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Mitigation of sound waves by wet aqueous foams

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ABSTRACT

We present macroscopic experiments that show how the decay phenomenon affects the sound wave mitigation in wet aqueous foams and how both effects depend on the mass concentration of added particles of coal fly ash. To measure the mitigation of a sound wave as a function of the drainage time and particle concentration both a standing-wave and a single-pulse methods were used. To the best of our knowledge, the combination of these two techniques, which complement each other, has not been done before. The tested geometry of the foam samples concerns that the drained liquid and the sound wave are both uni-directed. Generally, this simplifies the phenomenon, which could be treated as one-dimensional but becomes less evident if the particles leaving the foam introduce uncertainties into the analysis. It turns out that the standing-wave method is best suited for testing the dry ready-made or other stable foams, while for wet unstable foams the single-pulse methods is superior. On the limited evidence collected at this stage, it is found that in conventional (without particles) foams, the mitigation of a sound wave decreases in time due to the foam drainage, while in particulate foams, increased particle concentration reduces the drainage rate and increases the sound wave mitigation. From this it follows that a powder of coal fly ash could be safely used as a cheap and an effective solid additive to improve protective capabilities of aqueous-foam based barriers.

1. Introduction

Aqueous foams are large collections of gas bubbles stabilized by surfactants and separated by interstitial fluid, which forms a continuous channel-like network, which is unstable and ages due to drainage and coarsening processes. The fluid is found in three types of geometrical structures: (i) films, i.e, the regions between two adjacent bubbles; (ii) Plateau borders, i.e., the regions between three adjacent bubbles; (iii) nodes, i.e., tetrahedrally coordinated regions between four bubbles. Foam drainage is the gravity and capillarity driven flow of interstitial liquid out of the foam, and it primarily takes place in the Plateau borders and nodes [1–4]. Coarsening is the transport of gas between bubbles, which generally results from preferential gas diffusion from small bubbles to large bubbles through the films that rapidly drain [5], and the rupture of bubbles accelerates it. These two processes affect the distribution of the liquid volume fraction and the bubble size, which influence almost every property of the foam. The interplay between coarsening and drainage is very important since coarsening enhances drainage and drainage enhances coarsening. In many cases, the quickly occurring aging processes limit the use of foams and complicate their measurement. Previous experiments show [6,7] that aging dynamics indeed depends on the foam type. For example wet foams with high liquid volume fractions drain rapidly [8], while foams composed of small bubbles coarsen rapidly, as do foams with weak films that are prone to rupture. In contrast, the average liquid fraction of ready-made Gillette foams samples, remain constant for the first 2 h of foam aging [9]. Later, the foam decays slowly and a density gradient appears. However, these numbers are not universal and they depend on the sample height [10–14]. Models that successfully describe the diffusive coarsening process and the coupling of coarsening and drainage have also been formulated yet.

The aging process prevents wide using of aqueous foam absorbers, which demonstrate acoustic damping that is several orders of magnitude larger than that in polyurethane foams of similar densities. Contrary to a fairly comprehensive picture of the aging process, explanations of the very high mitigation of sound waves in aqueous foams are rare [15,16]. A simplified treatment [17,18] that included analysis of the liquid flow and inter-phase heat transfer revealed two possible mechanisms for the mitigation of sound waves: (1) reflection of the sound waves off the films [19] and (2) oscillation of the bubbles, which results in flow of the interstitial liquid in the Plateau borders (see e.g., [20–25]). Among the first, the sound wave mitigation in aqueous foam with liquid fraction of about $\varepsilon = 0.077–0.091$ was registered in the experiments [19] using a frequency of the probing signal of about 1 kHz. The registered coefficient of sound attenuation per length, was about $\alpha = 28.8\,\mathrm{dB\,m^{-1}}$. Thereafter, experimental data and numerical simulations demonstrating a strong dependence of sound wave attenuation on the liquid drainage were published [25]. As shown

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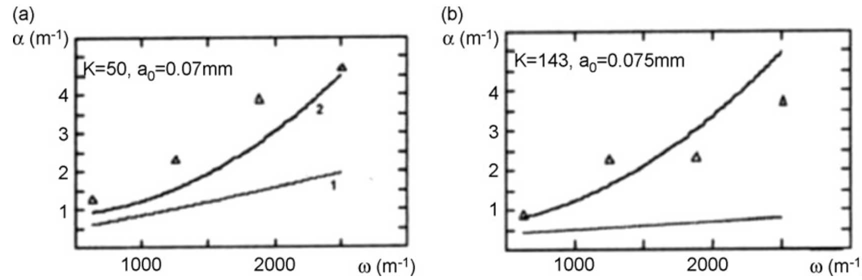

Fig. 1. Attenuation coefficient α vs. frequency, ω of the sound wave in aqueous foam having different expansion ratios: (a) $K = 50$ and (b) $K = 143$. Experiment (Δ) and simulated curves obtained without (1) and with (2) accounting for the foam drainage [25].

in Fig. 1, the coefficient α registered in their tests is very sensitive to the ratio of the wavelength to the bubble radius a_0. This explains why the sound wave attenuation registered in [19] also varied with frequency of the probing sound wave.

One of the more important and deeper discussions of this phenomenon was made by Mujica and Fauve [26]. While conducting detailed experiments with ready-made foams, they used two experimental setups: one for probing impulses with the frequency about $\omega = 5$ kHz and the other for $\omega = 37$, 63 and 84 kHz. Considering the time dynamics of the sound speed in a very long time-scale (up to 17 h of foam aging), they observed a reduction of the sound speed with time. They attributed this to the softening of the foam structure with time due to the presence of surfactant molecules, which changed the elasticity of the liquid matrix. The sound wave velocity and the absorption that were registered in their tests, also evolved with time as the foam coarsened and increased the radius of the bubbles. Since both registered parameters were found to be sensitive to the frequency of the probing impulses, this paper opened the avenue to frequency-dependent analysis of the coarsening mechanisms.

In contrast to ready-made, commercial foams, the decay of wet foams prepared in the laboratory, is quicker. Due to the fast drainage and coarsening, the foam becomes significantly drier at its top and wetter close to its bottom. The high gradient of the liquid fractions over the sample height affects the mitigation of the sound wave, which is lower in the dry part and much higher close to the bottom [27]. To better understand this feature, a series of controlled laboratory tests with foam samples that were left to decay for different time durations, Δt_i, and then were exposed to the probing pressure pulse were of great interest [28]. Recently, it was demonstrated that the addition of particulate matter, such as micron-sized soot particles, provides several interesting features affecting the foam performance. The first point to note was the fact that the additives modified the dynamics of the foam decay: reduced the drainage rate and slowed the coarsening [29–32]. Secondly, the particulate matter enhanced the total scattering of the sound wave since it acted as barriers for the liquid flow inside the plateau channels. Thirdly, they increased the effective viscosity of the foaming solution [21].

Though the physics behind these phenomena is not fully understood, there are clear evidences that the scattering mechanisms and the dissipation due to concomitant flow of interstitial liquid inside the plateau channels overlap each other (see the comment in Ref. [24]). Moreover, there is no consensus even about the final result caused by particles on the sound wave mitigation. In the experiments of [21] for example, the mitigation of the sound wave increased with the concentration of particulate matter (see Fig. 2a). In contrast, according to the data of [33], particle-free aqueous foams mitigate the sound wave stronger than particulate foams (see Fig. 2b). Two possible explanations for this apparent contradiction are possible: (1) the aging process was poorly controlled and unaccounted for and (2) in the experiments of [33], the particulate matter concentration was too high in the Plateau borders [34]. To clarify this issue, more experiments conducted in a wide range of the studied conditions and using various measuring procedures are necessary.

In this paper, we first review, in Section 2, some general characteristics of tested aqueous foams, the experimental setup and the acoustic measurement methods. Then our experimental data are presented in Section 3. Thereafter, in Section 4, we discuss how the draining foams respond to acoustic measurements and compare the registered mitigation of a sound wave in conventional foams with experimental data available from the literature. Final conclusions are given in Section 5.

2. Experimental procedures and apparatus

2.1. Foaming materials

While conceptually, it is easy to test the foam instability, the resulted gradient of the liquid fraction, which is responsible for the transient variation of the sound wave mitigation, is a parameter that is difficult to reproduce [35]. From this standpoint, to handle different foams, to test them in a single laboratory and then compare the results, is of important consideration. To realize this approach we used for the analyses two types of foams. The first is a Gillette series of ready-made foam (Procter & Gamble, England).

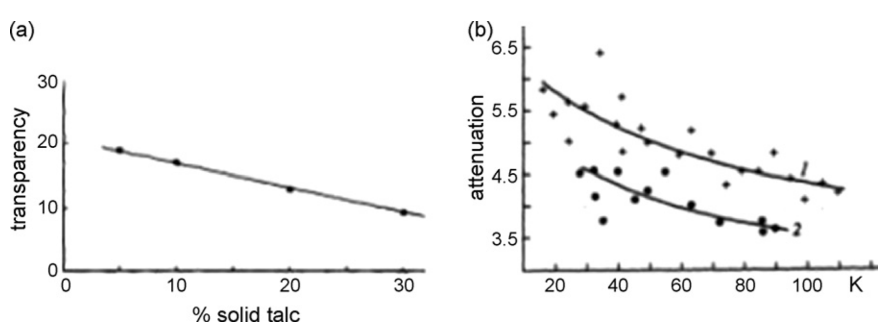

Fig. 2. (a) Attenuation of a sound wave in a particulate foam vs. the percentage of talc particles [21]. (b) Attenuation of a sound wave vs. the expansion ratio, $K = 1/\varepsilon$, in conventional (1) and particulate (2) aqueous foams [33].