Rheology of Aqueous Foams: a Literature Review of Some Experimental Works

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Rheology of Aqueous Foams: a Literature Review of some Experimental Works

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Résumé — Rhéologie des mousses aqueuses : revue bibliographique de quelques travaux expérimentaux — La mousse étant un système dispersé et instable par nature, sa caractérisation rhéologique est délicate. De nombreux paramètres doivent être pris en compte et contrôlés : la qualité de la mousse (fraction volumique en gaz), sa texture (distribution en tailles de bulles), la taille de l'appareil de mesure par rapport à la taille des bulles, l'influence du mode de formation, le glissement aux parois et la compressibilité de la mousse. D'autre part, la mousse doit être stable et ne pas évoluer dans les conditions de la mesure. Ces nombreux paramètres expliquent qu'il n'y ait pas, à l'heure actuelle, de consensus concernant le comportement de ce type de système. L'influence de la pression et de la température (ne serait-ce que sur le comportement en statique de la mousse) est très peu étudiée. Une étude expérimentale rigoureuse doit prendre en compte et contrôler tous les paramètres influençant la stabilité et la structure de la mousse.
Mots-clés : rhéologie, mousses.

Abstract* — *Rheology of Aqueous Foams: a Literature Review of some Experimental Works — *Foam is a dispersed system and is unstable by nature, its rheological characterization is very difficult. Numerous parameters have to be considered and controlled: foam quality, i.e. gas volume fraction, foam texture (bubbles size distribution), size of the measurement apparatus compared to bubbles size, influence of foam production method, wall slip phenomena and foam compressibility. Foam must be stable and must not evolve during measurement time. These numerous parameters do explain there is no general view concerning the behavior of this kind of system. Influence of pressure and temperature has not been the subject of many studies, even on static foam. A rigorous experimental method should consider and control each of these parameters affecting foam stability and structure.*
Keywords: rheology, foams.

INTRODUCTION

Aqueous foams are used in the petroleum industry for enhanced recovery or during drilling operations. As a drilling fluid, foam is used for drilling depleted reservoirs, in particular reentry operations, or for drilling in underbalanced conditions. Among the existing nonconventional drilling operations, underbalanced drilling offers several benefits under special conditions. In underbalanced drilling, the pressure of the drilling fluid is maintained below the formation pore pressure. It enables to increase penetration rate, to prevent lost circulation and formation damage and to minimize differential sticking. Special fluids are used in order to achieve underbalanced conditions: gas (nitrogen or air), mist (dispersion of droplets into gas), aerated mud or foam.

The number of underbalanced drilling operations should increase during the next decade, as it allows to recover some old depleted areas and to access to new ones where the formation pressure is low.

Foam is adequate for underbalanced drilling thanks to its low density and its good cuttings transport capacity. It is necessary to know precisely the evolution of the injected fluid under bottom hole conditions. Indeed, bottom hole pressure control is essential in underbalanced drilling. This pressure is strongly dependent on the kind and velocity of injected fluids, on reservoir pressure and on temperature. This is all the more true for horizontal wells. In order to predict accurately the pressure drops along the well, it is necessary to have a better understanding of foam rheological behavior, especially under high pressure and high temperature conditions (which are bottom hole conditions). This work is a literature review of different studies of foam rheology, and tries to point out the important parameters that control foam behavior before any experimental investigations.

1 GENERALITIES

Foams are dispersions of a gaseous phase in an aqueous phase containing surfactants. The foam "quality" is the volume fraction of gas. This volume fraction is generally very high and can exceed the "packing concentration" of a hard spheres suspension. For this kind of foams (called "dry" foams as opposed to "wet" foams where the suspending liquid phase volume fraction is high), gas bubbles are no longer spherical but warp into polyhedral bubbles separated by thin liquid films. The liquid phase is then principally contained in these thin films and in the "Plateau borders" at polyhedral bubbles intersections. This kind of system is considered as a continuous phase only if the bubbles size is small compared with the sample size.

If we study foam rheology, many parameters will play an important role. The bubbles size will have a major impact as well as the interfacial tension and the gaseous phase volume fraction. The bubbles size is often omitted as a parameter in experimental studies; yet this average size is likely to vary with time by gas diffusion from small bubbles to large bubbles or by coalescence; with foam production method (for example when the foam is created from flow of gas and liquid through a porous media: the bubbles size changing with the imposed flow rate); or with the shear rate experienced by foam (its structure is modified by viscosity measurements). Foam is an unstable system: a foam evolves by drainage of the liquid phase with time, by gas bubbles coalescence or by Ostwald ripening. Finally, the gaseous phase compressibility is an additional difficulty when one carries out measurements on flowing foams.

The rheological behavior of a foam presents singularities that one must consider: under a weak shear stress, foam behaves like a plastic solid, i.e. there is a yield stress and foam begins to flow when it is exceeded. Under a weak shear stress, foam can flow in "plug flow" by slipping on a thin fluid layer at the wall. This second point is very important: there is a wall slip velocity one must take into account. With all these parameters, foam rheology is a very complex problem which is a matter of debate at present time.

Foam flow and therefore foam rheology analysis have been the subject of numerous studies since about thirty years. We can divide these works into three major families:

- Experimental studies of foam rheology carried out with rheometers and laboratory configurations; numerous parameters are considered (yield stress, wall slip velocity, drainage phenomena, etc.), from these measurements, a rheological equation is proposed.
- Foam rheology measurements in conditions simulating petroleum industry reality: pressure drops measurements in large size pipes, comparison with foam flow model (*SPE* works). Many of these experiments consider foam flowing into porous media, since foam is used for enhanced oil recovery.
- Theoretical studies trying to describe foam rheology from a microscopic model: bubbles described as polyhedral bubbles, interfacial viscosity, etc. (Kraynik, Princen).

In this paper, we will focus on experimental studies in order to determine the important parameters to be considered for good and reproducible viscosity measurements.

2 MEASUREMENT APPARATUS GEOMETRY

Two publications give a general sight over the numerous studies made on foam rheology (Heller and Kuntamukkula, 1987); Prud'homme and Khan, 1996). The first impression is the lack of agreement between the different results and the frequent non-reproducibility of the measurements. The numerous parameters playing a non-negligible role we tell about in the introduction do explain this lack of coherence between the results: it is difficult to control all these parameters at the same time. Figure 1 gathers experimental measurements from three authors on the same graph and shows the disparity of the results for a same foam quality.

The first point is to determine the most adequate experimental system in order to measure foam viscosity. The characteristic size of the measurements apparatus must be widely larger than the average size of the gas bubbles in the foam, this average size being able to vary from a few micrometers to a few millimeters depending on pressure or shear rate conditions. A several millimeters gap at least is necessary in a coaxial geometry, which is attainable with difficulty. Moreover, in such a geometry, the volume of foam

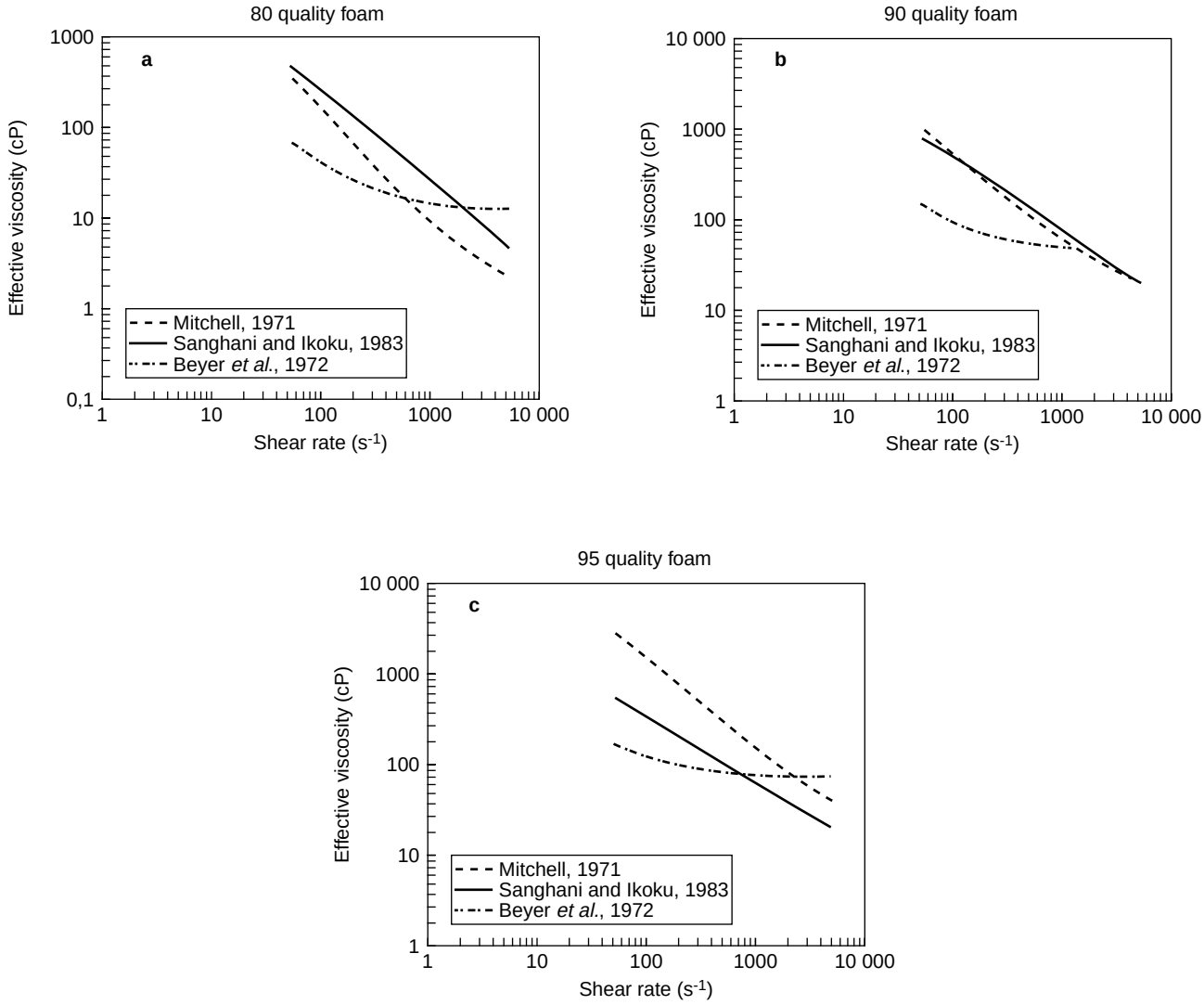
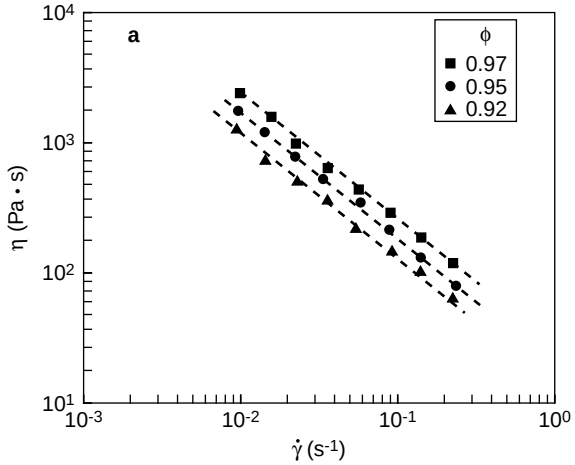


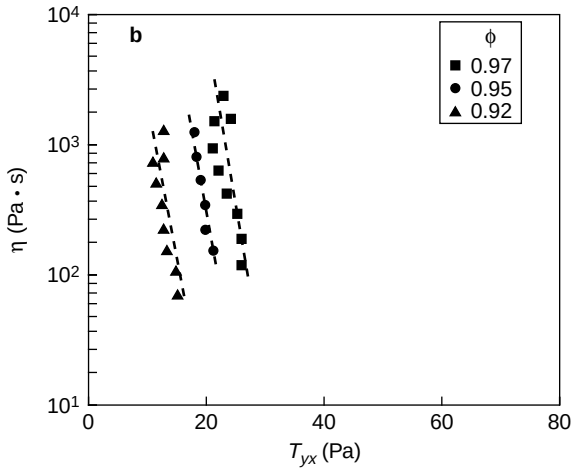
Figure 1

Effective viscosity of foam as a function of shear rate and foam quality. From *Underbalanced Drilling Manual, Gas Research Institute,* 1997.

sample is constant, the drainage phenomena and the foam compressibility will affect its stability during measurements. Khan, Schnepper and Armstrong (1988) have studied foam rheology with a parallel plate rheometer where foam is placed between two concentric discs. The gap is 2.4 mm high and authors have made sure that foam is stable during measurement time: with an imposed shear rate, they make sure that the torque measured is stable, a decreasing torque after some times shows degradation of foam. They also measured bubbles average size by an optical method before introducing foam into the gap, interfacial tension of liquid films and yield stress by a “stress relaxation” method. Khan *et al.* solved the slip velocity problem by an original mean: they covered rheometer walls with sand paper; measurements with different gaps showed similar results, which proved that there was no more wall slip velocity. Their results show that foam behaves like a Bingham plastic, effective viscosity varies between 60 and 3000 Pa·s and increases with foam quality; unfortunately, their measurements are limited to weak shear rates (from 10^{-2} to 10^{-1} s^{-1}), the geometry used doesn't allow larger shear rates (Fig. 2).



Foam viscosity as a function of shear rate for three different gas volume fractions.



Viscosity as a function of shear stress for three different gas volume fractions. The vertical asymptotes indicate the yield stress of the foam.

Figure 2

Effective viscosity of foam as a function of shear rate and stress. From Khan, Schnepper and Armstrong (1988).

It seems that an appropriate geometry in order to study foam rheology, especially under pressure and high temperature, should be flow in a capillary pipe.

This method consists in measuring the pressure drop generated by the flow of foam in a capillary pipe versus flow rate, allowing us to know the shear stress at the wall versus shear rate. Foam flows continuously, there is yet no more problems related to a finite volume of foam used for measurements.

3 WALL SLIP VELOCITY

On the other hand, wall slip problem is still present, and has been quoted by numerous authors (David and Marsden, 1969; Raza and Marsden, 1967; Beyer *et al.*, 1972; Patton *et al.*, 1983; Hirasaki and Lawson, 1983; Enzendorfer *et al.*, 1995). Experiments made on pipes having different diameters give different results for the same imposed ΔP, i.e. for the same wall shear stress, which proves the existence of wall slip velocity. There are methods to compute wall slip velocity values from these measurements: Mooney formalism (1931), assuming wall slip velocity is directly proportional to wall shear stress, has been used by these authors and gives no satisfactory results. Oldroyd-Jastrzebski method (1967), where wall slip velocity is assumed to be proportional to wall shear stress and inversely proportional to pipe's diameter, has been used by Enzendorfer *et al.* (1995) and gives good results. Thondavadi and Lemlich (1988) have studied foam flow in 3 m long horizontal pipes having diameters varying from 1 to 5 cm. Measurements are performed under weak shear rate (0 to 6.2 s^{-1}) in steel or acrylic pipes. Results show that foam flows almost solely by wall slip (Fig. 3) for acrylic pipes, whereas there is no slip velocity for flow in steel pipes.

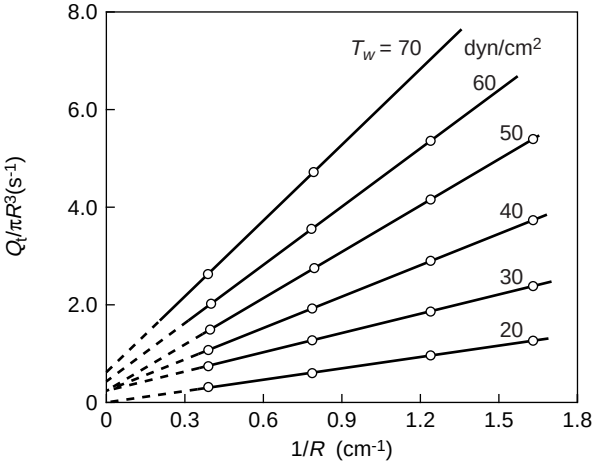


Figure 3

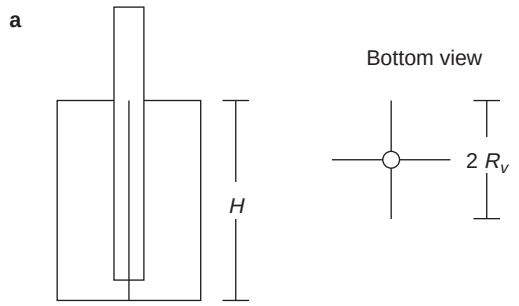
Apparent shear rate as a function of the inverse of acrylic pipe radius for various wall shear stresses. From Thondavadi and Lemlich (1985).

Harris and Reidenbach (1987) have studied foam rheology in a recirculating loop made of steel pipes (3 m long and 7.75 mm diameter) and observe no wall slip velocity. The

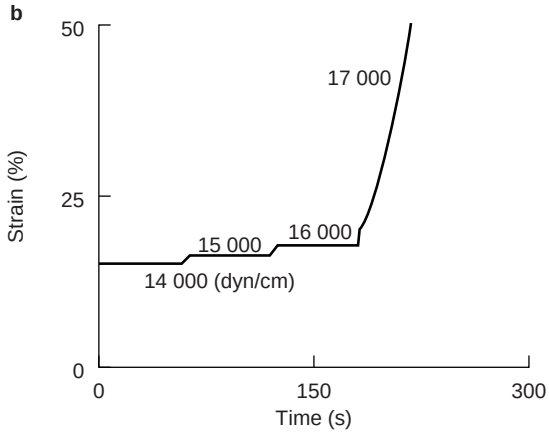
nature of the pipe used, especially the state of surface, will influence results, which is coherent with Khan *et al.* results in coaxial geometry. This wall slip velocity is due to the existence of a thin liquid film at the walls. Some authors have tried to evaluate this thin film thickness and the wall slip velocity variation with this thickness (Enzendorfer *et al.*, 1995; Thondavadi and Lemlich, 1985). According to Calvert and Nezhati (1986 and 1987), there is a correlation between this thin liquid film thickness and foam quality, the slip layer thickness being larger for smaller qualities; but as a first approximation, they find this film thickness to be independent of average bubble size.

4 YIELD STRESS

The existence of a "yield stress" is much debated because it is not easily measurable, especially in capillary geometry. Khan *et al.* (1988) measured a yield stress in coaxial geometry with the "stress relaxation" method: a shear rate is imposed then stopped, the torque value falls then to a non-zero value which is identified as the yield stress value. This yield stress value increased with foam quality and varies between 10 and 20 Pa. Numerous yield stress measurements methods do exist, among these are the use of a "vane device" or the stress relaxation method (Fig. 4).



Vane device for the measurement of yeld stresses.
The vane, which is attached to the torque transducer on a stress rheometer, is immersed in a larger cup containing the fluid with a yield stress.



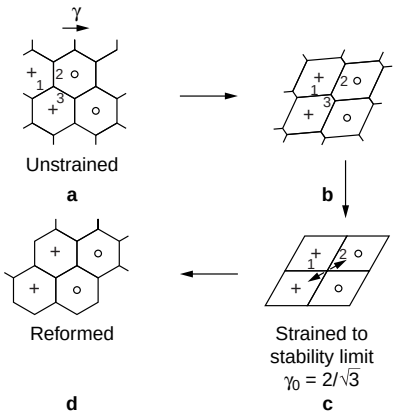
Angular deflection vs. time for an emulsion measured using a vane geometry. A serie of increasing shear stresses in posed on the emulsion. Below the yield stress the emulsion deforms and then comes to rest; above the yield stress the cup continues to rotate as the material shears.

Stress relaxation technique used to measure yield stress in foam. The figure at left shows the rotation rate applied to the upper disk of the parallel-plate geometry, and the figure at right shows the observed torque response. The residual stress after a steady shear flow corresponds to the yield stress.

Figure 4

Techniques to measure yield stress. From Prud'homme and Khan (1996).

When using capillary geometry, yield stress value is measured by extrapolating zero shear rate values. Some authors (Barnes and Walters, 1985) do consider that yield stress notion is erroneous and only represents "what can't be measured". Kraynik (1988) showed experimentally the presence of a yield stress in foam by observing near wall bubbles behavior in a transparent pipe. This "yield stress" notion is justified by theoretical arguments: it represents the amount of energy which is necessary to pass from a stable bubbles network to an other (Khan *et al.*, 1988) (Fig. 5). When shear stress is less than yield stress and when wall slip velocity is present, foam does flow entirely by "plug flow". Beyer *et al.* (1972), Kraynik (1988) and Thondavadi and Lemlich (1985) made experimental observations of this plug flow.



Sequence showing the deformation of monodisperse, two-dimensional, hexagonal foam cell in shear. The gas volume fraction is unity in this illustration. Increasing strain is applied moving through the sequence in a clockwise direction from a to d. The initial cell orientation shown here is θ = 0 relative to the direction of shear. In c the critical strain is reached where the cells become unstable, because side "3" has decreased to zero length.

Figure 5

Yield stress of a two dimensions hexagonal foam. From Khan, Schnepper and Armstrong (1988).

5 FOAM TEXTURE AND STABILITY

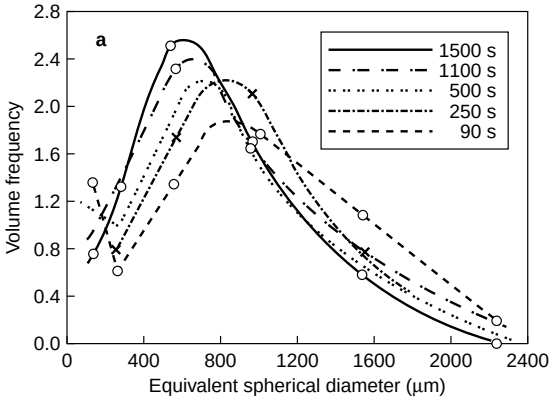
Foam texture is given by gas bubbles size distribution. Bubbles size may vary from a few microns for a fine foam to a few millimeters for a coarse foam. As we say in introduction, capillary pipe diameter must be widely greater than bubbles size — a ratio of ten seems to be a minimum (Prud'homme and Khan, 1996) — if we want to measure rheological properties of foam as a continuous medium. Numerous experimental works measure foam rheology in capillary pipes of very little dimension (less than one millimeter in diameter). This kind of analysis is more suitable to the study of foam behavior in a porous medium, the porous medium being represented by a group of little capillary pipes.

Foam is an unstable system: it can deteriorate by drainage of the liquid phase due to gravity. Liquid accumulates then at the bottom of the sample and foam can't be any longer considered as an homogeneous system (Princen, 1990). Bubbles size distribution of a polydisperse foam will also vary with time: pressure inside little bubbles is greater than pressure inside large bubbles, gas will then diffuse from small bubbles to large bubbles, changing distribution of sizes. Foam must be stable for at least measurements time. Bubbles size measurements and rheology measurements at the same time seems to be a necessity to numerous authors (Prud'homme and Khan, 1996; Calvert and Nezhati, 1986 and 1987; Harris, 1983 with Reidenbach, 1985, 1987, 1990, 1994, 1996) carried out a series of experimentations on foams and measured textures by an optical method or with a multichannel particles detector. Foam flows in a recirculating loop made of steel pipes, pressure drop over a certain distance being measured and rheological values being computed from these measurements. A constant shear rate (i.e., a constant flow rate) is imposed until foam texture is equilibrated, which can last thirty minutes depending on the kind of foam being studied. Foam texture is then dependent on the imposed shear rate (Fig. 6). When foam is equilibrated, Harris records pressure drops versus different flow rates, assuming values are measured rapidly enough so that foam texture does not have time to vary.

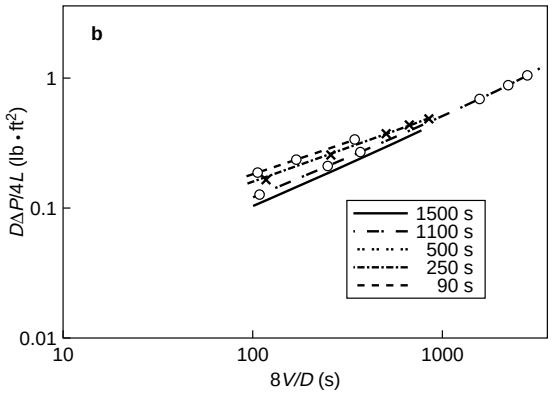
6 FOAM PRODUCTION

The foam production method must be well characterized. This production method has an influence on foam texture and quality and therefore on foam rheology; it is necessary to form a stable and well characterized foam in order to have reproducible measures. The most common foam creation method consists in injecting surfactant solution and gas through a porous medium. By varying gas and fluid flow rate ratio, it is possible to change foam quality. This porous medium is often constituted of sand (Burley and Shakarin, 1992; Enzendorfer *et al.*, 1995; Raza and Marsden, 1967) or of stacked glass beads (Patton *et al.*, 1983; David and Marsden, 1969); Harris (1983, 1985, 1987, 1990, 1994, 1996) produces foam by circulating first the fluid in the recirculating loop, and then injecting gas into fluid through a small opening (the fluid in excess is allowed to escape through a backpressure regulator). When using a mixer (Hanselmann and Windhab, 1996), foam quality can't be controlled.

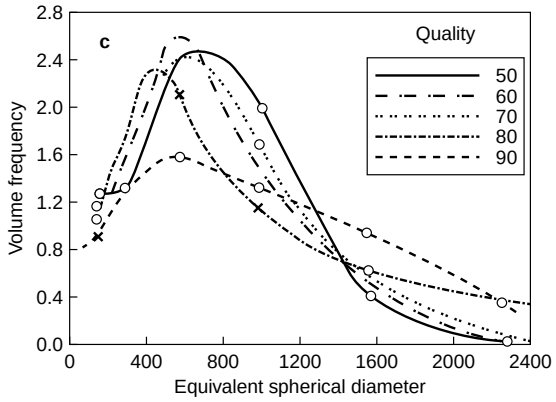
By varying gas and fluid injection rate into porous media, foam texture may be modified. Measurements made at different shear rates (i.e., made at different flow rates) are carried out on foams having different textures. Patton *et al.* solved this problem by imposing a constant flow rate at the porous medium entrance: the foam texture is then stable; a bypass pipe at the capillary entrance (i.e., at the porous



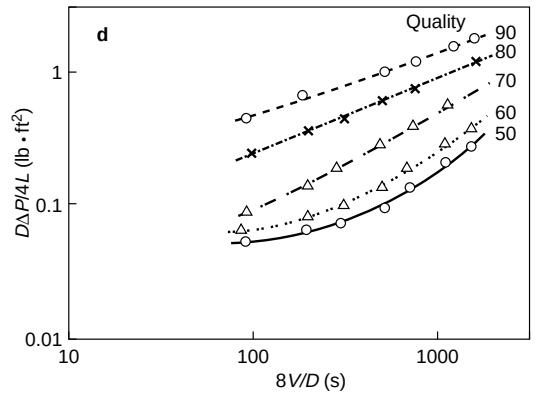
Frequency plots show smaller bubbles and narrower distributions from higher shear rates for equilibrated 70 quality foams.



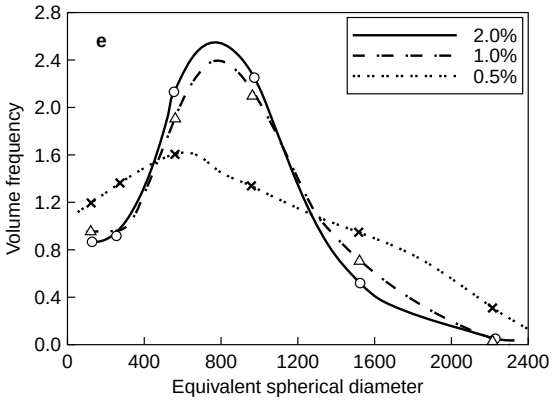
Rheograms show higher viscosity for foams equilibrated at low shear rate.



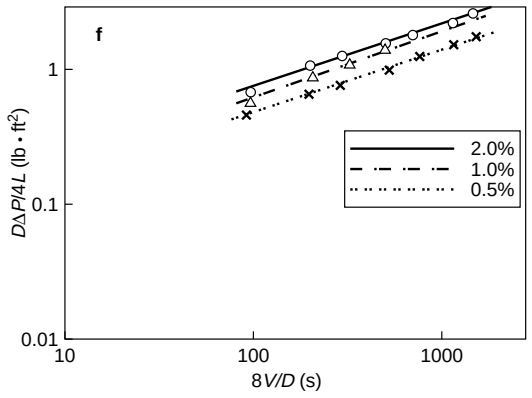
Texture plot shows 90 quality foam skewed to large bubble size.



Rheograms of 50-90 quality foam.



Higher surfactant concentration gives more uniform bubble size for 90 quality foams.



Higher surfactant concentration gives higher viscosity for 90 quality foams.

Figure 6

Experimental results of Harris (1985): texture and foam rheology.

medium exit) allows the flow rate to vary (and therefore the shear rate) in the capillary pipe without changing foam texture (Fig. 7). Using this technique, large quantities of foams are produced and then must be treated. With the recirculating loop used by Harris, this disadvantage is eliminated, measurements are carried out on equilibrated foams, flow rate can vary without affecting foam texture if measurements are made quickly enough.

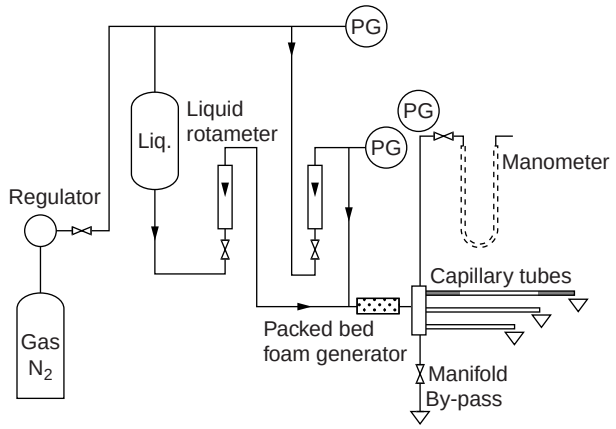


Figure 7

Experimental system, Patton *et al.* (1983).

7 FOAM COMPRESSIBILITY

Foam is made principally of compressible gas: a pressure change will have an influence on the sample volume. If the pressure drop in the capillary pipe is large, the foam compressibility must be taken into account. In underbalanced drilling, pressure drops along the wells are very large, foam compressibility will then play a major role. Lord (1981) presented a review of the equations of state and of the measurement methods proposed for compressible foams. The pressure drop due to flow through a pipe and the hydrostatic pressure do interact by means of density variation. Iterative calculation methods to compute pressure drop in a capillary pipe were developed by Beyer *et al.* (1972), Krug and Mitchell (1972) and Blauer and Kohlaas (1974). Valko and Economides (1992) developed an analytic method to compute pressure in a well. They introduce the notion of "specific volume expansion ratio" defined as the ratio of foam and liquid (in the foam) densities, compressibility is taken into account by the mean of a viriel like equation of state (restricted to the first terms). Foam quality and then "specific volume expansion ratio" ε vary with pressure. They consider that foam follows a rheological power law for every quality or pressure:

$$\frac{\tau}{\varepsilon} = K\left(\frac{\dot{\gamma}}{\varepsilon}\right)^n$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate and K and n are constant.

Experimental measurements are made on very large pipes (where the pressure drop due to the flow is large enough to induce foam quality variations) and the agreement is correct for large quality foams (> 70%) (Winkler, Valko and Economides, 1994); more recently, Enzendorfer *et al. (*1995) made measurements on small dimension pipes ($D \cong 1$ cm) under various pressures (up to 70 bar) and for foams of different qualities. They validate their results with Valko and Economides model and obtain good agreement for large shear rates (Fig. 8). Hanselmann and Windhab (1996) studied rheology of foams flowing into a pipe under moderate static pressure conditions (up to 3 bar), taking into account foam compressibility. They consider a pressure drop and compute the corresponding volume variations, using the equation of state of perfect gases for the gas. The volume variations are then measured experimentally in an expansion tube, and a good agreement is found with predicted variations. Variations of viscosity with pressure were studied: effective viscosity of foam decreases with increasing static pressure.

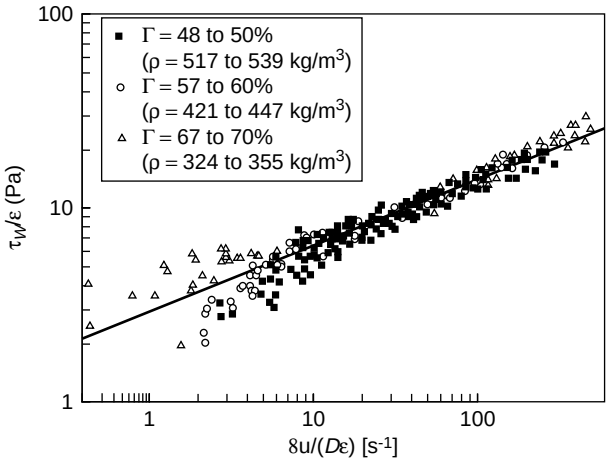
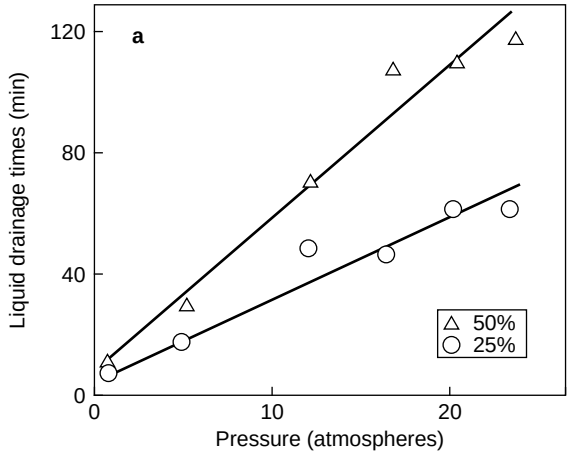


Figure 8

Rheological measurements presented with Valko and Economides model. From Enzendorfer *et al.* (1995).

Harris (1983, 1985, 1987, 1990, 1994, 1996) also studied foam rheology under pressure (69 bar) and high temperature (149°C) in a recirculating flow loop. However, there are very few results on foam behavior under high static pressure. The stability of a static foam under high pressure has been studied by Rand and Kraynik (1983). They measure drainage velocity of an aqueous foam formed under pressure (1 to 20 bar) in an autoclave. Their results show that drainage time

does increase a lot with pressure, the explication for this enhanced stability is a diminution of the bubble size — measured with microphotography — (Fig. 9).



Effect of autoclave pressure on the aqueous foam liquid drainage times.

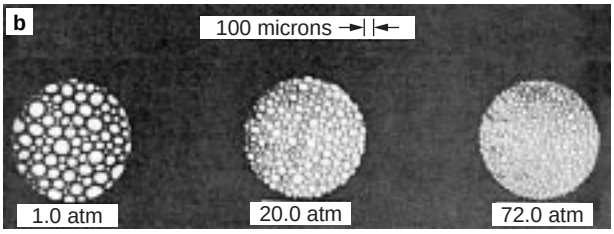


Figure 9

Effect of pressure on drainage time and on bubbles size. From Rand and Kraynik (1983).

8 RHEOLOGICAL EQUATIONS

Different rheological equations are proposed to describe experimental results. Foam is described as a non-newtonian fluid:

- pseudoplastic power-law (Thondavadi and Lemlich, 1988; Raza and Marsden, 1967; David and Marsden, 1969; Patton *et al.*, 1983; Sanghani and Ikoku, 1983; Enzendorfer *et al.*, 1995);
- Bingham plastic (Khan *et al.*, 1988);
- Herschel-Bulkley (Calvert and Nezhati, 1986; Burley and Shakarin, 1992; Harris, 1985).

A power law seems therefore appropriate to describe foam behavior. All authors agree that foam apparent viscosity for a given shear rate increases with foam quality, Valko and Economides (1992) propose an analytical relation that allows to deduce the rheological law for a certain quality from the one for a given quality. They introduce the notion of "specific volume expansion ratio" (ratio of foam and liquid densities) noted ε. The rheological equation is then (see Section 7):

$$\frac{\tau}{\varepsilon} = K\left(\frac{\dot{\gamma}}{\varepsilon}\right)^n$$

Viscosity variations with pressure have been studied by Harris (1985) and by Hanselmann and Windhab (1996). The apparent viscosity of foam decreases with increasing static pressure, especially at low shear rates. Harris shows concurrently that bubbles mean size decreases with pressure but that the distribution of size is broader for low pressure conditions.

Harris studied also the influence of temperature. When temperature increases, it is possible to work with a constant volume (and therefore to let the pressure increase), or to work with a constant pressure, allowing the volume to vary. Harris chose the first option and had the temperature varying up to 149 °C. The apparent viscosity at a given shear rate decreases with increasing temperature, this diminution being stronger for low quality foams than for high quality foams.

Finally, most of aqueous foams are adequately described as non-newtonian fluids following a power law with or without yield stress, and the viscosity of which decreases with increasing pressure (or temperature) and decreasing quality.

CONCLUSION

Regarding all the studies already done on foam rheology, a conclusion is that it is necessary to control different parameters when viscosity measurements are carried out. Texture (bubbles size distribution) should be characterized concurrently to rheology measurements. Viscosity measurements at different shear rates, i.e. different flow rates, must be carried out on identical foams (in particular of same texture) which are stable during measurement time. In addition, wall slip velocity and foam yield stress must be taken into account; in the same way, gas compressibility should play a role in pressure drops calculation. An experimental investigation of foam rheology should consequently present the following characteristics: a foam formulation stable during measurement time, a method to measure continuously foam texture (bubbles mean size), a rheological measurements system which allows to work on stable and equilibrated foams, and special care about wall slip velocity and yield stress measurements. Finally, experimental investigations must pay attention to the importance of the relation between structure (i.e. foam texture) and rheology of foam.

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