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The drainage of foamy granular suspensions

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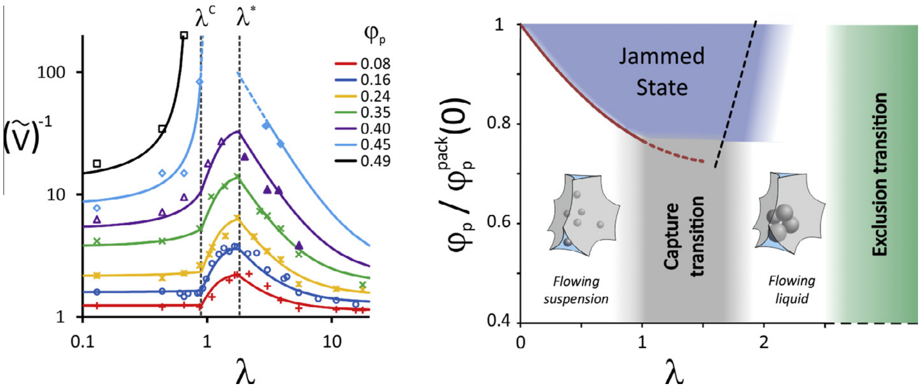
GRAPHICAL ABSTRACT



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ABSTRACT

Foam-based materials are promising micro-structured materials with interesting thermal and acoustical properties. The control of the material morphology requires counteracting all the destabilizing mechanisms during their production, starting with the drainage process, which remains to be understood in the case of the complex fluids that are commonly used to be foamed. Here we perform measurements for the drainage velocity of aqueous foams made with granular suspensions of hydrophilic monodisperse particles and we show that the effect of the particles can be accounted by two parameters: the volume fraction of particles in the suspension (φ_p) and the confinement parameter (λ), that compares the particle size to the size of passage through constrictions in the foam network. We report data over wide ranges for those two parameters and we identify all the regimes and transitions occurring in the $\varphi_p - \lambda$ diagram. In particular, we highlight a transition which refers to the included/excluded configuration of the particles with respect to the foam network, and makes the drainage velocity evolve from its minimal value (fully included particles) to its maximal one (fully excluded particles). We also determine the conditions (φ_p, λ) leading to the arrest of the drainage process.

1. Introduction

Foaming is widely encountered in industrial processes: gas is mixed to many materials in order to improve their thermal or acoustical performance or simply to make them lighter and to save raw materials. In the current climate of sustainable development, the production of foam-based materials is destined to expand. The matrix of those foamy materials is often composed of a complex fluid, such as a suspension for example. Typical examples for such mixtures can be found in the production of materials for the building industry [1], of ceramic foams [2], or in food [3] and cosmetic industries. Note also that the mining industry extensively

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Nomenclature

φ_p	volume fraction of particles in the interstitial phase of the foam
φ_p^{pack}	volume fraction of packed spheres
D_b	bubble size
ϕ	gas volume fraction
d_p	particle diameter
d_c	diameter of passage through constrictions in the foam network
$\lambda = d_p/d_c$	confinement parameter
r	characteristic size of a foam node
V	drainage velocity
$\tilde{V} = V(\varphi_p)/V(0)$	reduced drainage velocity
N	number of particles per foam node
μ_0, μ	shear viscosity of the suspending liquid, of the interstitial suspension
K	foam permeability
$\tilde{k}_n = K/r^2$	permeability coefficient of a foam node

resorts to mixtures of foam and particles through the flotation process that is widely used to separate ores [4].

The homogeneity of foamy materials can be drastically affected by the drainage of the interstitial phase (the continuous phase between the gas bubbles) and the simultaneous rising of the bubbles, resulting in the degradation of their quality and their functional properties. Note also that the drainage of the liquid phase – and the resulting increase of the gas volume fraction – promotes other detrimental aging processes, such as ripening and coalescence [5,6]. In order to control foam-based materials it is crucial to understand and to counteract as much as possible the drainage process. During the last two decades, most of the work realized in the field of foam drainage has concerned aqueous foams, i.e. dispersions of densely packed gas bubbles in a Newtonian liquid [5–7]. In fact, only a few recent studies have tackled the issue of foam drainage with complex fluids, such as clays [8,9], coal fly ashes [10], colloidal suspensions [11–14], emulsions [15–17]. These studies have highlighted finite size effects and particle trapping phenomena (clogging) occurring at the scale of the foam network.

Very recently, some of these effects have been rationalized thanks to experiments with model systems, and the so-called confinement parameter λ has been identified as a control parameter. λ compares the size of particles contained in the interstitial phase to the size of passage through the constrictions in the interstitial network: $\lambda = d_p/d_c$ (see Fig. 1). Two mechanisms for trapping of particles in aqueous foams have been understood: (i) the collective trapping – jamming – of the suspension for $\lambda < 1$ and for particle volume fractions above of a critical value that depends on λ [18], and (ii) the individual capture of the particles by the foam constrictions for larger λ values [19–21].

These two mechanisms give some insight into the drainage of foams in the presence of suspended particulate matter. However, the complete understanding of drainage laws requires more experimental work with such model systems. In this paper, we perform new measurements for the drainage velocity of aqueous foams in the presence of spherical particles. Thanks to an improved sample's generation method we obtain a new set of data for large λ values – up to 20 – and we complete our previous data obtained for $\lambda < 2$. This allows for a global physical picture to be proposed for the drainage of foamy suspensions.

2. Materials and methods

Samples are prepared from precursor liquid foams which are subsequently mixed with granular suspensions, as described in a previous work [18,21].

2.1. Materials

The foaming solution contains 10 g/L of trimethyl(tetradecyl)azanium bromide (TTAB) in distilled water with 20% w/w glycerol. With such a proportion of glycerol the density of the solution is 1050 kg/m^3 and matches with that of polystyrene particles used in the study. The surface tension of the liquid/gas interface is 38 mN/m and shear viscosity of the bulk is $\mu_0 \simeq 1.7$ mPa s. The suspension is prepared at a given particle volume fraction (φ_2) by mixing the foaming solution and polystyrene spherical beads (Microbeads®). The beads are quite monodisperse: $\Delta d_p/d_p \approx 5\%$ and we have used the following diameters: $d_p = 6$, 20, 30, 40, 80, 140, 250 and 500 µm. In the foaming solution, those particles behave as fully hydrophilic particles and they do not adsorb at bubble interfaces.

2.2. Generation of the precursor foams (schema 1 in Fig. 2)

Bubbles are generated in a T-junction with two entries (nitrogen and foaming solution) and one exit (bubbly solution). The bubble diameter was varied in the range $D_b \simeq 150–1000$ µm by tuning the flow rates of gas and liquid. The bubbles are continuously produced and released at the bottom of a column which is partially filled with the foaming solution. This results in the formation of foam in the column. During the production, the foam is imbibed with the same foaming solution in order to obtain stationary drainage conditions with a constant value of the gas fraction (ϕ_1) throughout the foam column [5,6,22].

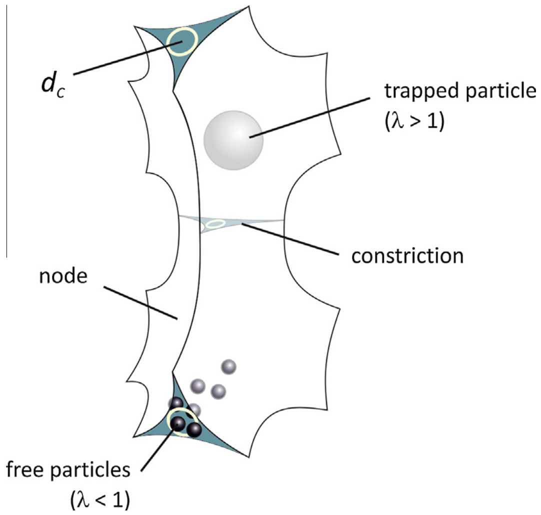

Fig. 1. The interstitial network of aqueous foams consists in nodes connected by constrictions. Particles suspended in the interstitial fluid can be either freely transported or trapped by constrictions. This behavior is described using the so-called confinement parameter, λ, that compares the particle size to the size of passage through those constrictions, d_c.