Aqueous foam drainage. Role of the rheology of the foaming fluid

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Abstract. We have studied the drainage of foams made with viscous solutions. In this way, drainage is slowed down, and microgravity conditions are approached. The behaviour of mixtures of water and glycerol follows the theoretical predictions, but that of aqueous solutions of a polymer (polyethylene oxide) do not : drainage is much faster than for water-glycerol mixtures of the same bulk viscosity. The origin of this puzzling behavior is still not understood.

1. INTRODUCTION

The behavior of foams in microgravity and on earth are very different, because the process of drainage is absent in microgravity conditions. By drainage, we are referring to the process of liquid in the foam flowing to the bottom of the container, and leaving the gas volume fraction highest at the top of the foam; in this case the bubbles deform to polyhedra throughout the upper portion of the foam, creating the so-called " dry foam". When the liquid films between the bubbles are very thin, they eventually break, and the foam collapses. This happens when stabilizing agents are absent (surfactants for aqueous foams). Microgravity offers the opportunity to investigate foam of limited stability (such as metallic foams for instance) and also the so-called "wet" foams, made of spherical bubbles, which cannot be stabilized on earth because of drainage.

With the aim of approaching microgravity conditions on earth, we have used foams made from viscous aqueous solutions to slow down drainage. The easiest way to obtain viscous solutions is to add polymers. However, the viscosity often depends on the flow characteristics (velocity, velocity gradient). This behavior is called "non-newtonian" and can influence the drainage. In addition to the classical viscous resistance to shear, decribed by the shear viscosity η, certain polymers such as polyethylene glycol (PEG) show an additional resistance to normal stresses, characterized by an "elongational viscosity". This second viscosity is associated to the deformation of the polymer coils by the flow and also depends on velocity and velocity gradients. The work presented here initiated in order to investigate and possibly exploit these non-newtonian effects.

We have chosen to study the process called forced drainage in which the solution is poured from the top into a foam column under normal gravity conditions. In this configuration, the boundary between wet and dry foam moves downwards at a constant velocity V(solitary wave) [1]. The water volume fraction in the foam is measured with a

series of electrodes regularly spaced along the column, allowing the precise determination of the velocity V. Theory predicts that V is a power law of the flow rate Q, with an exponent α that depends upon the boundary conditions at the surface of the bubbles and Plateau borders : $\alpha=0.5$ if the fluid velocity vanishes at the surface, meaning that the flow is Poiseuille-like in the liquid channels separating the bubbles (Plateau borders) and $\alpha=0.33$ if the bubble surface is fully mobile, meaning that the flow in the Plateau borders is plug-like. The first situation was encountered with foams made with dobanol and other surfactants [1], the second with foams made with sodium dodecylsulfate (SDS) and other surfactants [2]. The transition between the two regimes was observed with mixed solutions (SDS+ dodecanol) [3], indicating that surface rheology has an important effect on drainage : for small amounts of dodecanol, the bubble surface is mobile, and the flow is plug-like, for larger amounts of dodecanol, the surface becomes rigid, and the flow is Poiseuille-like.

Here we did not use SDS since it is known to form surface complexes with PEG [4]. We have chosen to use instead tetradecyltrimethylammonium bromide (TTAB), also mixed with dodecanol to work with rigid boundary conditions ($\alpha=0.5$). In order to check for the behaviour of newtonian liquids, we have also studied mixtures of water and glycerol of similar bulk viscosities.
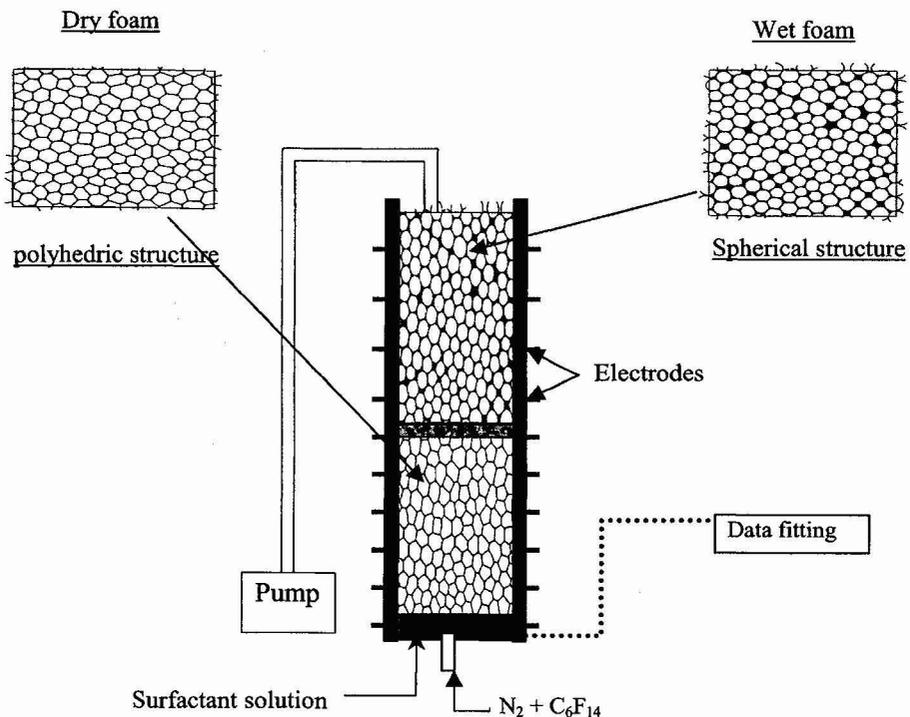
2. EXPERIMENTAL TECHNIQUE

Figure 1. Experimental set-up to measure foam conductivity vs height and time

In a drainage experiment, the liquid fraction is a function of time and vertical position. One method to measure the liquid volume fraction is to measure the electrical conductivity at various heights by using electrodes regularly spaced along the foam column. The experimental set-up used is shown in Figure 1.

The foam is produced by blowing gas through a porous disk into the foaming solution. Here we use mixtures of nitrogen and vapours of perfluorohexan to slow down coarsening. Once formed, the foam is allowed to dry and to age. The final water volume fraction is below 1% and the bubble diameters are of the order of 1mm. The bubble size evolution is regularly checked by visual inspection. Further experimental details can be found in [1-3].

3. RESULTS

3.1 Effect of the surface rheology

In our experiments we have chosen TTAB as surfactant instead of SDS, in order to avoid surface complexation with PEG [4]. We have worked with solutions containing 30mM surfactant (10 times the critical micellar concentration). Figure 2 shows the velocity of the liquid front V as a function of flow rate Q for two weight ratio of TTAB/dodecanol, R=1500 and 2000. For R=1500, $\alpha \sim$ 0.5, for R=2000, α is smaller, $\alpha \sim$ 0.37, indication an evolution towards a plug-flow regime. The typical error on α is ± 0.02. We therefore find a result completely similar to that of the mixed solutions SDS/dodecanol, where the transition between the two regimes also occurs around R=1500 [3].

In the following, we have chosen to work in the Poiseuille flow regime and we have fixed R=1000.
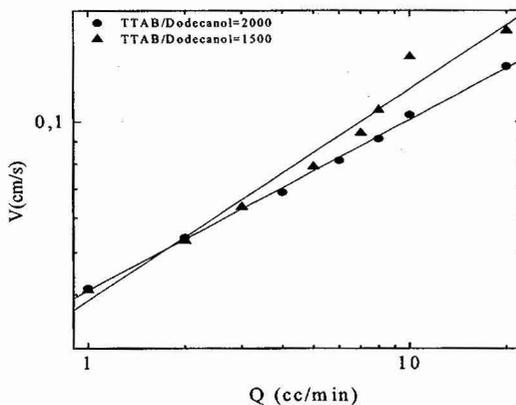

Figure 2. Front velocity vs flow rate for mixed TTAB/dodecanol solutions

3.2 Effect of the bulk viscosity. Case of newtonian fluids

Before studying non-newtonian fluids, we have first checked that the flow regime was not affected by the simple fluid shear viscosity. We have used mixtures of water and glycerol, known to behave as newtonian fluids. This also provides reference experiments to compare newtonian and non-newtonian fluids with the same shear viscosity. Figure 3 shows that the exponent α does not change when the amount of glycerol is increased up to 70%. For a given

flow rate, the velocity decreases as expected. Indeed, the theory elaborated for a Poiseuille regime predicts that [1] :

$$V^2 = AQ/\eta \qquad\qquad (1)$$

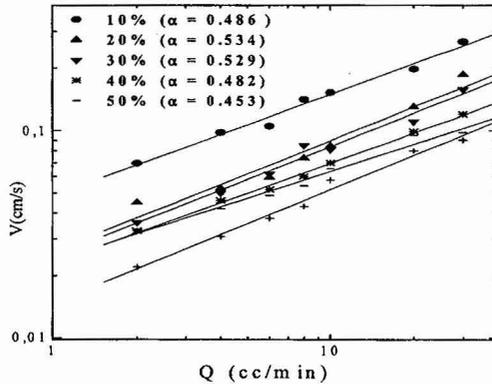where η is the fluid bulk shear viscosity and A is a function of bubble size.

Figure 3. Front velocity vs flow rate for mixed water/glycerol solutions

The variation of V^2/Q with $1/\eta$ is shown in figure 4. In these experiments the bubble radius a is constant and equal to a=(1±0.3)mm. We obtain a linear variation, in good agreement with equation 1. Note that a similar result was obtain earlier with SDS and dobanol solutions [1][5].
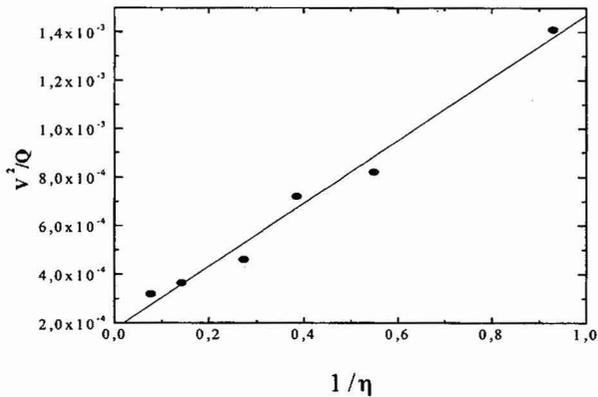

Figure 4. V^2/Q vs $1/\eta$ for mixed water/glycerol solutions.

3.3 Effect of the bulk viscosity. Case of non-newtonian fluids

As explained earlier, we have chosen to study polyethylene glycol (PEG), because this polymer possesses high non-newtonian elongational viscosities, [6] likely to play roles in processes where the fluid is forced to flow through porous media. This polymer is known to induce drag reduction effects when forced through cylindrical tubes. Moreover, flow through porous granular media is strongly influenced by these high elongational viscosity fluids. We have used polymers of different molecular weights M, from 1000 to 5.10^6. The elongational viscosity remains small for the small molecular weights, up to 200,000. The PEG concentration c in the aqueous solutions is 3g/l excepted for the largest molecular weight, where c= 0.75g/l. We have found as for glycerol, that the addition of PEG does not change the flow regime (figure 5). The effect of the bulk shear viscosity is shown on figure 6.
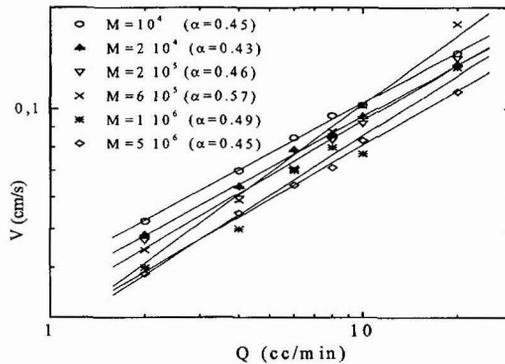
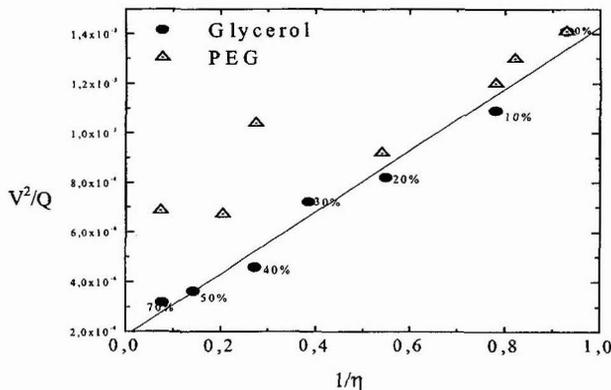Figure 5. Front velocity vs flow rate for various PEG solutions

Figure 6. V^2/Q vs $1/\eta$ for mixed water/glycerol and various PEG solutions

We can distinguish here two types of behaviors : the first corresponds to the short polymers ($M=10^4$ to $2 \cdot 10^5$) who have a behavior similar to glycerol, the square of the velocity being inversely proportional to viscosity. The longer chains ($M=6.10^5$ to 10^6) show a different and surprising behavior : the drainage velocities are larger for the polymer solutions than for the glycerol solutions with the same bulk viscosity. The inverse result could have been explained by an energy dissipation induced by the distortion of the polymer coils in the flow process which gives rise to the elongational viscosity. Such a behavior is indeed observed in the process of splash (high speed impact of drop of solutions on a solid substrate)[7]. The origin of the observed acceleration in flow here remains to be explained. One hypothesis is suppression of flow eddies (as in drag reduction in pipes) at the plateau border junctions.

4. CONCLUSION

The drainage of viscous solutions is therefore very different for newtonian and non-newtonian fluids. The addition of glycerol or of polymer does not change the flow regime in the Plateau borders which remains Poiseuille-like. However, the velocity of drainage is larger than expected for the solutions of polymers of large molecular weights. Because the bulk shear viscosities of the polymer solutions studied here are not very high and matched by the glycerol reference solutions, it is likely that the differences in drainage behavior are related to the important elongational viscosities of these solutions. Current experiments are in progress to clarify the origin of this effect.

Acknowledgements

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