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Timing Film Formation during the T1 Process

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The T1 process is that by which a new film is formed as bubbles rearrange themselves in evolving foam to achieve a more stable configuration. We focused on the effect of surface viscosity and shear viscosity in the bulk of the fluid on the T1 process in foam evolution in this study. Experiments were designed to examine the validity of a proposed theoretical model of the effect of surface viscosity and elongational viscosity of the bulk of the fluid on the time of the T1 process. Some background on the T1 process, the proposed model, our experiments and the conclusions gathered thus far from our study of the time dependency of T1 process are presented.

Introduction

Beautiful bubbles, nothing worth, Joy catches breath and they are gone, You who despise their easy birth Forget that they have ever shone: Live with your books and still decry, All things that lack solidity, But I'll blow bubbles till I die.

- E Andrade[4]

Foam

We have all been exposed to foams in places such as the bathroom while shampooing hair or taking a bubble bath, and in washing up after a meal in the kitchen (before the days of the evil dishwasher.). The dynamic nature of foams is quite evident. A foam is made up of bubbles which can be seen as a network of fluid films separated by ordered pockets of air. It is a metastable structure, in which the ongoing reduction of surface area of the films achieves greater and greater levels of stability[4].

Two- Dimensional Foams

In a 2-D foam, (see **Figure 1**) films meet at Plateau borders. By Plateau's laws for a two dimensional foam, three films always meet at each Plateau border, at equal 120^{o} angles[4].

This angle arrangement produces equilibrium between the films at a Plateau border, as they all exert surface tensions of equal magnitude at the junction, and require minimum energy for this formation (see **Figure 2** below).

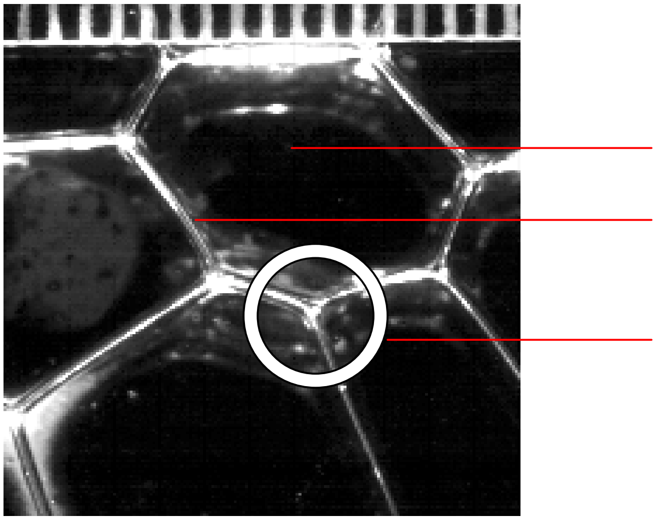


Figure 1: Three films meet at the Plateau border at an angle of 120º in 2-D foam.

Dynamics in foams

The structural evolution of a foam to reduce surface area can be encompassed in various permutations of two processes: the T1 process, as seen in **Figure 2**, and the T2 process, which is simply the disappearance of a three – sided bubble to produce a Plateau border. The focus of this study however, is specifically the T1 process, and more specifically the nature of its progress through time.

The T1 process

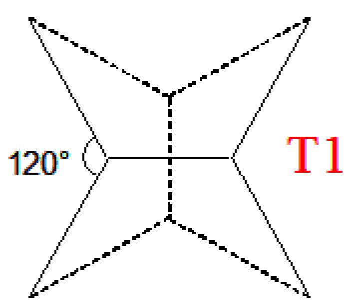
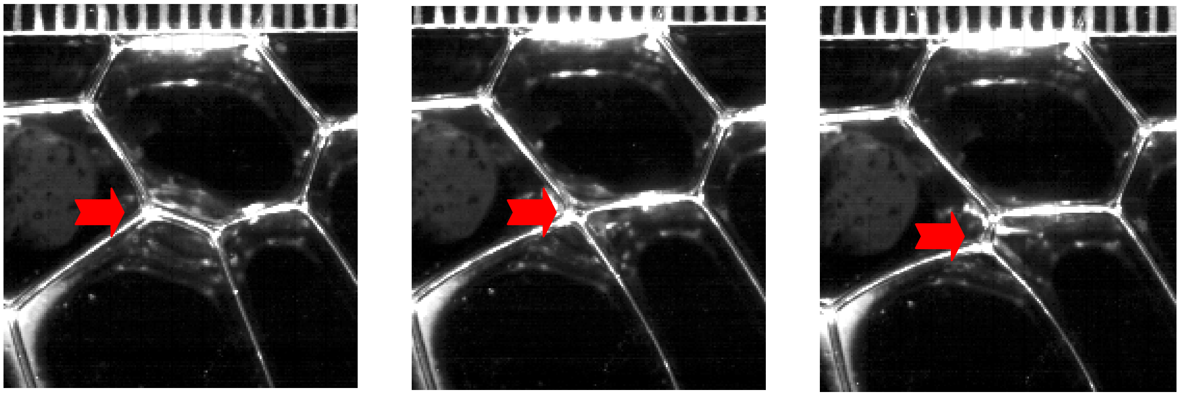


Figure 2: The T1 process is the rearrangement of films in a two dimensional foam via the disappearance of the dotted film network and the growth of the solid film network. These two configurations represent the minimal paths between the same four corner points.

The T1 process (see **Figure 2**) can be seen as a micro-flow phenomenon that is easily observed in two-dimensional foam models. It is the process by which local rearrangements occur within foam as individual Plateau borders collapse and then get pulled out and formed again as the foam slowly evolves[4]. The films end in a position of equilibrium, after a T1 process, as captured in **Figure 3**.



(a) **(b)** **(c)**

Figure 3: Pictures of the T1 process, taken in this study.

Figure 3 depicts a system of bubbles in a foam, during the T1 process. The subject film, as indicated by the red arrow in **Figure 3(a)**, contracts to the length shown in **Figure 3(b).** The four films meet momentarily at a Plateau border as shown in **Figure 3(b)** and then a new film grows as the one indicated by the red arrow in **Figure 3(c)**. My study primarily consisted of timing the transition from the stage depicted by **Figure 3(b)** to the stage depicted by **Figure 3(c)**, for different surfactant solutions at various viscosities. A schematic of the growth of the film highlighted in **Figure 3 (c)** is shown in **Figure 4**. This figure represents a magnification of a growing Plateau border in the T1 process and shows the change of the film's longitudinal cross section with respect to time. At time t=0, the film is pictured to be approximately square in cross section. During the T1 process the film is drawn into a progressively elongated rectangle. As a consequence of viscous effects being large, we expect that the film has a nearly uniform thickness at any time, as sketched in the figure.

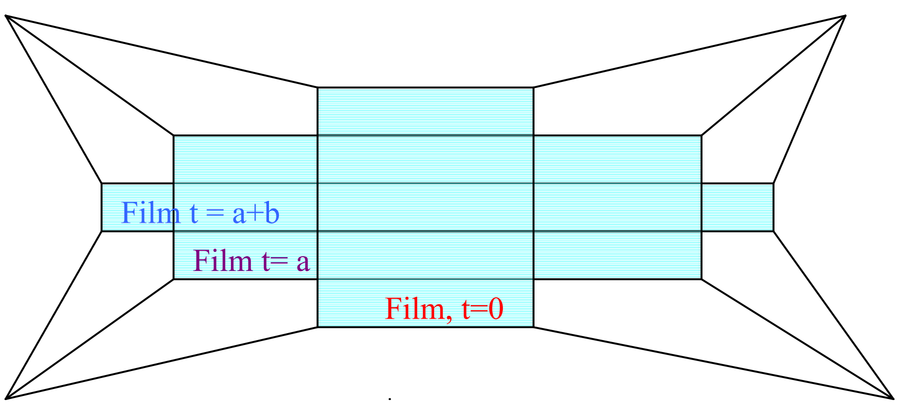


Figure 4: Bird's eye view of a growing Plateau border during a T1 process. N.B. ***a* and *b*** *are positive constants*

The Study

Our study consisted of two parts: first to develop a mathematical model for the relationship between the film's length and the time of its growth during the second half of the T1 process, then to find a way to gather and use experimental data to test the model. This section presents the theoretical model and then goes into details about the actual experiments.

The Model

Diagrams 1 & 2 show the magnification of half a film representing the growing length by **X (t)** on the horizontal axis, and its decreasing thickness as **2h(x, t)** on the vertical axis. This is the schematic that was used to develop the model our study proposed, where **m** represents the fixed mass of fluid in the growing film, $\mathbf{L_x}$, $\mathbf{L_y}$ and $\mathbf{L_z}$ represent lengths in the horizontal, vertical, and perpendicular into the page directions, respectively, $\boldsymbol{\gamma}$ represents the surface tension, $\boldsymbol{\mu}$ represents the elongational viscosity of the bulk fluid in the film, $\boldsymbol{\rho}$ represents the density of the fluid used and $\boldsymbol{\mu_s}$ represents the surface viscosity of the fluid.

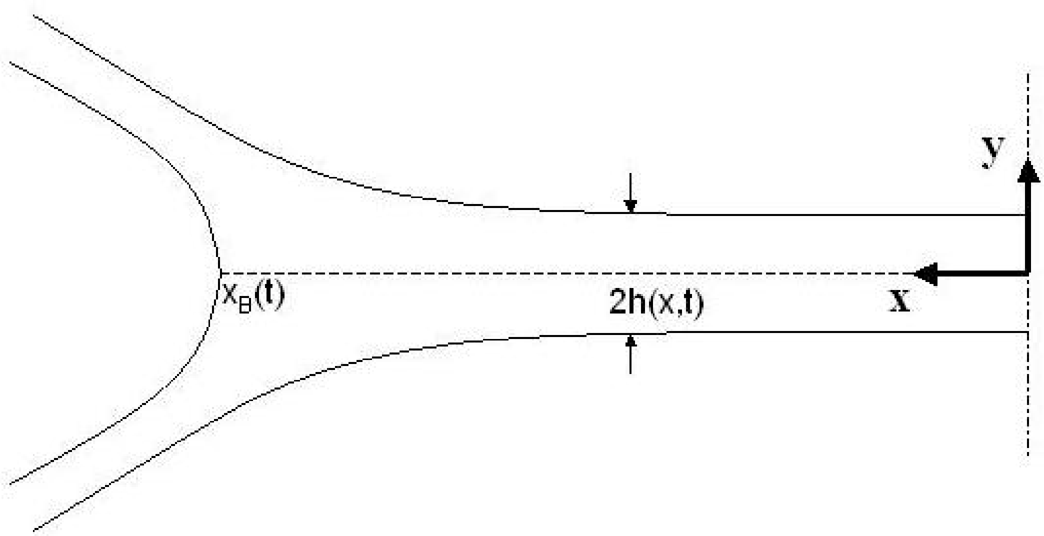


Diagram 1: Schematic for half of the film undergoing growth during the T1 process

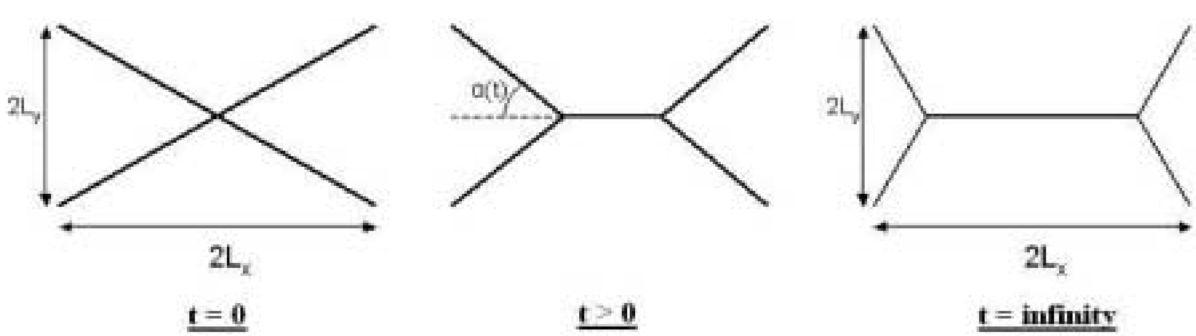


Diagram 2: Schematic for the film undergoing growth during the T1 process developed in this study

The suggested relationship for the main variables involved in this film's growth, according to Newton's second law, is a second order ordinary differential equation: -

$$\frac{m}{8L_z}\frac{d^2 x_B}{dt^2} = \gamma\left(\frac{\sqrt{3}L_y - x_B(t)}{\sqrt{L_y^2 + \left(\sqrt{3}L_y - x_B(t)\right)^2}} - \frac{1}{2}\right) + \mu\frac{\partial h}{\partial t} + \mu_s\frac{1}{h(t)}\frac{\partial h}{\partial t}$$

$$h(t) = \frac{m}{2\rho L_z x_B(t)}$$

Thus far, as can be seen, the model has the general form of a damped oscillator. Each of these terms has a physical significance. The term on the left is the inertia or acceleration of the fluid. The first term on the right is the net effective surface tension force (in parentheses,) whereas the second term on the right is the viscous resistance from the bulk and the third term on the right is the viscous resistance from the surfactant film. This differential equation is being numerically solved at present.

The Experiments

The Aqueous Solution

In our experiments foams were generated with surfactants (surface active constituents) and water. The two specific surfactants used in this study were Sodium Dodecyl Sulfate (SDS) and Bovine Serum Albumin (BSA) which was always accompanied by Propylene Glycol Alginate (PGA) for increased foam stability. Surfactant molecules are made up of a polar (hydrophilic) head and a non-polar (hydrophobic) tail[1]. The film in a foam consists of a layer of water trapped by two layers of surfactant molecules (see **Figure 5**).

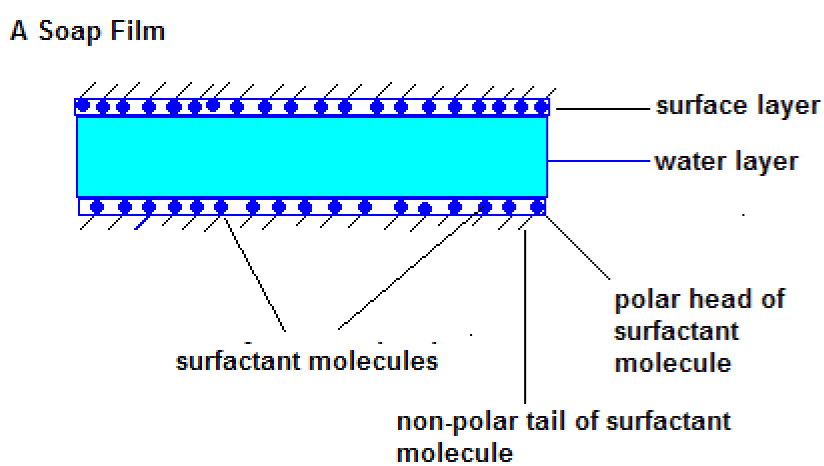


Figure 5: A Soap Film

The shear viscosity of the bulk of the fluid was raised by adding glycerol to the mixtures of each of the two surfactants and water. After varying these two components in different ways, with our choice of surfactants and glycerol concentrations, five final fluids were chosen. The relevant data for these five fluids are displayed in **Table 1**. Because of high glycerol concentrations in the three fluids where glycerol was used, we assumed that the surfactants would not change the shear viscosity of the bulk fluid in these solutions, and used shear viscosity values of glycerol/water mixtures.

SOLUTION	SDS	SDS GLY	SDS GLY 2	BSA/PGA	BSA/PGA GLY
Shear viscosity of bulk g/cm/s	0.01	10.681	27.625	0.07	10.681
Volume of water / ml	300	137.5	95	300	137.1
Volume of glycerol / ml	0	162.5	205	0	162.9
Glycerol mass concentration % (CRC Handbook of Chemistry and Physics)	0	60%	72%	0	60%
Mass of surfactant used/ g	1.44	1.44	1.44	1.2 (BSA) 1.2 (PGA)	1.2 (BSA) 1.2 (BSA)

Table 1: Properties of the five fluids used to produce foams in this study[2, 3].

The Experimental set-up

The T1 process can be observed by placing two transparent plates closely together and blowing bubbles between them. A foam formed by these mainly hexagonal and pentagonal bubbles can then be seen, through the transparent plates. The first challenge was to design a set-up that consisted of a controlled arrangement (see **Figure 6**) with which to mechanically produce bubbles, and then to trigger and visually record occurrences of the T-1 process between the plates. The final experimental set-up was as follows.

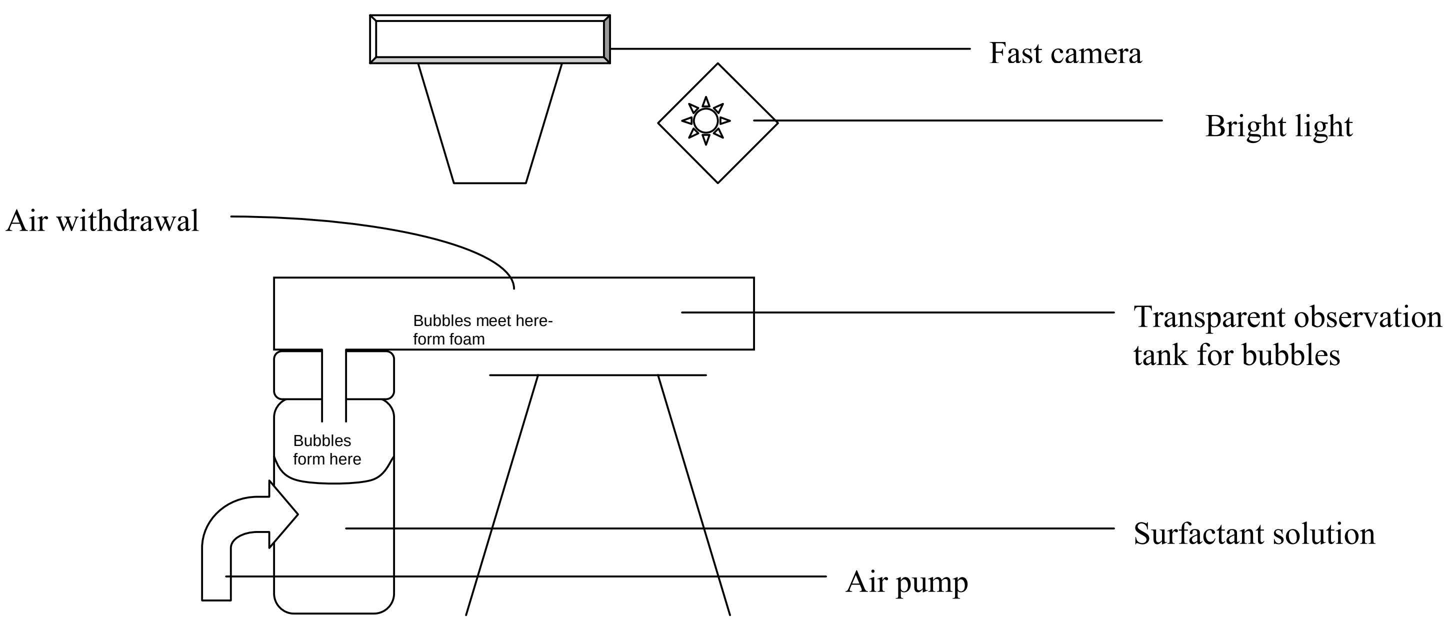


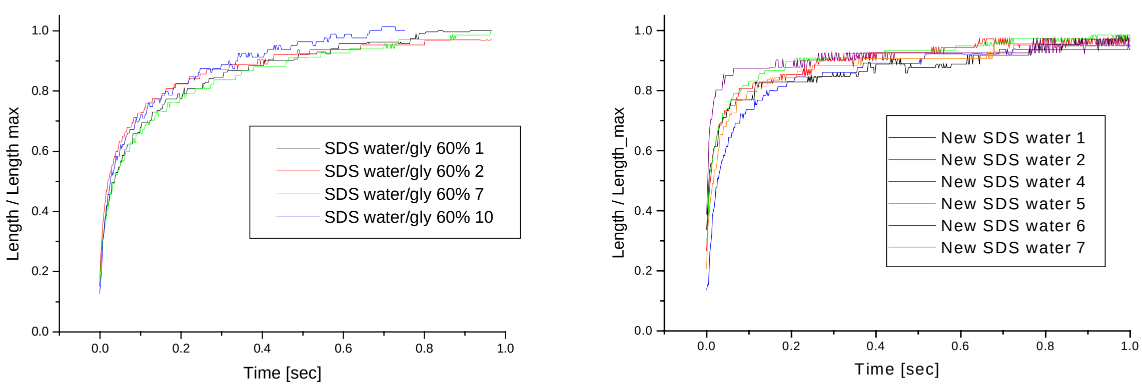
Figure 6: Experimental Set-up

- Air was pumped into the bottle on the left
- Consequently, bubbles formed in the area indicated, over the meniscus in the bottle
- The bubbles traveled through the passage on the top of the bottle and entered the transparent observation tank
- A foam therefore gathered in the observation tank
- The bubble size was manipulated by adjusting the air pump, so that there was only one layer of bubbles (hence making a 2-D film)
- T1 processes were observed (through the transparent glass plates) and recorded (using a high speed camera)
- When T 1 processes were irregular in a foam, due to the foam's high stability, we triggered them by withdrawing air from the top of the observation tank, using a withdrawal pump.

Our procedure was simple but required much time (several weeks) and patience, as we had to take a total of over sixty movies in order to be sure of our data analysis.

Results

These are actual results from the sample of solution of SDS and water with 60 % mass concentration of glycerol.



(a) (b)

Figure 7: (a) Results gathered in this study for Time vs. Length Ratio for growth of a film in the second half of a T1 process in a solution of SDS and water with a 60 % mass concentration of glycerol; (b) Results gathered in this study for Time vs. Length Ratio for growth of a film in the second half of a T1 process in a solution of SDS and water

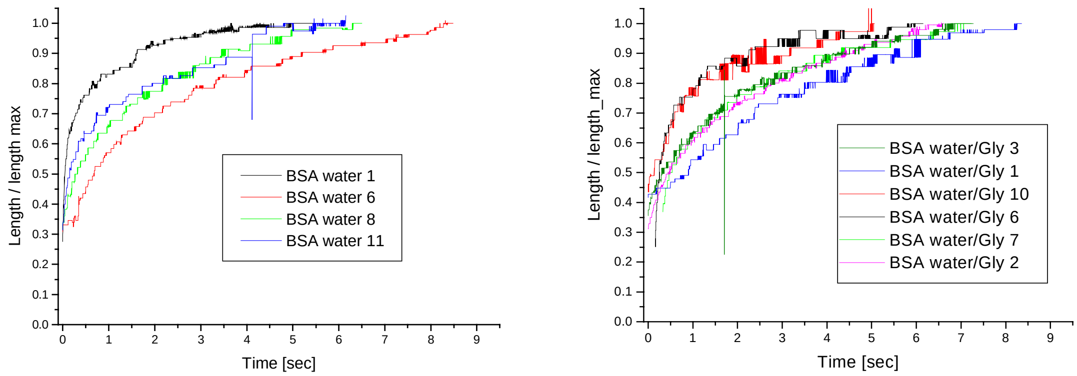


Figure 8: (a) Results gathered in this study for Time vs. Length Ratio for growth of a film in the second half of a T1 process in a solution of BSA and water; (b) Results gathered in this study for Time vs. Length Ratio for growth of a film in the second half of a T1 process in a solution of BSA and water with a 60 % mass concentration of glycerol

Already, these results show that the surface viscosity, dependent upon the type of surfactant used, had a greater effect on the advance of a T1 process through time than the elongational viscosity did. This can be seen in the graphs for different surfactants seen in **Figures 7 & 8**. The time scale of the T1 process through SDS fluids is of the order of one tenth the time scale of the T1 process in BSA fluids. The graphs for the SDS solutions show smaller variances from each other than can be seen in the graphs of BSA solutions. This is directly related to the longer time scale for the T1 process in BSA.

Although the graphs for the five fluids resemble the shape of the theoretical model of a damped oscillator, we are yet to produce an actual numerical solution for the model for any of the five solutions, with which the experimental data is close enough to an exact fit.

Analysis / Conclusion

At present our theoretical model is being refined to better match the experimental results. If the final model graphically matches the gathered data well enough, one useful application of the study would be to determine the surface viscosity for a surfactant solution directly from any plot set up as in **Figure 7**.

Another useful application of this feat would be to improve the prior idealized models of the T1 process which only focused on simulating the positions of, and time between, separate T1 processes throughout a foam system, neglecting the advancement of the individual processes through time[4].

How can this research be taken further?

The effect of elasticity is another interesting property that will be observed in later stages of this study. This will be achieved by studying the time dependency of T1 processes in the foams of non-newtonian or visco-elastic fluids.

References:

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