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Exploring Foam Drainage in Fiber-Foam: A Review

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Abstract

The foam drainage is extremely important in many situations where fiber foams are used. Enhancing wet foam stability requires a complete understanding of the mechanisms and factors affecting wet foam drainage. Investigation of the drainage behavior of fiber foams has been studied in this review. The mechanics behind fiber foam drainage are discussed in detail, along with the influence of surfactant concentration, fiber consistency, and other variables. It also investigated adding additives, such as chemi-thermo-mechanical pulp (CTMP), affects foam drainage. Highlighting the most recent developments in experimental and theoretical methods for describing and forecasting foam drainage behavior are presented. This review acts as a reference to offer useful understanding of the essential factors of foam drainage in fiber foams solution.

Keywords: drainage, foam, fibre, pulp, formability, stability

1. Introduction

Foam is a dispersion system that consists of air bubbles surrounded by liquid (Weaire and Hutzler, 1999; Weaire et. al., 2006; Denkov et al. 2009). Foam can be classified as either wet or dry according to the air content within the foam. When the air content is higher than 80% the foam is called dry. On the other hand, when the air content is between 60% and 80% the foam is called wet. In the case of dry foam, the shape of the bubbles is polyhedral and spherical for wet foam (Al-Qararah et. al. 2012).

In the past few years, considerable interest has been devoted to foam forming technology, where foam is used as a material carrier in producing novel fibre structures (Lehmonen et. al., 2013; Al-Qararah et. al. 2013; Koponen et. al., 2016; Kiiskinen et. al., 2019; Ketoja et. al., 2019). In foam forming, the wood-pulp is mixed with foam, and this mixture is transferred through the headbox to the wire, where foam is removed using a vacuum. The fibres are essentially separated by foam bubbles until they collapse due to the vacuum.

In industry, foam-forming technology presents a challenge due to the numerous interdependent interactions between foam and fibres. The inclusion of fibres in the wet foam, in particular, commonly impacts the foam's bubble size, stability, rheology, and drainage as well (Al-Qararah et. al., 2015). Therefore, comprehending these interactions and considering them during the foam-forming process is of utmost significance.

The drainage behavior of fiber foams is examined in this review in order to better understand the underlying mechanics. It has widely investigated how factors such as surfactant content, fiber consistency, and adding additives such as chemi-thermo-mechanical pulp (CTMP) affect foam drainage. The theoretical and experimental approaches for defining and forecasting foam drainage behavior are also included in the review. This review acts as a helpful resource for researchers and industry professionals by providing deep information on the critical factor of foam drainage in fiber foams.

Studying the fiber-foam drainage equation is very important to understand how water is removed, as it helps us to improve fiber-foam products. It enables the improvement of efficient processes, enhanced fiber-based materials, and advanced solutions for different industrial and environmental applications.

The purpose of this work is to provide a comprehensive overview of fiber-foam drainage. It will contribute to current knowledge by highlighting the most important research papers that have worked on this topic and examining the factors affecting foam drainage and the effects on the performance of manufactured materials.

2. Drainage of Fiber Foams

Several variables impact foam drainage, including the effect of gravity downward flow of liquid, the coarsening effect (where small bubbles combine with bigger bubbles caused by pressure-driven gas diffusion), and the rate at which foam is demolished due to bubble coalescence. During drainage, liquid moves through a bubble matrix in both wet and dry foams. Bubbles have increased freedom of movement in bubbly liquids, and drainage can first be viewed as an upward motion of bubbles driven by hydrostatic pressure. The process of foam drainage is critical for preserving foam stability. In case of dry foam, the liquid layers between the bubbles grow thinner and can rupture, resulting in the collapse of the foam structure. Unfortunately, most drainage studies have concentrated on dry foams where the air content is higher than 80%. This type of foam is not used in foam-forming technology where the foam is wet in this case.

As shown in Figure 1, dry foams are composed of liquid in the Plateau borders and connecting nodes between bubbles. (Stevenson, 2006) utilized dimensional analysis to demonstrate that, when inertial losses and coalescence are ignored, the dimensional drainage rate $\tilde{j}$ of both node and channel demonstrated foam follows a simple power law:

$$Sk = \frac{\mu_o j_d}{\rho g r^2} = m\varepsilon^n \quad (1)$$

where ε is liquid fraction, j_d is drainage rate, μ_o is the viscosity of the solution, ρ is the liquid density of liquid, g is the gravitational acceleration, and r is the average bubble radius. The m and n are dimensionless constants and depend on the surface shear viscosity.

It is difficult to create a mechanistic model for foam drainage in the absence of prior knowledge regarding surface shear viscosity and a lack of research assessing losses at the nodes. Because there are two unknowns in the system, any model for foam drainage must include at least two adjustable constants. However, it has been proved in (Stevenson, 2006) using dimensional reasoning that, if inertial losses are ignored, the non-dimensionalised drainage rate, represented by the Stokes number, may be stated as a function of the liquid hold-up alone. Furthermore, a basic power law connection between these two variables has been demonstrated as a suitable approximation for both channel-dominated and node-dominated foam drainage, as well as more sophisticated treatments that integrate an inferred value of viscosity.

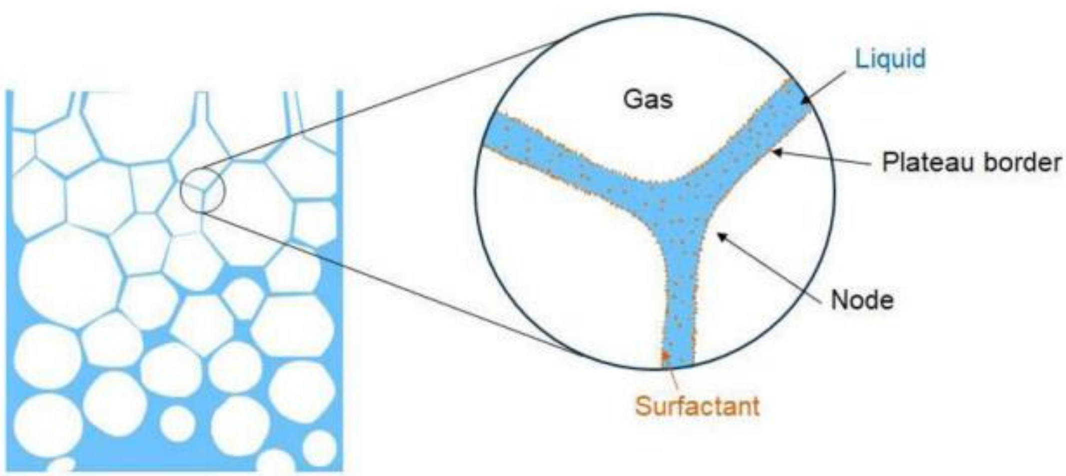

Figure 1. The typical foam structure is in which gas bubbles are surrounded by liquid-containing surfactant molecules. These molecules stick to the boundary between the liquid phase and gas phase, increasing the foam stability.

Stevenson conducted experiments with several foams reported in the literature and found that Equation (1) suited the data well. The liquid volume percent was consistently less than 0.2 in various studies. When several foams made using anionic sodium dodecyl sulfate (SDS) surfactant were examined, the value of n in the equation was found to be about 2, whereas the parameter m fluctuated between 0.01 and 0.02.

(Koponen et. al., 2018) studied drainage using bubbly liquids and wet SDS foams containing softwood fibers in their study. Surprisingly, Equation (1) was found to be valid between 0.25 and 0.5 of liquid fraction. However, at increasing liquid volume percentages, the drainage qualitative behavior changes, and the drainage rate increases rapidly as the liquid fraction increases. In the same study, the foam drainage in pilot scale was investigated including softwood fibers. The investigation involves changing the concentration of SDS surfactant in the range of 10-180 ppm, as well as modifying the air content between 30-70%. It was discovered that the half-life of the foam drainage depends on the surfactant concentration (C_{SDS}) and air contents as:

$$t_{1/2} = \alpha \frac{C_{SDS}}{\varepsilon^n} + \beta \qquad (2)$$

The regression coefficients α =0.33, β =0.33, and $n = 1.9$ were found in this study. Interestingly, including the proportion of injected air in the model did not increase its statistical significance. This shows that the in-line production mechanism produces reasonably uniform foams. Furthermore, it was discovered that decreasing bubble size had little influence on increasing half-life, however, this effect was minor and lacked statistical significance.

In a recent study conducted by (Mira et. al., 2014) fibre foam drainage was studied using a series of surfactants with adding chemi-thermo-mechanical pulp (CTMP) at 1.5% consistency in order to make foam-formed sheets. The results presented in Figure 2 show that, increasing the surfactant concentration enhanced the foam stability. However, adding CTMP fibers can slow down the drainage.

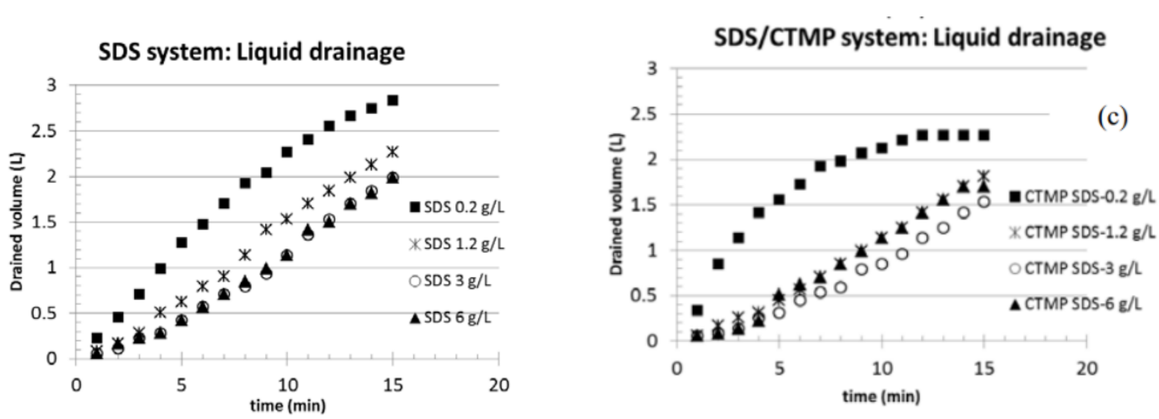

Figure 2. Foam drainage with SDS solution (left) and SDS with CTMP fibre (right) (Mira et. al.,2014).

A study conducted by (Li et. al., 2016) fiber foams was generated by adding pine fibres into an aqueous solution of carboxymethylated lignin (CML). The results, illustrated in Fig 3, show that the formability (air content) and foam stability of fiber foam are enhanced by increasing CML concentration. Nevertheless, adding more fibers with the CML aqueous solution can increase the formability and foam stability. Surprisingly, the half-life time of fiber foam with a 0.6% concentration of CML aqueous solution is ten times longer compared to pure CML based foam.

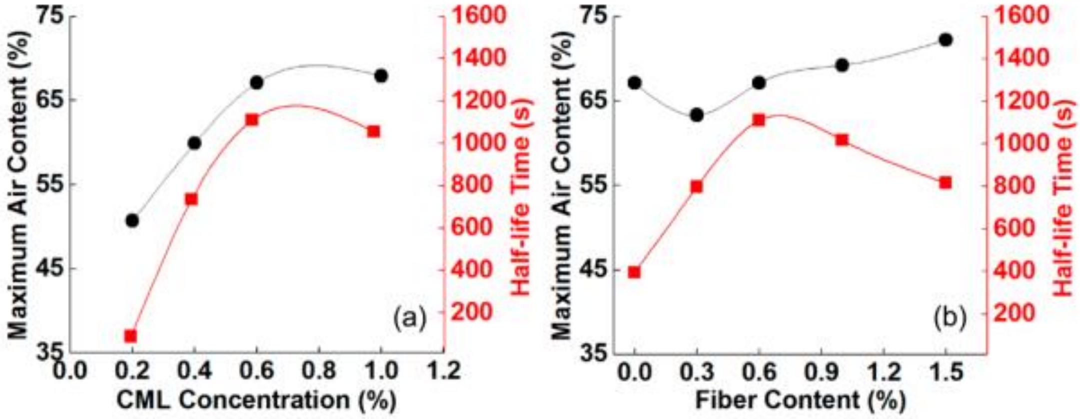

Figure 3. Air content (circle symbol) and half-life time (square symbol) in terms of CML concentration (a) and fiber consistency (b) (Li et. al., 2016)

Another study by (Haffner et. al. 2016) investigated the fibre foam drainage at different fiber consistency as shown in Figure 4. The initial bubble diameter was fixed (170 μm). However, for the first 300 seconds, the liquid fraction follows a similar trend. Beyond this point, the liquid fraction starts to decline more quickly than what was predicted by the numerical solution of their drainage equation Eq. (3). Foam coarsening, becomes evident over this time period. As the bubble size increases, the liquid fraction decreases.

$$\frac{\partial \phi}{\partial t}+\frac{1}{\eta^*}\frac{\partial}{\partial z}\left(\rho g \frac{V_b^{2/3}}{5.35}\phi^2-\frac{C\sigma}{2}\sqrt{\frac{V_b^{2/3}}{5.35}}\phi\frac{\partial \phi}{\partial z}\right)=0 \quad (3)$$

where ϕ is the liquid fraction, $\eta^*$is the effective foam viscosity, g is the acceleration due to gravity, σ is the surface tension, and $V_b=\frac{\pi}{6}D_{32}^3$, where D_{32} is the bubble Sauter diameter.

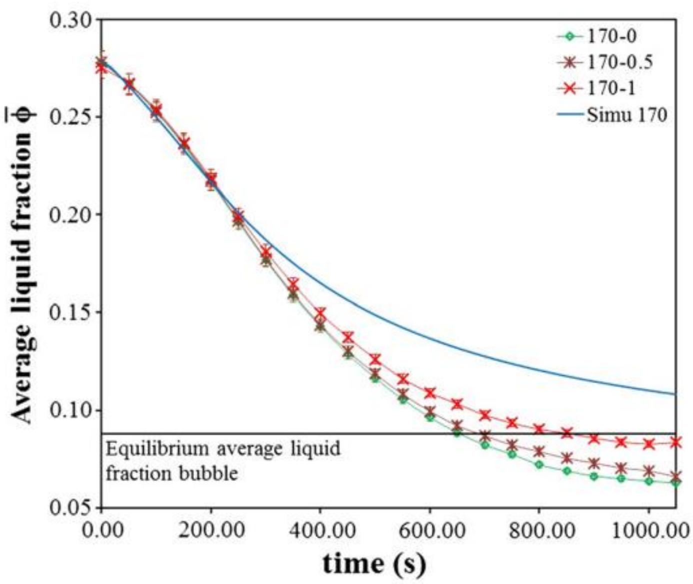

Figure 4. Liquid fraction at a bubble diameter of 170 μm for different fiber consistencies (0%,1%,1.5%) along with the numerical results obtained from Eq. (4) (Haffner et. al. 2016)

3. Conclusions

In conclusion, enhancing wet foam stability depends greatly on the drainage behavior of fiber foams. Deep knowledge of the mechanisms and factors affecting wet foam drainage has been made possible by this review. The influence of surfactant concentration, fiber consistency, and other factors has been studied in depth, along with the mechanics of fiber foam drainage. The experiment additionally examined at the impact of additives on foam drainage, including chemi-thermo-mechanical pulp (CTMP). The most recent developments in theoretical and experimental approaches to defining and forecasting fiber foam drainage behavior have also been highlighted in this study. Overall, this comprehensive review is a useful resource that provides insightful information on the essential factors involved in foam drainage in fiber foam systems.

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