Chemical Engineering Science 122 (2015) 250–269

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Effect of liquid fraction and bubble size distribution on the polarised light scattering characteristics of Casein foam

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HIGHLIGHTS

- Investigated five polarisation parameters of light scattered from Casein foam.
- Liquid fraction and bubble size distribution were measured individually.
- Individual effect of these two foam factors was analysed by multiple regression.
- Four of the polarisation parameters were associated with these two foam factors.
- Orientation angle of polarisation ellipse was completely independent of them.

ARTICLE INFO

Article history:
Received 7 August 2014
Received in revised form
15 September 2014
Accepted 23 September 2014
Available online 2 October 2014

Keywords:
Polarised light
Casein Foam
Bubble column
Bubble
Bioprocessing
Flotation

ABSTRACT

A polarised light scattering experimental set-up was designed to conduct experiments using Casein foams with monodispersed and bidispersed bubble size distributions. Foams were initially generated under forced drainage conditions to maintain a uniform axial liquid fraction profile. Subsequently, the foams entered a free drainage period. During this period, the liquid fraction, the bubble size distribution and the polarisation parameters of scattered light due to the foam were measured individually. It was found that both the liquid fraction and the bubble size distribution of Casein foams varied simultaneously with drainage time. Therefore, multiple regression analysis was performed to investigate the individual effect of these two foam factors on the polarisation state. Four of the polarisation parameters (degree of polarisation, degree of linear polarisation, degree of circular polarisation, ellipticity angle) were shown to be associated with the liquid fraction and/or the bubble size distribution to different extents. However, the remaining parameter, orientation angle, was completely independent of the liquid fraction and the bubble size distribution. These results can be used for the development of the polarised light scattering method in the study of protein foams.

1. Introduction

Liquid foams are ubiquitous. They are frequently encountered in daily lives in the form of foamy food, cosmetic foams, detergent foams, fire-fighting foams etc., and foams are even used as a temporary visual marker on the field in high level soccer matches. Foams are also of industrial importance. For instance, foams are widely used in mineral recovery (Farrokhpay, 2011; Yang et al., 2009), enhanced oil recovery (Schramm and Novosad, 1992), isolating toxic material (DiMaio and Norman, 1990), dyeing and frost protection of crops (Choi et al., 1999). Foams are also the subject of process innovation in paper-making (Al-Qararah et al., 2012) and biological material (protein, biomass) harvesting (Zhu and Wang, 2011).

Given the technological importance of foams in various applications, the pursuit of methodologies for probing the bulk properties of foams has attracted significant interests from both the industry and the academia. A typical means of characterising foams is to measure the liquid fraction and the bubble size distribution, as all the phenomena contributing to foam dynamic behaviour are reflected as variations in these parameters (Narsimhan and Ruckenstein, 1986; Weaire and Phelan, 1996).

As bubbles are good scatterers of light, multiple light scattering has been used to probe foam structural evolution. In the method of Durian et al. (1990, 1991a, 1991b), foams are modelled as air bubbles separated by liquid and a model for photon transport based on random walk is applied. The resulting photon transport mean free path is correlated with the average bubble size. Their discovery of depolarisation of scattered light has promoted the

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http://dx.doi.org/10.1016/j.ces.2014.09.038

research on foam particularly using polarised light. However, thus far only a few studies on the application of polarised light scattering techniques on foam have been reported in the literature.

The theoretical simulation results showed that the effect of foam properties (i.e. bubble size distribution, bubble separation distance, polydispersity) on the light intensity and the level of depolarisation (due to multiple scattering) for both reflected and transmitted light was significant, particularly at backscattering angles of 120–135° (Wong and Mengüç, 2002). Circularly polarised light proved to be a better choice than linearly polarised light in terms of characterising the properties of a foam (Wong et al., 2003). Further, the Plateau borders were identified as major contributors to the depolarisation effects due to large numbers of total internal reflection events occurring within them (Sun and Hutzler, 2007). Limited experimental results from polarised light scattering technique applied to foam showed that the sensitivity of different Mueller matrix elements to the average bubble size, liquid fraction and polydispersity were different. For the case of shaving foam, Mueller matrix elements M_{11}, M_{12}, and M_{33} were sensitive to the bubble size and the liquid fraction and showed a dynamic range especially at backscattering angles between 120° and 135° (Swamy et al., 2009). For the case of young foams, the parameter $M_{11}\pm\pm M_{12}$ showed good correlation with the bubble size whilst ($M_{11}\pm M_{33}$) is affected by the polydispersity of foam (Swamy, 2007). For a continuous foam fractionation column, the time average ($M_{11}+M_{12}$) showed a direct proportionality with the enrichment values (Swamy et al., 2010). It should be noted that foams investigated in these studies are not typical foams used in the industries and these studies did not measure the liquid fraction and the bubble size distribution independently.

In our previous studies, polarised light scattering technique has been successfully used in SDS (Sodium Dodecyl Sulphate, a low molecular weight ionic surfactant) foams based on the sensitivity of the parameters of polarised light to SDS foams (Qian, 2012), and this technique can be used to monitor SDS foams through certain Mueller matrix elements which are correlated with the liquid fraction and the bubble size distribution of the foam (Qian and Chen, 2013).

In addition to the foams being stabilised by low molecular weight surfactant, for food-related applications, foams are mostly stabilised by protein molecules (Prud'homme and Khan, 1996). Proteins, which involve hydrophilic and hydrophobic amino acid ends, are natural macromolecules with surface activities (Neurath and Bull, 1938). The biggest advantage of protein type surfactant is that they are non-toxic to humans, so they are widely used as the foaming agent in the pharmaceutical extraction and food production industries.

As properties of foams are strongly dependent on the foaming surfactant, foams stabilised by low molecular weight surfactant such as SDS and proteins have very different dynamic characteristics such as different gas–liquid interfaces (Bos and van Vliet, 2001; Koehler et al., 1999; Saint-Jalmes et al., 2005) and different drainage regimes (Gol'dfarb et al., 1988; Verbist et al., 1996). Taking these different foam properties into consideration, the aim of this study is to examine the effect of protein foam properties (liquid fraction and bubble size distribution) on the polarisation state of the incident light due to successive scattering events, which is a prerequisite for the use of polarised light scattering technique in the study of protein foams. For this purpose, Casein is chosen as the protein foaming agent since most of its properties are available in the literature. The initial liquid fraction and initial bubble size distribution of the foams are well-controlled and independently measured. The polarisation parameters of Casein foams (degree of polarisation, degree of linear polarisation, degree of circular polarisation, orientation angle, and ellipticity angle) are investigated and reported here for the first time.

2. Polarised light and Stokes parameters

Before proceeding to a description of the experimental programme, it is pertinent to review some properties of scattered light. In the current research, polarised laser light is used on the foam. When the light passes through the foam, it may be absorbed, reflected, refracted or transmitted. With these interactions within the foam, there are changes in the polarisation state of the initial incident light along with attenuation in the light intensity. Thus, more information about the foam is expected to be obtained by examining the polarisation properties of light scattered from the foam than simple intensity attenuation measurements (Marston, 1983; Wong and Mengüç, 2002; Wong et al., 2003).

To fully describe the polarised light, the formalism of the Stokes vector was used in this study (Goldstein and Collett, 2003). The Stokes vector consists of four physical real parameters S_0, S_1, S_2 and S_3. Such a representation enables an understanding of how scattering events can change intensity, type, and degree of polarisation of the incident light. For any given beam, the Stokes vector can be expressed using the parallel and perpendicular electric field components of the light given as follows(Bohren and Huffman, 1983; Goldstein and Collett, 2003; Mishchenko et al., 2000):

$$S=\begin{pmatrix}S_0\\S_1\\S_2\\S_3\end{pmatrix}=\begin{pmatrix}\left\langle E_xE_x^*+E_yE_y^*\right\rangle\\\left\langle E_xE_x^*-E_yE_y^*\right\rangle\\\left\langle E_xE_y^*+E_yE_x^*\right\rangle\\\left\langle i(E_xE_y^*-E_yE_x^*)\right\rangle\end{pmatrix}=\begin{pmatrix}\left\langle E_{0x}^2+E_{0y}^2\right\rangle\\\left\langle E_{0x}^2-E_{0y}^2\right\rangle\\2\left\langle E_{0x}^2E_{0y}^2\ \cos\ \delta\right\rangle\\2\left\langle E_{0x}^2E_{0y}^2\ \sin\ \delta\right\rangle\end{pmatrix}\tag{1}$$

where the brackets ⟨ ⟩> indicate a time-averaged quantity which makes the practical measurement possible. E is the electric field of light. E_0 is the maximum amplitude of the electric field of light. Subscripts x and y represent the parallel and perpendicular components of light, respectively. δ is the phase difference between two orthogonal light components. As the nomenclature for the Stokes parameters is not universally agreed, Collett's (Goldstein and Collett, 2003) notation is adopted herein. The four Stokes parameters have a physical meaning in terms of intensity. S_0 represents the total intensity of the light. S_1 represents the difference in the intensities of the linear parallel and perpendicular polarisation, S_2 represents the difference in the intensities of linearly+45° and −45° polarisation, and S_3 is the difference in the intensities of right and left circular polarisation within the beam. Thus, S_1, S_2, and S_3 can be regarded as the "horizontal preference", "+45°", and "right-handed circular preference" respectively. For example, if S_3 has a positive value, it indicates that the polarisation is right-handed circularly polarisation, whereas a negative value indicates left-handed circularly polarisation.

Certain characteristic parameters of polarised light can be described in terms of Stokes parameters. The degree of polarisation P is defined as follows (Bohren and Huffman, 1983; Goldstein and Collett, 2003; Mishchenko et al., 2000):

$$P=\frac{I_{\mathrm{pol}}}{I_{\mathrm{tot}}}=\frac{(S_1^2+S_2^2+S_3^2)^{1/2}}{S_0},\quad 0\le P\le 1\tag{2}$$

where I_{pol} is the intensity of the sum of the polarisation components and I_{tot} is the total intensity of the beam. The value of $P==1$ corresponds to completely polarised light, whereas $P==0$ corresponds to unpolarised light, and $0<P<<1$ indicates partially polarised light. The degree of linear polarisation P_{L} and the degree of circular polarisation P_{C} are defined as follows:

$$P_{\mathrm{L}}=\frac{\sqrt{S_1^2+S_2^2}}{S_0}\tag{3}$$