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Interactions of fibres with simple arrangements of soap films

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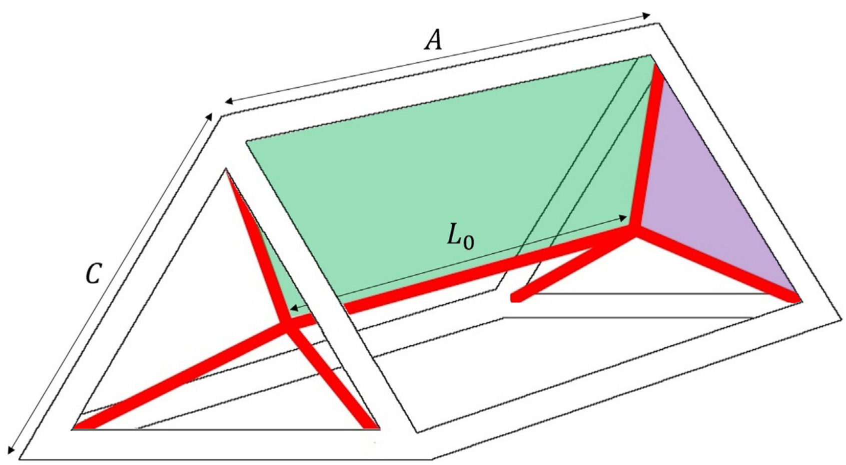
HIGHLIGHTS

- The introduction of fibres into simple configuration of soap films modifies their equilibrium configurations.
- Computer simulations using the Surface Evolver software agree well with experimental results.
- The pinning of films to fibres is likely to contribute to the slowdown in coarsening of fibre laden foams, as feature in paper making using foam forming.

GRAPHICAL ABSTRACT



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ABSTRACT

We present experiments and Surface Evolver simulations concerning the interaction of fibres with simple arrangements of soap films, which constitute model systems for dry foams. For a fibre inserted into a soap film which spans two Plateau borders, our simulation accurately predicts the variation in the length of the film as the fibre width is varied. For a fibre introduced into a Plateau border, simulations accurately predict the variation in length of the Plateau border as the fibre diameter is varied, and as it is moved. We suggest that the force necessary to move the fibre from its equilibrium position may act to inhibit foam coarsening, in line with previous observations from experiments on fibre-laden foams.

1. Introduction

In the paper making industry, *foam forming* is a relatively new manufacturing technique in which the suspension of cellulose fibres in water is foamed before drying it to form paper [1]. The bubbles act to space out the fibres more evenly, improving the homogeneity and the strength of the final product. For this reason, foam forming is of great advantage to the papermaking industry. Related is the use of this technique for the production of novel non-woven fibrous material for thermal insulation. Although the technique has been known since 1974 [1] it has been only very recently that the interactions between fibres and foam have been examined in greater detail [2–8].

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Adding fibres to a liquid foam alters its physical properties (*e.g.* drainage rate, bubble size distribution, coarsening rate) significantly. Recent work [2–4] concerned mainly *wet* foams, *i.e.* those with liquid volume fraction $\phi \gtrsim 0.2$, and focused on the effect of the presence of fibres on global properties, such as stability of the foam [5] or rheology [9] of fibre suspensions.

Here as a first initial approach of studying the interaction of fibres with films and Plateau borders, we have considered stiff fibres (both in our experiments and simulations). In application for papermaking this might not always be realistic, but our findings should nevertheless serve as a guide how fibres behave in a foam. We present two experiments probing the interaction of a single fibre with the simplest possible model systems for dry foams: one essentially 2D in character, the other fully 3D.

In particular the 3D experiment has relevance in papermaking, where also fibre thickness (50 μm) is much smaller than fibre length (≈2 mm), which in turn exceeds the average bubble diameter (200 μm) [2].

We compare data from our experiments to that obtained from simulations using the Surface Evolver software package [10] for the case of infinitesimally thin liquid films.

Finally we suggest that this fibre–film interaction plays a role in the observed reduction of coarsening rate in fibre-laden foams. Liquid retention in the presence of fibres cannot be probed in our experiments but may also contribute.

2. The effect of fibres on soap films between two parallel plates

Soap films, under the action of surface tension, attempt to minimize their total surface area. For dry foams (low liquid volume fraction) in equilibrium the resultant structures obey *Plateau's laws* [11,12]:

1 Soap films are smooth surfaces of constant mean curvature.
2 Soap films meet in threes at angles of 120° at liquid channels called *Plateau borders*.
3 Plateau borders meet in four-fold vertices at angles of ∼109.43°.

In two dimensions these rules are related to the *Steiner problem*: finding the shortest possible length of lines linking a set of points. Solutions to the Steiner problem consist of sets of straight lines meeting in threes at angles of 120°, analogous to Plateau's second law. The solution for the corners of a square is shown in Fig. 1(a). Simple geometry gives the length L_0 of the central line as

$$\frac{L_0}{S} = 1 - \frac{1}{\sqrt{3}} \approx 0.42, \qquad (1)$$

where S is the side length of the square.

Fig. 1(b) shows a corresponding experimental apparatus consisting of two parallel Perspex plates, bridged by four graphite pins arranged in a square. We have used this to investigate how the addition of a fibre changes the equilibrium configuration of soap films. If the apparatus is dipped vertically in a surfactant solution, the network of films formed between the pins is a Steiner tree of the same form as Fig. 1(a). Since the films are parallel to the two perspex plates, we call this a *quasi-2D* apparatus.

In our experiments (Fig. 1) we place a flat wooden stick (thickness of 1 mm) into the plane of the central film and measure the variation in the length L of the film, as viewed from the top, for various fibre widths W. Fig. 1 shows the definitions of the relevant lengths (*i.e.* the pin separation S, the plate separation D, the fibre width W and the length of the central film L) for our setup. Since the liquid films meet the fibre at right angles this results in an increase in the length L as compared to L_0, its length in the absence of a fibre. The experiments were repeated for three different aspect ratios D/S, see Fig. 1.

The cases $W = 0$ (i.e. no fibre) and $W = D$ (fibre spanning the space between the two plates) result in $L/S \approx 0.42$ (Steiner problem) and $L/S = 1$ respectively. This is regardless of the aspect ratio D/S of the set-up.

Fig. 2 shows measured values for the variation of L/S with W/D. The relationships are highly non-linear with a strong dependence also on the different aspect ratios of D/S. Also shown are results from computer simulations using the Surface Evolver program [10], a software which has been employed previously to model similar soap film configurations [13,14] (details of the simulation are left to Appendix A). For all three aspect ratios used experimentally, our simulation accurately predicts the variation of film length with fibre thickness. Also the respective values of L in the limits $W = 0$ and $W = D$ are reproduced.

Our experimental and numerical data (Fig. 2) is well approximated by the empirical equation

$$\frac{L}{S} = k_1 + k_2\,\frac{\exp(\beta W/D) - 1}{\exp(\beta) - 1}, \qquad (2)$$

with only one free parameter β, and constants $k_1 = 1 - 1/\sqrt{3}$ and $k_2 = 1/\sqrt{3}$. The theoretical endpoints (for $W = 0$ and $W = d$) are fixed by this form, and in the limit $\beta \to 0$ we recover a straight line between these endpoints. In Fig. 3(a) we show fits of Eq. (2) to our Surface Evolver data for three different values of D/S. The inset shows that the parameter β increases approximately linear with aspect ratio D/S, i.e. $\beta \simeq \alpha D/S$, with a fitting constant $\alpha \simeq 3.19$. We thus arrive at the following empirical relationship for the variation of central film length (as viewed from the top),

$$L/S = k_1 + k_2\,\frac{\exp(\alpha W/S) - 1}{\exp(\alpha D/S) - 1}, \qquad (3)$$

which is plotted in Fig. 3(b).

3. The effect of fibres on a single Plateau border

Having shown that our Surface Evolver simulations are successful in modelling the altered film configuration due to the presence of fibres in a quasi-2d set-up, we will now turn to the influence of a long fibre on a simple 3d film configuration. Such configurations may be obtained by withdrawing wire frames from a surfactant solution. Indeed it was this type of experiments that lead Joseph Plateau to the formulation of the equilibrium rules for soap films [11], as stated in Section 2, see also [14,15].

When a wire frame in the shape of an equilateral triangular prism (see Fig. 4) is dipped into a surfactant solution (in our case commercial detergent Fairy Liquid, 3 g/L), a single central Plateau border is formed, connecting two fourfold Plateau border junctions, similarly to Plateau borders in a dry bulk foam.

In our experiments we feed the wire frame from the top with a burette containing the surfactant solution (flow rate ≈0.25 mL/min) to prevent thinning of the films and hence their breakup. (In our experiments we were able to maintain the films for more than 10 min.) Plateau border lengths were measured using ImageJ sofware [16] from side-view pictures taken from a Canon EOS 50D camera.

From here on we will normalize lengths by the length of the triangular side C of the frame (see Fig. 4), defining our aspect ratio $a = A/C$ and a normalized Plateau border length $l_0 = L_0/C$, where L_0 is the length of the central Plateau border in the absence of fibres. In total, four frame aspect ratios have been used for the experiments (see Table 1).

According to Plateau's third rule (Section 2), the Plateau borders meet at angles of $\arccos(-1/3) \approx 109°$. Hence via simple geometry