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Experimental results on the flow rheology of fiber-laden aqueous foams

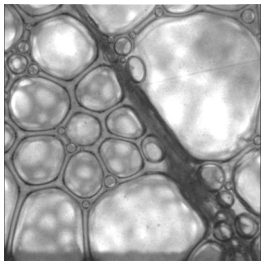
Ari Jäsberg*, Pasi Selenius, Antti Koponen

VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Finland

HIGHLIGHTS

- The first published results on the rheology of fiber-laden aqueous foams.
- No Mooney analysis needed for the calculation of rheological properties.
- A simple and robust method to measure the slip velocity at the pipe wall.
- A link from fiber-foam rheology to the properties of foam formed paper.

GRAPHICAL ABSTRACT



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ABSTRACT

We report here the first experimental results on the rheology of fiber-laden aqueous foams. The measurements were carried out in a laboratory-scale environment with a glass pipe of diameter 15 mm. The slip velocity at the pipe wall was measured with high-speed video imaging. Plain aqueous foam was generated from 8.5 mM aqueous solution of sodium dodecyl sulphate (SDS). Foam generation was realized as a combination of tank mixing and injection of compressed air in a special inline generation block (turbulence generator) installed into the flow loop. Fiber-laden foam was prepared by dispersing hardwood fibers into the SDS solution at consistency of 20 g/kg.

In the measurements, an absolute slip velocity was observed that increased with the wall shear stress. On the other hand, the relative slip velocity decreased with the wall shear stress. At highest shear stresses relative slip values of *ca.* 10% were observed, *i.e.* considerable shearing took place inside the foam. At low wall shear stress relative slip velocities up to 40% were measured. The addition of wood fibers decreased the absolute slip by *ca.* 25% while the relative slip increased by a factor close to four.

The real wall shear rate in foam was calculated with the Weissenberg–Rabinowitsch correction. All the studied foams could be modeled with Herschel–Bulkley law with flow behavior index $n = 0.5$. The viscosity of the fiber-laden foam was *ca.* 100% larger than that of the plain aqueous foam at same density and temperature. This increase in viscosity is much less than in the case of plain aqueous fiber suspension, where the viscosity increases by a factor five or more due to fibers being in continuous contact in shearing. Thus the current results imply that in aqueous foams fibers do not interact or flocculate to the same extent as in plain aqueous suspensions.

By applying the methodology described here on the data measured with one pipe diameter, one can calculate real material properties that are independent of boundary effects like slip velocity.

* Corresponding author. Tel.: +358 403515588.
E-mail addresses: Ari.Jasberg@vtt.fi (A. Jäsberg), Pasi.Selenius@vtt.fi (P. Selenius), Koponen@vtt.fi (A. Koponen).

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1. Introduction

Liquid foams are concentrated dispersions of gas bubbles in a surfactant solution. The thickness of the liquid films separating neighboring bubbles is generally between 10 nm and a few μm. The gas–liquid interfaces are covered by surfactant molecules preventing the rupture of the liquid films. In equilibrium, the pressure in the liquid is determined by the laws of hydrostatics, and the gas pressures in the bubbles differ from this due to capillary and disjoining pressures [1,2].

On the macroscopic scale, foams appear to be homogeneous and can be characterized by their gas volume fraction ('foam quality') and bubble size. Although they are composed only of fluids, the mechanical properties of foams can be either solid-like or liquid-like, depending on the applied stress. The elasticity of liquid foams arises because a small applied stress increases the gas–liquid interfacial area, and thus the energy density of the system. If the applied stress is increased beyond the yield stress, it triggers irreversible bubble rearrangements and foam starts to flow like a viscous non-Newtonian shear thinning fluid. The viscosity of foam is typically a few orders of magnitude above that of pure water [3,4].

The uncommon mechanical behavior of foams combined with their low density and large specific surface area give rise to a large variety of industrial applications. Foam has *e.g.* been used as a carrier material for many substances. For instance, in the widely used process called flotation, liquid foams are employed to separate minerals from extracted ore. Foams are also used as drilling fluids in oil production, and as fire fighting agents for polar-solvent and oil fires. In everyday life, they are encountered in many food products and cosmetics. Foams are also used in making laminates and composites, and in various coating processes [5–9].

In the 1970s several articles on foam, as a replacement for water in paper making, were published [10–12]. In this process aqueous, viscous foam is used to transport fibers and to deposit them *via* a drainage process. Foam-forming aroused interest, as the movement of fibers is restricted in the foam and flocculation is thus reduced – this gives the web an outstanding uniformity. In the mid-70s a few pilot paper machines utilizing foam-forming were indeed run rather successfully, but it was not widely adopted in the paper industry. The process was later further developed for the nonwoven industry for transport of polymeric, metal, glass and other mineral fibers, and is nowadays used for making various nonwoven products.

After a long silent period, foam-coating [13,14] and foam-forming are now attracting increasing interest in paper industry [15–20]. The use of foam allows the inclusion of a wide variety of alternative raw materials, such as nanoparticles [21], nanocellulose [22] and long flexible fibers. This technique will also lead to more versatile production methods that are required for manufacturing new types of end products, such as high-porosity cellulose nanofibril (CNF) aerogels [23]. Naturally, energy efficient technologies are also of interest due to rising energy costs, and with foam-based techniques in paper making, water consumption is reduced and less energy is needed in drying.

In all of those new applications, the rheology of the foam must be tuned to meet the requirements of the product or process. However, although rheology of plain aqueous foams has been studied extensively, particle-foam systems have got much less attention [24]. Moreover, there is practically no information available on the rheological behavior of fiber-laden foams. Systems of fibers and gas bubbles have been studied in relation to the flotation process both in the mining and paper industry [25], but almost all public results on true fiber-laden foams can be found in patents for producing nonwoven products. There is thus urgent need for fundamental research of the underlying physics and physical chemistry of fiber-laden foams.

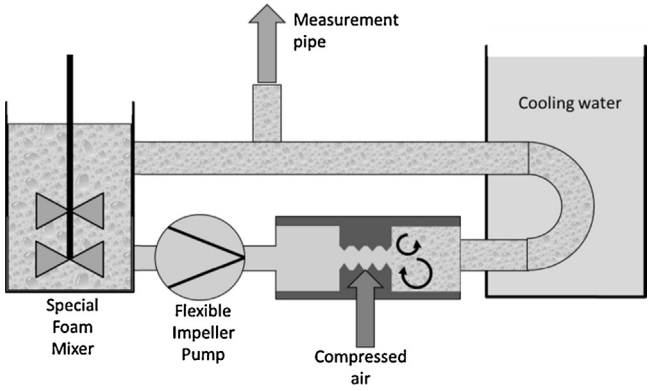

Fig. 1. A schematic view of the foam generation system. Foam is generated by a combination of tank mixing and injection of compressed air into highly turbulent flow inside a specifically designed contraction block.

Due to problems related to aging of foam and often strong slip flow at solid boundaries, rheological analysis of liquid foams is not feasible with most traditional rheometer geometries. Instead, pipe flow has mainly been used, and the effect of slip has been determined with Mooney analysis, *i.e.* by assuming

$$v_s = \frac{\beta \tau_w}{D} \tag{1}$$

Above v_s is the slip velocity, τ_w is the wall shear stress, and D is pipe diameter. The dependence of coefficient β on the wall shear stress is determined by performing the measurements with several different pipe diameters [26,27].

In this paper, we present a novel method for the rheological analysis of foams and present brand-new results on the rheology of fiber-laden foams. The measurements are based on pipe flow, but the slip velocity and also the bubble size are measured explicitly utilizing high speed imaging. Optical coherence tomography (OCT) is also used to verify these results. Most previous studies have concentrated on dry foams. In this work the air content of the foam is that of a typical foam foaming process, *i.e.* 70%, we are thus in the wet foam regime [28]. Hardwood fibers are used and the fiber mass consistency (defined as the ratio of the mass of fibers to the total mass) is 2.0%.

2. Materials and methods

2.1. Foam generation

The measurements were carried out by using aqueous foams with and without added wood fibers. Aqueous foams were generated from a solution of tap water and anionic surfactant sodium dodecyl sulfate (SDS, $C_{12}H_{25}SO_4Na$). Fiber-laden foams were prepared by adding wood fibers into the initial SDS solution. All foams were generated with a combination of tank mixing and inline generation in a short flow loop, see Fig. 1. The tank mixer has been specifically designed for foam generation and it has two round impeller plates with opposite edges slightly bended up and down [16]. The inline generation was implemented by injecting compressed air into the SDS solution in a specifically designed inline generation block where the flow field is highly turbulent.

The foam generation phase was started by adding the SDS solution into the tank, tank mixer was started, and air was injected into the solution until the target value of foam density was reached (this was obtained from the surface level of the foam inside the tank). During the measurements, the air content and bubble size of the foam was stabilized before measurements by pumping it continuously through the inline generation block (without air injection), and by mixing the foam inside the tank to minimize density