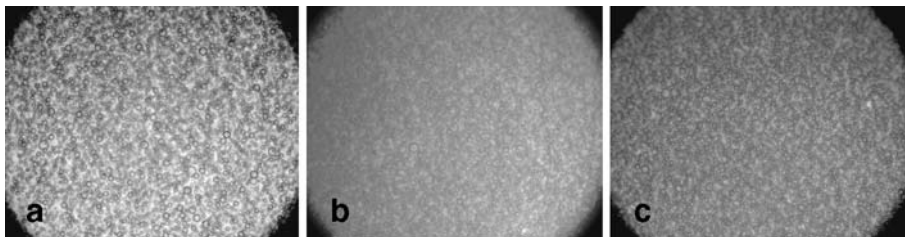


Fig. 6 Images of the dispersed gas phase in 1 Pa s glucose syrup with 2% WPI and 0.01% PAA for $N=800$ rpm and $G/L=10$ (**a**), $G/L=20$ (**b**), $G/L=30$ (**c**)

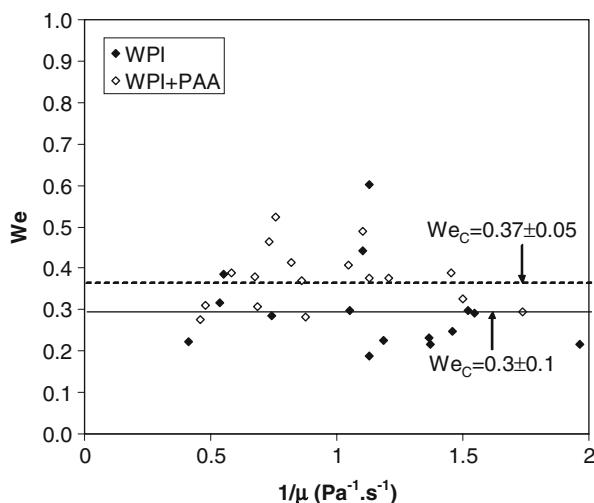
follows. First, when G/L remains moderate (e.g., 10/30), whey proteins and viscosity control both Eff and bubble diameter; the effect of matrix elasticity appears only on bubble diameter that is larger due to an additional force that stabilize bubbles against break-up. Conversely, when G/L becomes higher, matrix elasticity plays a positive role both on Eff and bubble size because it opposes coalescence and maintains simultaneously higher Eff and smaller bubbles (if blow-by is taken into account) than in inelastic fluids. The viscoelastic character of food may finally play either a positive or a negative role on foaming operation, depending on the objectives in terms of foaming efficiency, bubble size, and visual aspect.

Dimensional Analysis of Foaming Operation

Weber number We (Eq. 6) is a dimensional parameter that should be able to correlate the average bubble diameter d_{32} to operating conditions N through viscous and interfacial forces taken into account by η and σ . In concentrated emulsions and foams based on WPI [20, 24], We must be plotted as a function of $1/\mu$ where μ is the process viscosity estimated during foaming operation by means of torque measurements, instead of $1/\eta$ used in the conventional diagrams for a single bubble or a single drop. This approach supposes however that gas dispersion is total and it has been applied only to foams formed using glucose syrups including 2% WPI, with or without PAA. In turn, for the given formulation and operating conditions, We allows to predict a priori the average bubble size and thus the quality of the foamed products.

Figure 7 illustrates the evolution of We as a function of $1/\mu$. As expected for foams based on WPI, this number remains roughly constant with PAA addition, showing that there exists a constant critical Weber number We_C for which $We = We_C$ when the dynamic equilibrium between coalescence and break-up is established during foaming operation in the range of operating conditions studied. Statistical analysis shows that $We_C = 0.37 \pm 0.05$, regardless of rotation speed, gas flow rate and PAA content. The agreement between We_C and experimental We values in Fig. 7 is remarkable if one considers that these cumulate the experimental errors on measurements of d_{32} and torque. For foams without PAA, Narchi et al. [17] had found that We was nearly constant with $We_C = 0.3 \pm 0.1$ (Fig. 7). These

Fig. 7 Evolution of the laminar Weber number We as a function of the $1/\mu$ for WPI food models



quantitative results confirm that for the same operation conditions, We_C is higher with PAA, which leads to higher d_{32} values for the same viscosity as without PAA. The negative role of matrix elasticity on bubble size division is quantitatively confirmed, leading to bubbles 25% larger at constant μ . On the other hand, the dispersion of the data around the mean $We_C=0.37$ with PAA is also lower than without PAA [17], which is probably due to the stabilizing effect of matrix elasticity on bubbles and therefore on foaming efficiency. Finally, a last key point is that the effect of matrix elasticity seems only slightly dependent on Wi , as no significant difference could be found in Fig. 7 when PAA content was increased from 0.01% to 0.05%. This implies that very low levels of matrix elasticity (such as $Wi \approx 0.2$) are able to modify substantially foaming operation, while a further increase of elastic forces induces only a low reinforcement of the main trends induced by elasticity. This may be of utmost importance in food formulation.

Conclusions

Continuous foaming is a complex operation that depends widely on the interplay between the operating conditions (such as gas and liquid flow rates, rotation speed, but also pressure that has not been studied in this work...) and the formulation of the continuous phase. It seems clear from the above-mentioned results that for achieving successful foaming, a raw material must always contain an effective surface-active agent with a high surface elasticity, such as WPI. Conversely, most physical parameters and operating conditions may play at the same time an opposite role: For example, high rotation speed enhances viscous forces responsible for bubble break-up, but also the probability of bubble collision, which reinforces coalescence. Similarly, high viscosity increases viscous forces, but this may sometimes enhance bubble deformation at the expense of bubble division; additionally, η usually reduces the amount of gas that can be dispersed. In this work, it has been shown that the viscoelastic behavior that characterizes most complex foods played also a role on foaming operation. Matrix elasticity affected mainly the stabilization of the gas phase, even when matrix elasticity remained weak ($Wi \approx 0.2$). As a result, it could contribute to higher foaming efficiency when coalescence was the limiting step of foaming operation, for example for high G/L ratio and high rotation speed. On the other hand, enhanced bubble stabilization could contribute to limit gas dispersion and lead therefore to foams with larger bubbles, which could in turn affect the long-term stability of foams. As a conclusion, this point must be particularly accounted for by food processors when they add stabilizers in foams, such as thickening or gelling agents, which are aimed at increasing the shelf-life of the product. Indeed, their choice must take the development of the viscoelasticity of the continuous phase into account to optimize the nature and the amount of stabilizers to add. In this way, methods such as dimensional analysis based on We number can constitute useful tools.

Nomenclature

d_i	bubble diameter (m)
d_{32}	Sauter diameter (m)
De	Deborah number
Eff	foaming efficiency (%)
El	Elasticity number

G	gas flow rate (ml/min)
G'	elastic shear modulus (Pa)
G''	viscous shear modulus (Pa)
K_S	dimensionless shear rate constant
L	liquid flow rate (ml/min)
L_0	stirrer length (m)
N	rotation speed (s^{-1})
N_1	first normal stress difference (Pa)
PAA	polyacrylamide
r_0	internal radius of the virtual Couette geometry (m)
Re	Reynolds number
t_f	time scale of fluid (s)
t_p	time scale of process (s)
T	torque (N m)
$\tan(\delta)$	tangent loss
w_{PAA}	mass fraction of PAA in food model (%)
We	Weber number
We_C	critical Weber number
Wi	Weissenberg number
WPI	whey protein isolate

Greek symbols

γ	shear rate (s^{-1})
ε	gas volume fraction in foams (%)
ε_T	theoretical ε value for total gas incorporation (%)
μ	process viscosity (Pa s)
η	viscosity (Pa s)
η^*	complex viscosity (Pa s)
ρ_F	foam density (kg/m^3)
ρ_L	density of the continuous phase (kg/m^3)
σ	surface tension ($N m^{-1}$)
τ	shear stress (Pa)
ω	frequency of small-amplitude deformations (s^{-1})

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