Interactions between liquid jets and soap film

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Abstract

The interaction between thin jets of water and soap films have been studied. The experiments conducted for this thesis are the first done on jet - soap film interaction with different liquids in the two components. The results are very different from earlier studies where the same liquid was used for both components.

Two behaviors were found for the interaction, depending on the incident angle between the incoming jet and soap film and the We number. For low incident angles the jet is bent by the soap film, making it possible to define an index of refraction for the soap film. The bending of the jet done by the soap film increases rapidly when approaching a We number of zero. For We numbers higher than five the jet passes through the film without changing direction. For high incident angles and low We number (≤ 1) the jet rebounds on the film, in analogy with total reflection in optics.

The lifetime of the film is measured for different jet speed leading to the conclusion that there is mass exchange between the jet and film. This makes experiments impossible to perform at We ≥ 17, corresponding to a speed of 1.2 m/s. At this speed the soap film breaks before measurements can be done.

Contents

1 Introduction

This thesis is inspired by the 2013 International Young Physicists Tournament problem: Jet and Film. The problem formulation states:

> A thin liquid jet impacts on a soap film. Depending on relevant parameters, the jet can either penetrate through the film or merge with it, producing interesting shapes. Explain and investigate this interaction and the resulting shapes.

The interaction between jets and films of the same liquid have been studied before by Kirstetter *et al.* [1]. We want to study the interaction between jets and films of different liquids and compare this to what happens when the same liquid was used. This is interesting because most industrial applications use different liquids for the jet and film.

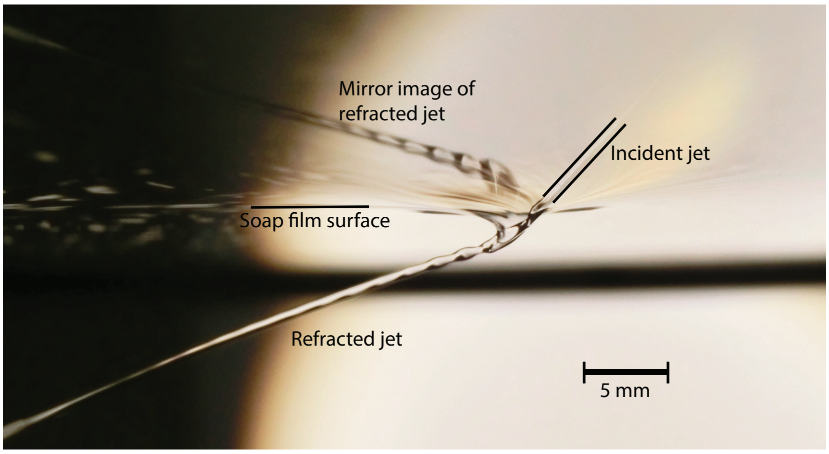

Figure 1: The incoming jet interacting with the soap film

The penetration of the jet through the film can be seen in Figure 1. An incoming jet of water strikes the soap film, interacts with it and changes direction on the way out. The interesting shapes mentioned are not seen, but this can be explained as will be seen later on. The relevant parameters that first come to mind when studying Figure 1 are the inclination angle of the jet towards the film surface, θ_i and the Weber number. The Weber number is a dimensionless number which describes the relative importance of inertial forces to surface tension and is defined as

$$\mathrm{We} = \frac{\rho v^2 R_i}{\gamma} \tag{1}$$

where ρ is the density of the jet, v is the velocity of the jet, R_i is the radius of the incoming jet and γ is the surface tension of the film liquid.

A water jet is in many ways just a collection of drops. Therefore it is interesting to look at how drops behave when interacting with a soap film. Impact by droplets on a stationary soap film was first described by Courbin and Stone [2]. It was shown that for low We numbers the droplet bounced on the film, and for high We numbers it passed through the film without rupturing it. Instead the drop partly coalesces with the film while passing through, letting the film self-heal after the passage. The interaction between soap films and various objects has since been thoroughly studied. Interactions with droplets [2–6] and liquid jets [1, 7, 8] have been performed in various ways. The motion of a water droplet dropped on a static or vertically oscillating soap film has been used to find that a soap film can be considered a nonlinear spring for a static film and linear spring for an oscillating film [3, 4]. The droplet motion can be considered to be in different periodic states (simple, complex, multi-periodicity) or chaotic depending on the initial conditions [3].

The behavior of thin liquid jets have been studied in the Kaye effect [8], by looking at water jet interaction with hydrophobic and superhydrophobic liquids [9, 10] and electrowetting of plates [10]. Both these phenomena will be covered in more detail in section 2 of the thesis.

The properties and behavior of thin liquid jets is interesting for many industrial applications, for example Drop-on-demand (DOD) for inkjet printing [11] or Laser-induced forward transfer (LIFT) [12]. In LIFT a pulsed laser is used to expel a high velocity micro-jet from a thin donor film. There are also applications in biology. For example, the controlled breakup of thin jets is very important in biological encapsulation for the production of monodisperse capsules [13].

This thesis is divided into five main sections. In the section 2 soap films from a general point of view are introduced and the behavior of jet impacts on different liquids is discussed. In section 3 the thickness of soap films is described. Different measurement methods are described and results using thin film interference are presented. In section 4 the surface tension is measured using the Du Noüy ring method and a Drop Profile Tensiometer. In section 5 the lifetime of a soap film and its implications for performing the experiments are presented. The lifetime of the film for different jet speeds has been measured. In section 6 the interaction between the jet and the soap film is described theoretically and experiments to determine an index of refraction as a function of We number and the transition from refraction to reflection is described.

2 Introduction to Soap films

2.1 What is a soap film?

A soap film is a thin bulk layer of water, a lamella, bordered by soap molecules, which have one hydrophobic and one hydrophilic end. This means that the surfaces of the film will be hydrophobic since the hydrophilic ends orients itself inwards to the lamella. For soap films with a high concentration of soap molecules there is an excess of soap molecules to border the film. This means that there will be a lot of soap molecules inside the lamella. These can form a variety of structural constellations, see Figure 2.

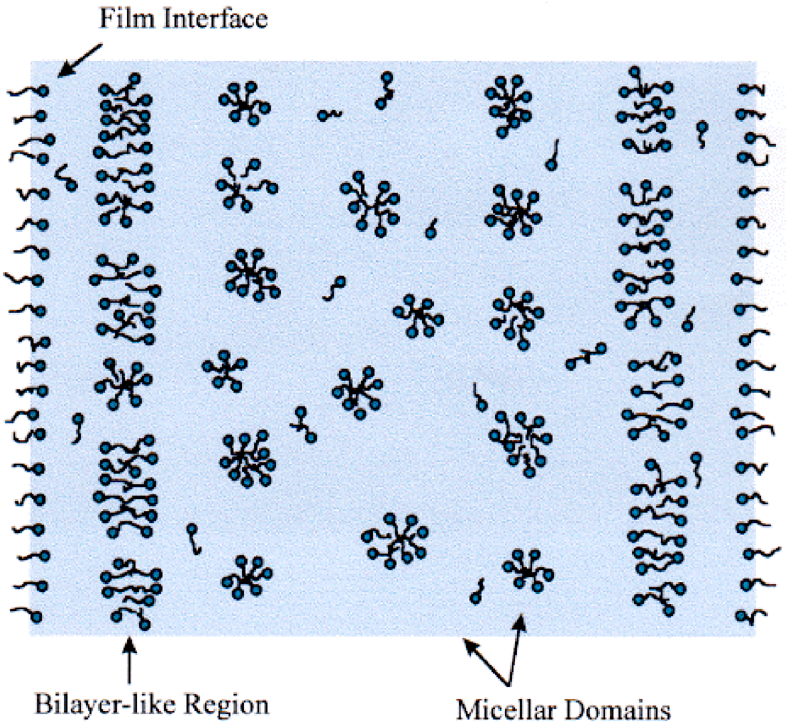

Figure 2: A sketch of how high micellar concentrations looks. Figure by Bergeron [14].

The concentration of soap in the liquid for the film is very important since it influences the surface tension. If the concentration of soap is too low no film can be formed. It is important to have reached critical micelle concentration (CMC) of soap in the liquid so that the surface tension is constant over the film. CMC for our case is defined as the concentration of soap at which the surface tension no longer changes when more soap is added. Since the experiment is conducted with a water jet interacting with the soap film it is also desired to be well above CMC to ensure that the surface tension stays constant even if there is mixing between jet and film. At CMC there are micelles in the lamella as well, ensuring that the surface is always covered with soap molecules.

Surface tension, γ, is a measure of the energy that must be added to increase the surface area [15]. It is therefore a very important quantity for these kinds of experiments. The force on the jet generated by the surface tension is also dependent on the contact angle between the jet and film. The contact angle is a measure of the wettability of a solid surface [15]. In our case the wettability between the soap film and the jet is interesting because if there is not total wetting between them the surface tension does not act maximally since it will not be directed normal from the jet.

2.2 Jets on hydrophobic liquids

A hydrophobic liquid is a liquid that has a high contact angle for water. A superhydrophobic liquid has a contact angle of more that 150°. The soap film is supposedly hydrophobic on the outer surfaces. It is therefore interesting to see how water jets behave on hydrophobic liquids [9, 10]. When a water jet hits a hydrophobic surface it sticks to it, after a while giving rise to meanderings along the hydrophobic surface [9]. This effect is similar to what has been reported for soap films interacting with a jet of the same liquid where the incoming jet gets stuck in the film and undulates [1]. When a water jet is instead shot at a superhydrophobic surface it will be reflected in different angles depending on the degree of hydrophobicity. The degree of hydrophobicity can be controlled by electrowetting, where the wetting of the surface is altered by applying electric fields over it. See Figure 3 for a water jet impacting a superhydrophobic liquid.

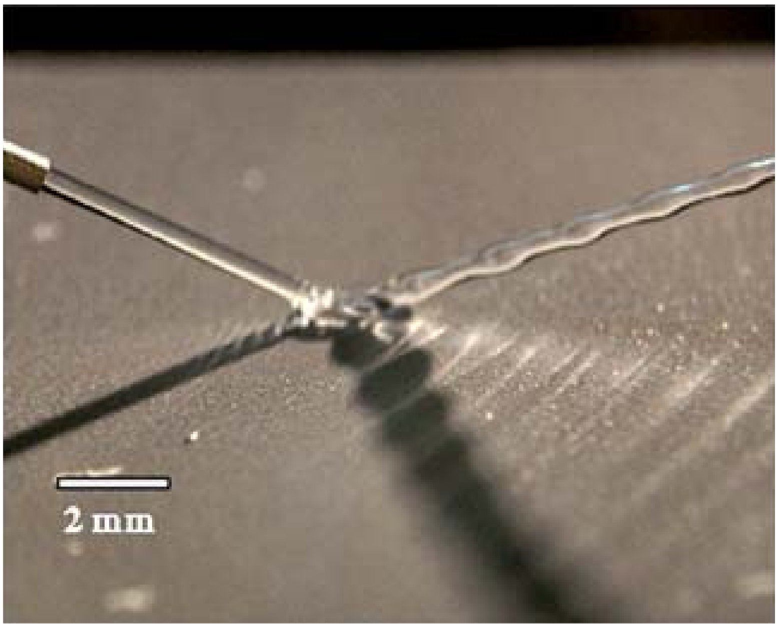

Figure 3: Water jet hitting a superhydrophobic surface. Photo by Celestini et al. *[9].*

The outgoing jet in Figure 3 has oscillations similar to those seen in the outgoing jet in experiments done for this thesis, see for example Figure 1. These oscillations are caused when the jet takes off from the substrate. The jet is changing from a a flat geometry on the substrate to a free cylindrical geometry in the air to minimize surface energy. The oscillations occur during the reshaping process. The oscillations are similar to those produced when ejecting a jet from an elliptical nozzle. The oscillations in the outgoing jet suggest that there is interaction between the jet and film which changes the jet geometry when passing through the film.

2.3 The Kaye effect

Versluis *et al.* [8] have done a lot of research on the Kaye effect. They found the cause behind the phenomenon and have made it work under different conditions.

The Kaye effect is a liquid phenomenon where a thin jet of a shear-thinning liquid hits a surface of the same liquid and a small pile is built. This pile will be under high shear stress and therefore form a low viscosity interface where the jet hits. The pile then acts as a slide for the jet causing it to leap upwards. See Figure 4.

The effect can be conducted with different shear-thinning liquids for the surface and the jet. The basic demands for the effect to occur is a viscous surface which can form a dimple and a low viscosity jet. For shear-thinning liquids these two conditions are fulfilled [8]. In the Kaye effect there is no net mass transport from the incoming jet to the heap [8].

The same group recently demonstrated that the Kaye effect can occur on soap films. Between the incoming jet and the heap or film there is viscous friction. A parameter that influences the amount of friction is the contact length between the jet and substrate. Longer contact length gives lower outgoing jet velocity [8].

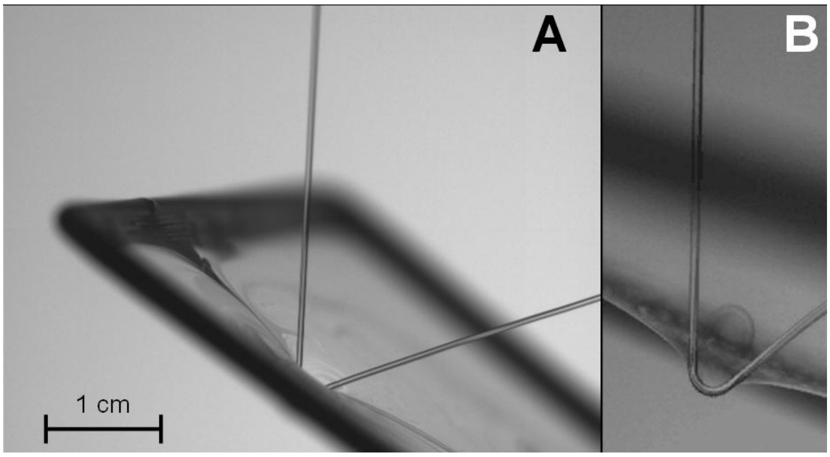

Figure 4: Kaye effect on a soap film. Photograph by Versluis et al. [8]

The Kaye effect is interesting for this thesis since it is another jet-film interaction phenomenon. According to Versluis *et al.* it would be possible to conduct with different liquids in the jet and film.

3 Thickness of soap films

When the jet is interacting with the film it can be assumed that the thickness of the film is important. The jet will have a certain length where it interacts with the film, depending on the jet speed, v, jet angle, θ_i, and the film thickness. If this interaction length is longer or shorter it would affect the total force from the film on the jet [8].

3.1 Ways of measuring the thickness of soap films

The thickness of a soap film is often measured with thin film interference, as this thesis has made use of. This utilizes the fact that different colors will be prominent at different film thicknesses. There are other ways of finding out the thickness of a soap film. One of these is Frankels law, which governs the thickness of a soap film that is withdrawn with the film frame perpendicular to the surface of the liquid bath. See Figure 5 for withdrawal orientations.

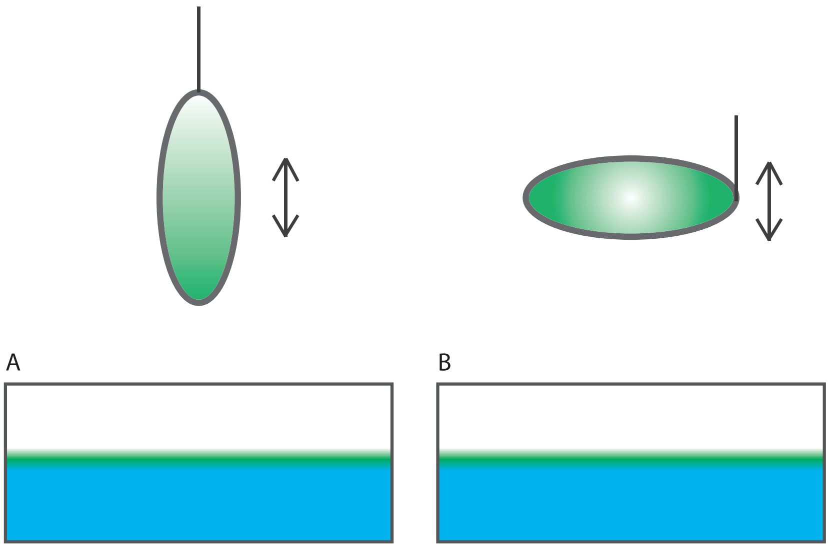

Figure 5: A: Withdrawal method consistent with Frankels law. B: Withdrawal method used in this thesis.

This states that the thickness of a soap film, d, is proportional to the speed with which it is withdrawn from a bath, U, the surface tension of the film liquid, γ, as well as the density, ρ and viscosity, η, of the film liquid.

$$\frac{d}{\ell_c} = 1.89\left(\frac{\eta U}{\gamma}\right)^{2/3} \tag{2}$$

where $\ell_c = \sqrt{\frac{\gamma}{\rho g}}$ is the critical length scale for the phenomenon and g is the gravitational acceleration [16, 17]. There is no similar expression for a film that is withdrawn with the film frame parallel to the liquid bath as is the case for this thesis. However, it can be assumed that the same parameters are relevant. This would mean that if all parameters are kept constant the film thickness would stay the same all the time.

In the experiments done in this thesis all parameters except the speed of withdrawal are kept constant. It is not kept constant but is kept roughly the same. If equation (2) is correct for horizontal films as well, then a small change in withdrawal speed would only give a very small uncertainty in film thickness.

3.2 Thin film interference: Theory

The thickness of a soap film can be measured using thin film interference. When light hits the soap film from above it will be partly reflected and partly refracted. Here the light will also undergo a phase change of π radians when it is reflected due to that water is optically denser than air.

The refracted light will be partly refracted and partly reflected in the lower soap-air boundary of the film as well. The light once again hits the upper soap film boundary where it is again refracted and reflected. There are now two parallel rays of light going away from the film upwards. The two rays have a phase difference of π radians. For constructive interference to occur any phase difference which is a multiple of π will work. See Figure 6.

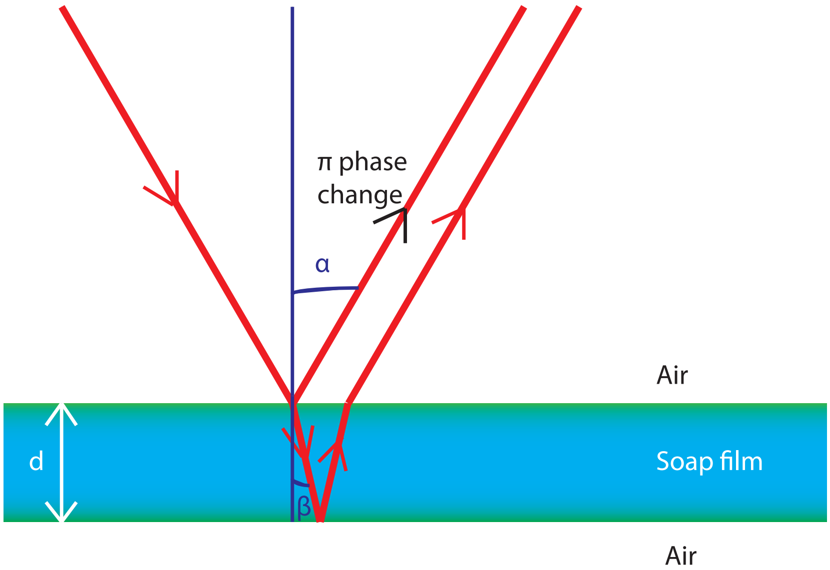

Figure 6: The path of a light ray

From these conditions equation (3) can be derived, which can be used to determine the thickness of the film.

$$2n_{soap}d\cos\beta = (m - \frac{1}{2})\lambda_r \tag{3}$$

where n_{soap} is the refractive index of the soap film, d is the thickness of the film, β is the angle of reflection inside the film, m is the order and λ_r is the wavelength for maximum reflection.
β is difficult to find experimentally, but it can be found using Snells law. This gives

$$\sin\beta = \frac{n_{air}}{n_{soap}}\sin\alpha \tag{4}$$

where n_{air} is the refractive index of the air and α is the angle of incidence on the first air-soap boundary. Combining equation (3) and (4) gives:

$$2n_{soap}d\cos\left(\arcsin\left(\frac{n_{air}}{n_{soap}}\sin\alpha\right)\right) = (m - \frac{1}{2})\lambda_r \tag{5}$$

Using trigonometric identities one gets

$$2n_{soap}d\left(1 - \left(\frac{n_{air}}{n_{soap}}\right)^2 \sin^2(\alpha)\right)^{-0.5} = (m - \frac{1}{2})\lambda_r \tag{6}$$

The thickness, d, can then be found as

$$d = \frac{(m - \frac{1}{2})\lambda_r}{2n_{soap}}\left(1 - \left(\frac{n_{air}}{n_{soap}}\right)^2 \sin^2(\alpha)\right)^{-0.5} \tag{7}$$

Equation (7) can be used to find the thickness of the soap film from measured quantities.

3.3 Thin film interference: Experimental method

A circular wire frame of radius 10 cm was suspended by three copper wires from an identical wire frame held by two clamps and stands. The lower wire frame was fastened with a thin thread to the copper wires to minimize influence to the soap film. The suspension wires were chosen to be of copper which is deformable to make it easier to control the length and thereby keep the film horizontal.

A large container with the soap mixture was lifted up by hand until the wire frame was well covered in liquid. The mixture consists of deionized water with 5% commercial soap (Brand: YES) and 5% glycerol for stability. The container was then carefully withdrawn with approximately the same speed every time.

A lamp was placed at an angle towards the soap film. A digital camera (CASIO Exilim ZR-1000) was placed at angle α at which interference fringes could be clearly seen. The camera took a photo of the soap film on auto-settings since the intensity was not of interest. The camera and soap film was photographed using a cell phone camera to find the angle α.

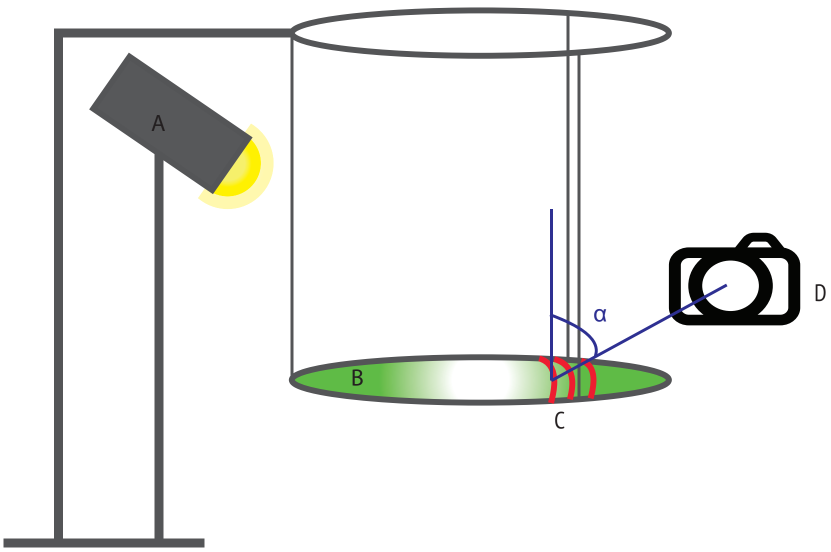

Figure 7: Setup for measuring thickness of film with thin film interference. A: Lamp B: Soap film C: Interference fringes in film D: Camera

3.4 Thin film interference: Results

The film thickness can be found using thin film interference, using equation (7).

$n_{air} = 1$, the index of refraction for the soap mixture is almost the same as for water which gives $n_{soap} = n_{water} = 1.33$. This choice was made since the soap film mixture is 90% water.

The red fringes were chosen for the measurements, setting $\lambda \sim 600$nm. Since the film should be thicker in the center and there is a clear region of no interference along the rim the orders can be counted. (See Figure 8) The pattern is not perfectly radially symmetric, but this can be attributed to a not completely horizontal film. It is difficult to get the film exactly horizontal. Three orders of red can be seen with ease, giving $1 \leq m \leq 3$. The angle between the camera and the normal at the third red fringe is $\alpha = 72°$.

Inserting these values into equation (7) gives a thickness, d, varying between $0.2 \leq d \leq 0.8\mu$m at the three red fringes. Different soap films have a slight variation in thickness, but $0.2 \leq d \leq 0.8\mu$m is a representative thickness for most films.

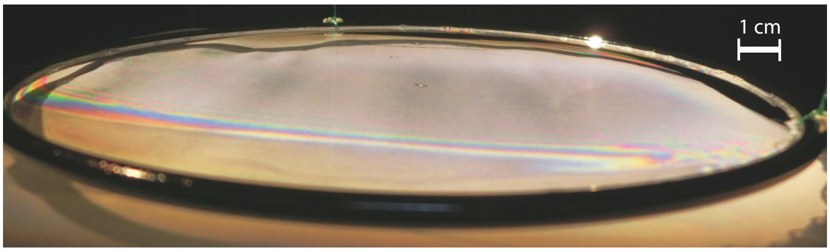

Figure 8: Interference fringes in soap film.

The interference fringes look almost the same for all soap films, indicating similar thicknesses. Measurements were not done on all experiments since the thickness variation over a single film is too large to be useful. If the thickness would be measured continuously during the experiments it could give an indication to how the interaction between the jet and film looks like.

4 Surface tension

The surface tension was determined using both a Du Noüy ring [18] and a Drop Profile Tensiometer [19], using standard methods. The Profile Analysis Tensiometer is a PAT-1 from SINTERFACE Technologies. It has a resolution of 0.1mN/m for surface tension measurements.

A film can be created in the 10 cm radius frame with a soap concentration of 0.06% soap or higher. At 0.06% the film breaks immediately after formation. Soap mixtures with less than 0.25% have a very short lifetime and cannot be used for studying the interaction between a jet and the film.

From Figure 10 it can be concluded that CMC has already been reached for 0.25% soap, meaning that the surface tension is not dependent on the soap concentration during the interaction experiments.

This means that if the film breakage was only due to the local change in surface tension it will be around the point where the soap concentration drops below CMC.

As can be seen in Figure 9 A and B, drops from the hypodermic needle are sometimes absorbed and sometimes pass through the film. This interaction between the drops and film could change the surface tension locally. It is therefore very important to have a soap concentration well above CMC.

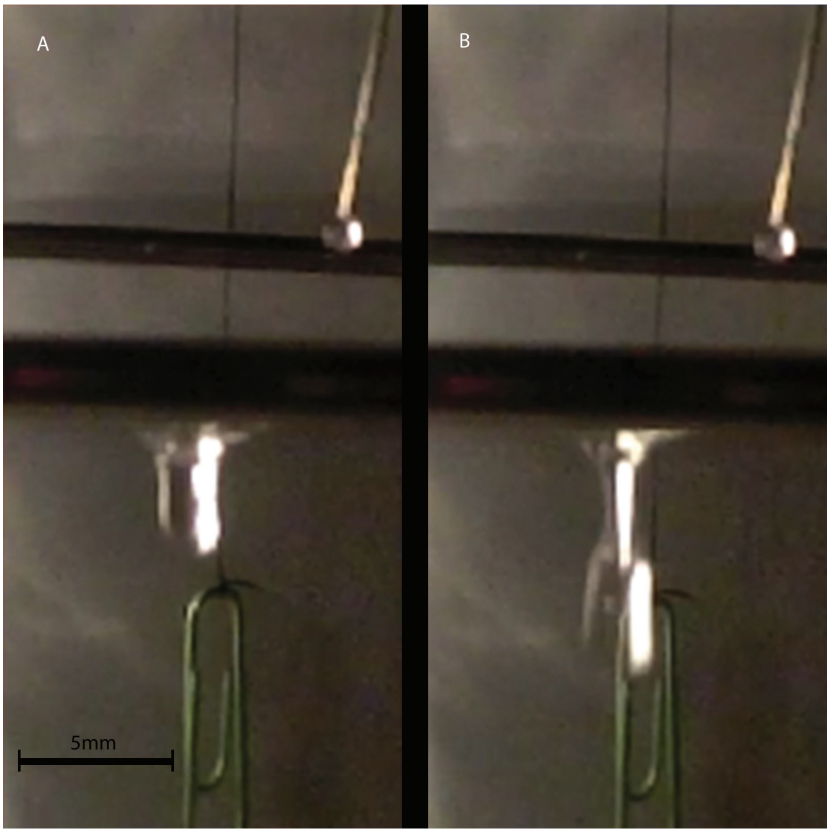

Figure 9: A drop extending and falling through the film

4.1 Surface tension: Results

The values and error bars for the Drop method were computed using the Bootstrap method on the raw data. For the Ring method the average of three measurements was taken as the value. The data is plotted in Figure 10. The error bars are computed to include all measurements within two standard deviations. CMC is reached before 0.25% soap meaning we will most likely not drop below CMC during experiments.

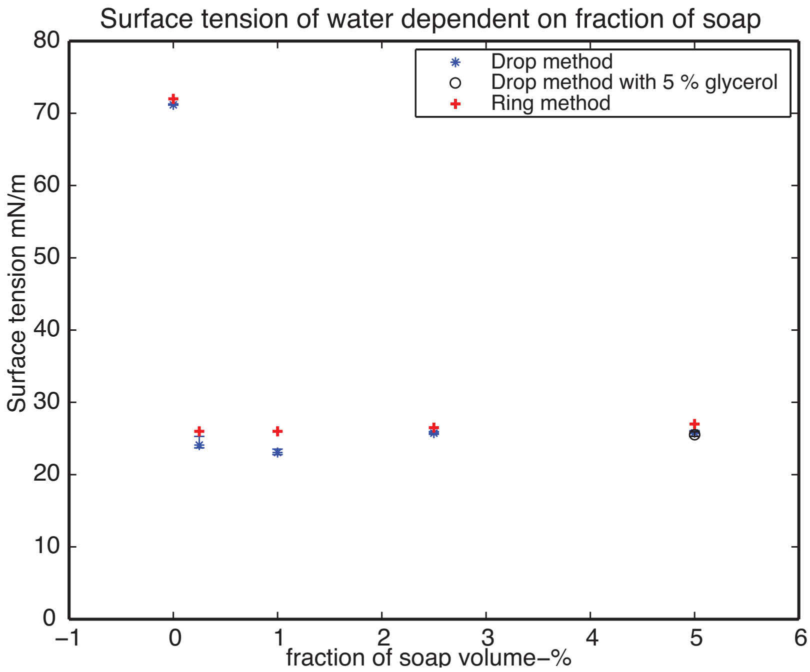

Figure 10: Surface tension data. Error bars are two standard deviations.

5 Lifetime of soap films

The lifetime of free unpertubed soap films is dependent on how thick the water lamella in the film is. The lamella drains slowly due to evaporation and when it is thin enough somewhere the film ruptures, since it can no longer carry its own total mass. The lamella can also be drained by the accumulation of water in the center of the film, where a drop is formed and leaves the film. When the jet goes through the film at some velocity, v, it interacts with it, draining the lamella and transporting away soap molecules. If the jet transports away a lot of soap molecules so that the concentration drops below CMC that would change the surface tension locally. Too high velocities cause the film to rupture almost immediately after impact. One then suspects the lifetime of the soap film to be inversely proportional to the jet velocity to some exponent, since the faster the jet moves the faster it drains the lamella and the faster the film breaks. Higher velocities also means higher stress on the film, indicating that we could suspect that the lifetime is proportional to a higher exponent than v^{-1}.
The lifetime of the film is interesting, since this controls how long time we will have to conduct our experiments. A too short lifetime doesn't allow the film to stop oscillating after creation before breakage occurs, which means that no measurements can be made.
The lifetime was measured by filming all the interaction experiments where the jet was refracted. The time from jet impact on the film until film rupture was measured in the movies.

5.1 Lifetime of soap films: Results

When comparing A and B in Figure 11 we can clearly see a color change. It is obvious that during jet impact the system is not static. The thickness of the film is changing and soap molecules are transferred from the film to the jet. This can be seen in the container for collecting the outgoing water jet, where a foam is created. A foam would not be created if it was only water being collected, while if the jet took soap molecules with it from the film a foam would be created.

The lifetime of the soap film should be at least inversely proportional to the speed of the water flow since this interaction drains the film, both of soap molecules and water lamella.

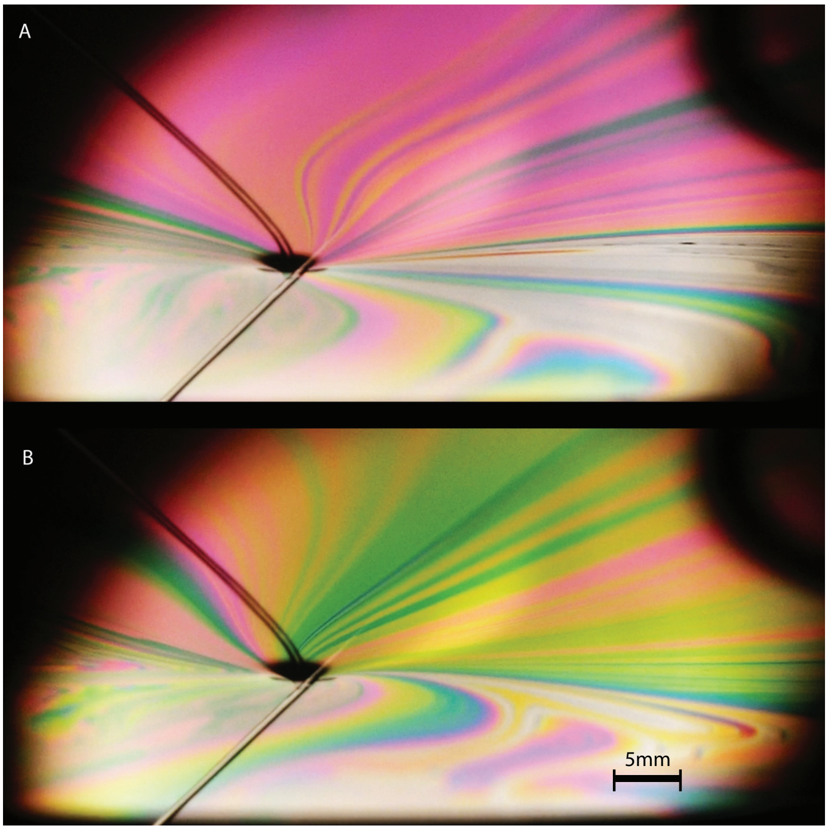

Figure 11: A: View of film from underneath. B: Same view 5 seconds later.

In Figure 11 we see that the color is not symmetric around the film. This means that the film is not uniformly thick, and the thickness is difficult to measure during the interaction. The color structure is directed radially outwards, indicating that the water jet drags the film with it downwards.

In Figure 13 we see the a plot of the lifetime versus the speed of the jet, v. In Figure 13 the same data are plotted but with the speed of the jet to the power of negative two.

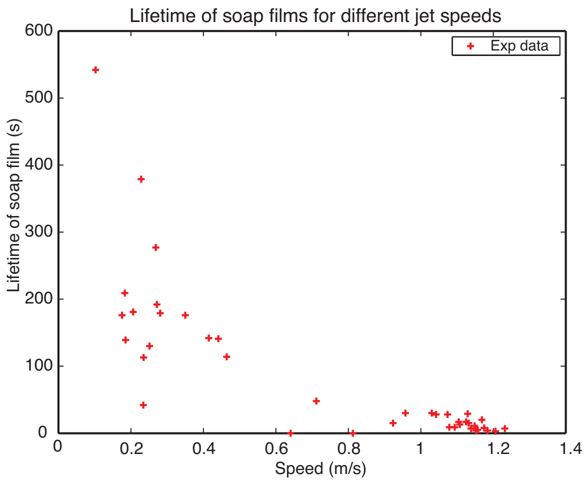

Figure 12: The lifetime of the soap film as a function of jet speed.

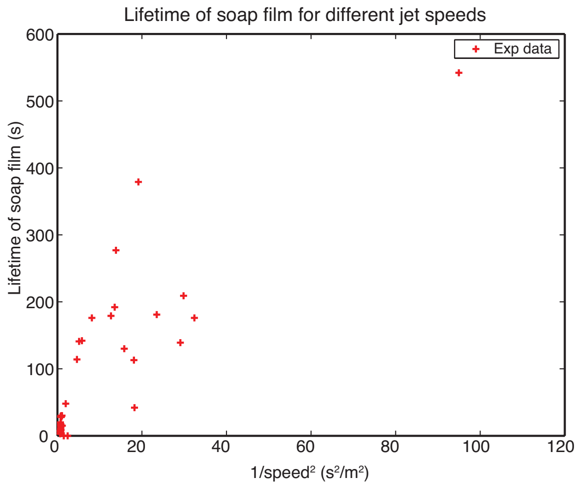

Figure 13: The lifetime of the soap film as a function of jet speed to the power of negative two.

By studying Figure 12 we see that the lifetime decreases as the jet speed increases. It can be concluded that it is not possible to conduct experiments at velocities above 1.2m/s, since the film then breaks before any measurements can be made. At velocities below 0.06m/s the jet separates into drops before impacting the film, thus making speeds below that impossible to use.

By studying Figure 13 we see that the a straight line could be fitted but not with very high accuracy. This indicates that there are other factors affecting the lifetime of the soap film that have not been considered.

6 Interaction between jet and film

The interactions between a thin water jet of radius 0.60 mm and a soap film have been studied for different velocities (0.06 – 1.2m/s) and different incident angles (9° – 72°). The jet behaves in two ways for different velocity and incident angle regimes, either penetrating and getting refracted by the soap film or being reflected against the film. The refraction is described theoretically using mass conservation and surface tension forces. The reflection is not described theoretically but the transition regime from refraction to reflection is argued for.

6.1 Jet-Film interaction: Theory

The velocity was measured in kg/s by collecting the jet over one minute and weighing it. To find the speed of the jet from kg/s to m/s equation (8) was used.

$$v = \frac{m}{\rho \pi r^2 t} \tag{8}$$

where v is the ejection velocity of the liquid, ρ is the density of the liquid, m is the ejected mass of liquid after time t and r is the radius of the needle.

The equations of the interaction have been presented in by Kirstetter *et al.* in previous work for jet and soap film interaction [1]. These equations are valid for jets and films of the same liquid, but it is interesting to see if, and how well, the equations work for jets and films of different liquids.

For the interaction an *index of refraction* can be defined, in analogy with optics, as

$$n = \frac{\sin \theta_r}{\sin \theta_i} \tag{9}$$

where θ_r and θ_i are the angle of refraction and incidence respectively.

To describe the interaction theoretically a few new quantities needs to be introduced, see Figure 14. If a plug flow is assumed in the jet then mass balance, D, for the interaction writes as

$$D = \pi R_i^2 V_i = \pi R_r^2 V_r \tag{10}$$

where R are the radii for the jet and V is velocity of the jet. The indices i and r are for incident and refracted respectively.

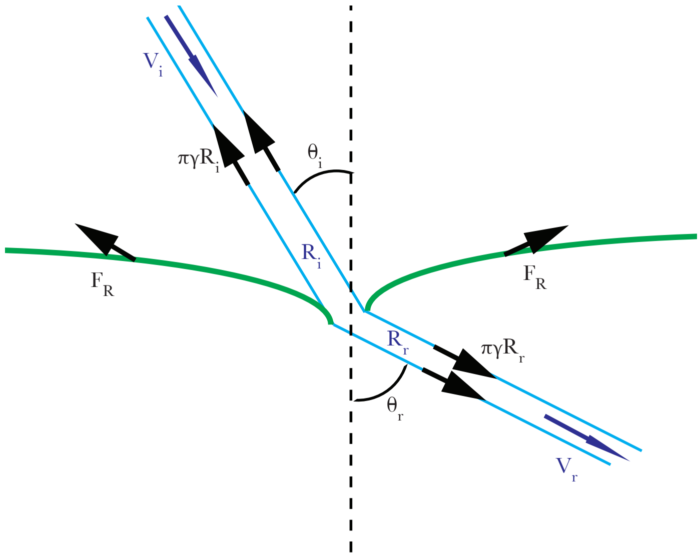

Figure 14: The quantities and forces important for the theory. V is incident jet speed, R is jet radius, θ is angle and indices i and r are for incident and refracted respectively. F_R is the force from surface tension.

The force balance in x (equation (11)) and y (equation (12)) is achieved by balancing momentum rate of change (left hand side) with forces on the system (right hand side). The forces included are the Young-Laplace capillary force and the surface tension.

$$D(\rho V_r \sin\theta_r - \rho V_i \sin\theta_i) = \pi\gamma(R_r \sin\theta_r - R_i \sin\theta_i) \tag{11}$$

$$D(\rho V_r \cos\theta_r - \rho V_i \cos\theta_i) = \pi\gamma(R_r \cos\theta_r - R_i \cos\theta_i) - F_R \tag{12}$$

where F_R is the interaction force which is assumed to be perpendicular to the soap film - jet contact. This can in turn be simplified to

$$(D\rho V_r - \pi\gamma R_r)\sin\theta_r = (D\rho V_i - \pi\gamma R_i)\sin\theta_i \tag{13}$$

$$(D\rho V_r - \pi\gamma R_r)\cos\theta_r = (D\rho V_i - \pi\gamma R_i)\cos\theta_i - F_R \tag{14}$$

Now we can multiply equation (13) with $\cos\theta_r$ and equation (14) with $\sin\theta_r$ and eliminate the left hand side. Then we get

$$0 = (D\rho V_i - \pi\gamma R_i)\sin\theta_i\cos\theta_r - (D\rho V_i - \pi\gamma R_i)\cos\theta_i\sin\theta_r + F_R\sin\theta_r \tag{15}$$

Now we divide with $\pi\gamma R_i$

$$0 = (\mathrm{We} - 1)\sin\theta_i\cos\theta_r - (\mathrm{We} - 1)\cos\theta_i\sin\theta_r + \frac{F_R}{\pi\gamma R_i}\sin\theta_r \tag{16}$$

Rearranging gives

$$(\mathrm{We} - 1)(\cos\theta_i\sin\theta_r - \sin\theta_i\cos\theta_r) = \frac{F_R}{\pi\gamma R_i}\sin\theta_r \tag{17}$$

Which can be simplified to

$$(\mathrm{We}-1)\sin(\theta_r-\theta_i)=\frac{F_R}{\pi\gamma R_i}\sin\theta_r \tag{18}$$

Assuming small inclination limit the following simplifications can be made

$$\sin\theta_i\sim\theta_i \qquad \sin\theta_r\sim n\theta_i \qquad F_R\sim 4\pi\gamma R_i$$

where the simplification for F_R is done assuming total wetting [7] and that the jet-film contact is R_i. This all leads to

$$(\mathrm{We}-1)(n\theta_i-\theta_i)=4n\theta_i \tag{19}$$

which finally becomes

$$n=\frac{\mathrm{We}-1}{\mathrm{We}-5} \tag{20}$$

This is of course only relevant for We > 5, since the expression goes to infinity for We $= 5$. In the experiments both refraction and reflection are observed for different inclination angles and speeds. It is physically relevant to expect this to occur when $\sin\theta_r = 1$, when the jet is exiting parallel the film. In the theoretical model this would correspond to $\sin\theta_i = 1/n$ for transition or

$$\theta_i=\arcsin\left(\frac{\mathrm{We}-5}{\mathrm{We}-1}\right) \tag{21}$$

Equations (11) to equation (21) have been modified in different ways; to account for the different surface tensions of the water jet and soap film, using the correct expression instead of small angle approximation and to account for the only partial wetting between jet and film. None of these corrections improved correlation between theory and result and are therefore not presented.

6.2 Jet-Film interaction: Experimental method

A sketch of the setup can be seen in Figure 15. The basic setup is the same as described in section 3.3: Thin Film Interference: Experimental method. Two circular metal wire frames with a radius of 10 cm are used where the lower one holds a soap film.

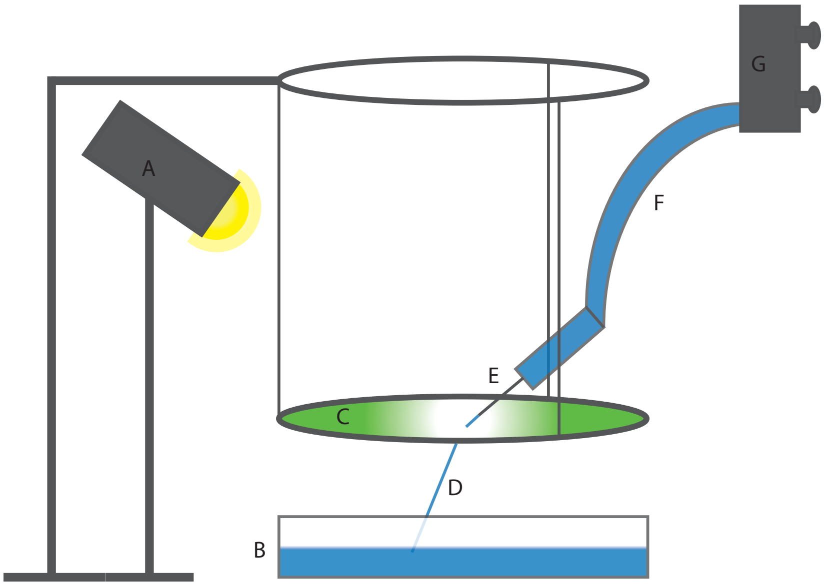

Figure 15: Setup. A: Lamp B: Container for water collection C: Soap film D: Outgoing water jet E: Hypodermic needle (R_i = 0.60mm) and incident water jet F: Water hose G: Double needle valve

A large container with the soap mixture was lifted up by hand until the wire frame was well covered in soap mixture. This soap mixture container was then put away with a lid on to prevent evaporation. The soap mixture consisted of deionized water with 5% commercial soap (Brand: YES) and 5% glycerol for stability. The surface tension for this mixture was measured to 25.5 mN/m using a Drop Profile Tensiometer. See section 4 for surface tension measuring procedure and Figure 10 for all surface tension values. The container was then carefully withdrawn with approximately the same speed every time to create a soap film. After withdrawal the film oscillated most of the times. The film was allowed to settle, which took approximately 5 seconds.

A jet was produced by connecting a double needle valve to the faucet which held a constant water pressure. The needle valve was connected to a plastic water hose, which in turn was connected to a syringe. A hypodermic needle of inner radius 0.30 mm was placed on the syringe. This is three times larger than those used for experiments by Kirstetter *et al.* [1]. The needle was polished so that the point end became smooth. The polishing process limited the radius choices for the needle since all smaller radii became clogged during polishing. The syringe and needle were moved over to the soap film where it was placed as close to the soap film as was allowed by the setup (5-10 mm) and at an incident angle θ_i towards the film. The needle was placed so that the jet would impact at the center of the soap film.

The water flow was then started by turning the fine "knob" on the needle valve. At first a few drops fell from the hypodermic needle but after a few seconds the water jet had reached its terminal velocity. When the drop reaches and detaches from the film it starts oscillating. The oscillations dampen completely within a few seconds. Experiments were conducted in a dark room with the film illuminated by a bright lamp so that the film and jet would be clearly visible. See Figure 1 for an example of the camera view. The whole process was recorded using a digital camera (CASIO Exilim ZR-1000) at 25 fps in level with the soap film. Lower frame rate was not feasible due to the lighting conditions needed to view both the jet and film simultaneously.

When the soap film broke the recording was stopped. The ejected mass over approximately 60 seconds was collected, and weighed, twice to get the average water speed. The movie was later analyzed for incident angle θ_i and refracted angle θ_r using motion tracking software Tracker (freeware from Cabrillo College). The lifetime of the soap film during jet impact was measured in the movies. Anomalies were noted and could almost always be explained by the jet not hitting the center of the soap film. Anomalies include jets depressing the film and then spiraling down in this depression and jets being both refracted and reflected.

On finding out when the transition from refracted to reflected occurred a slightly different approach was employed. The hypodermic needle was placed over the soap film at a fixed angle and photographed to find the angle. The jet speed was set to around 0.5m/s initially and was then lowered until the transition occurred where the speed was noted using the same procedure as previously. The angle was changed and the procedure repeated.

6.3 Jet-Film interaction: Results

When initiating the experiments a few drops would always fall on and through the film when starting the jet. This would often induce oscillations of the film. After a few seconds the jet reached its terminal velocity and the oscillations died out over a few seconds. When the film oscillates the outgoing jet changes direction since the incident angle changes. The force is not constant if the film is vibrating. No measurements were therefore done until the film was at rest.

In Figure 16 the different interactions can be seen. All the pictures are on the same soap film with the same incident angle, θ_i, but with lowering speed going from A to D. In Figure 16A and Figure 16B the refracted jet clearly has different outgoing direction. This shows that the index of refraction should increase with lowering velocity. In Figure 16C absorption of the jet into the film can be seen. This phenomenon is difficult to observe since it can only occur when the film is very stable and the speed and angle are correct. This means that it is a transient phenomenon for our experiments. When the film wobbled slightly or the velocity dropped marginally the jet got reflected instead, see Figure 16D. For all lower speeds the jet was reflected until the jet splits into drops.

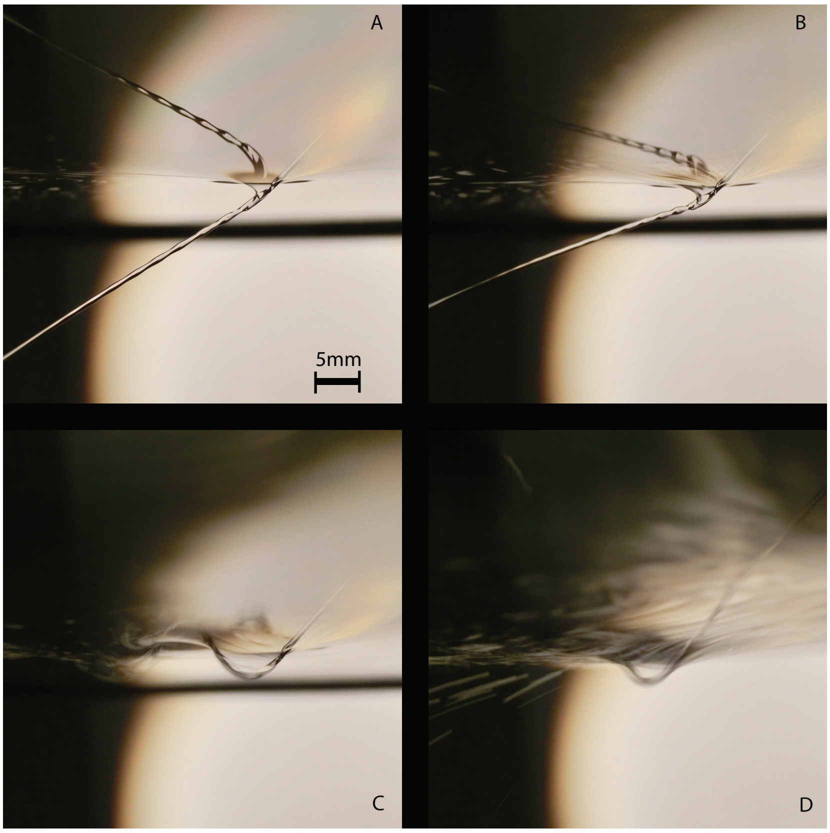

Figure 16: A: Jet passing through film getting refracted. B: Lowering velocity increases angle of refraction. C: Lowering velocity even more gives transient absorption. D: Slightly lowering velocity gives total reflection.

When the jet is refracted through the film there is barely a disturbance in the film and the film is not noticeably depressed. When the jet is reflected the film is stable if the jet hits the center of the film. If the jet instead hits the film a bit from the center a myriad of phenomenon can occur. It can induce wobbling in either direction in the film, spiraling jet or droplets into a centrally created depression.

For refraction we assume that slower speed gives longer contact length. This can be seen in Figure 16 when comparing A and B if the interaction point is studied closely. When the jet moves slower it can't put as much pressure on the film and the film tries to go back to its undisturbed flat shape. This means that the jet is tilted more towards the film, increasing the angle of refraction.

In Figure 17 we see the index of refraction for different We numbers plotted. The theoretical line is described in equation (20) and is valid for having the same liquid in the jet and film.

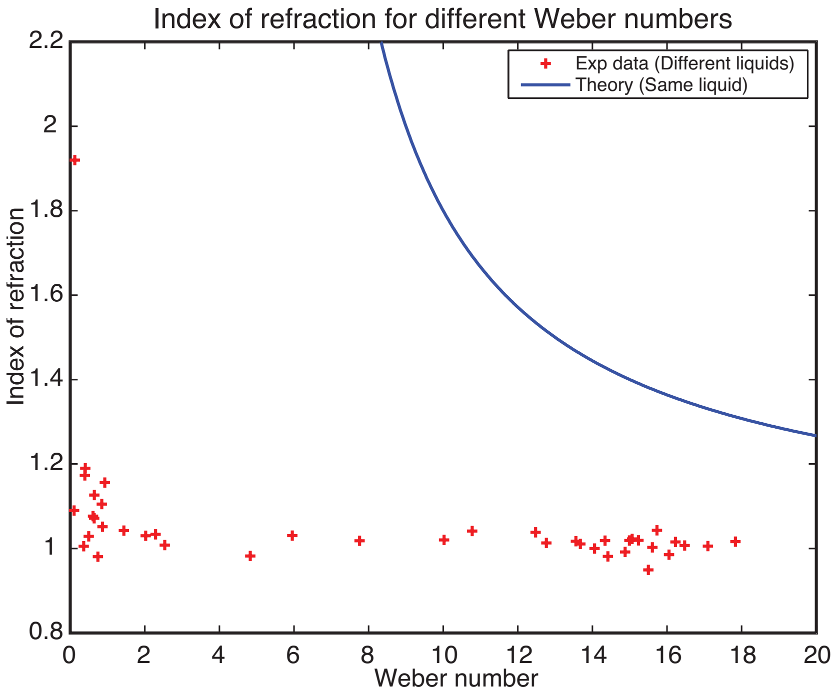

Figure 17: The index of refraction for different We numbers. Theoretical line is equation (20) (from [1]) which is derived for jet and film of the same liquid.

As can be seen in Figure 17 the theory from Kirstetter *et al.* [1] does not fit the data. This means that conducting the experiments with different liquids in the jet and film is a radically different phenomenon from when having the same liquid in the jet and film. They have the same general shape but it is clear that they are at least shifted in relation to each other. The experimental data for different liquids show a steeper increase when the We number goes towards zero than the theory for same liquids predicts. It could be thought that this is due to the fact that the jet radius used is slightly larger than those used by Kirstetter *et al.* but the jets used by them had a size range from 80-270 μm, where the results from the different radii collapsed onto the same curve. Despite several tries at modifying the theory for water in the jet, we can conclude that this is either a completely new phenomenon or a very weak version of the previously studied phenomenon [1]. This means that a new theory has to be developed to describe what happens when a water jet interacts with a soap film.

In Figure 18 the We numbers and angle at which the jet transitions from being refracted to being reflected. The fact that we have reflection as a stable regime is the most important indication that this is an entirely new phenomenon as opposed to a weak version of the jet-film interaction when they are of the same liquid. When having the same liquid reflection is only a transient regime and a reflected jet is quickly captured by the film and gives rise to an absorption regime.

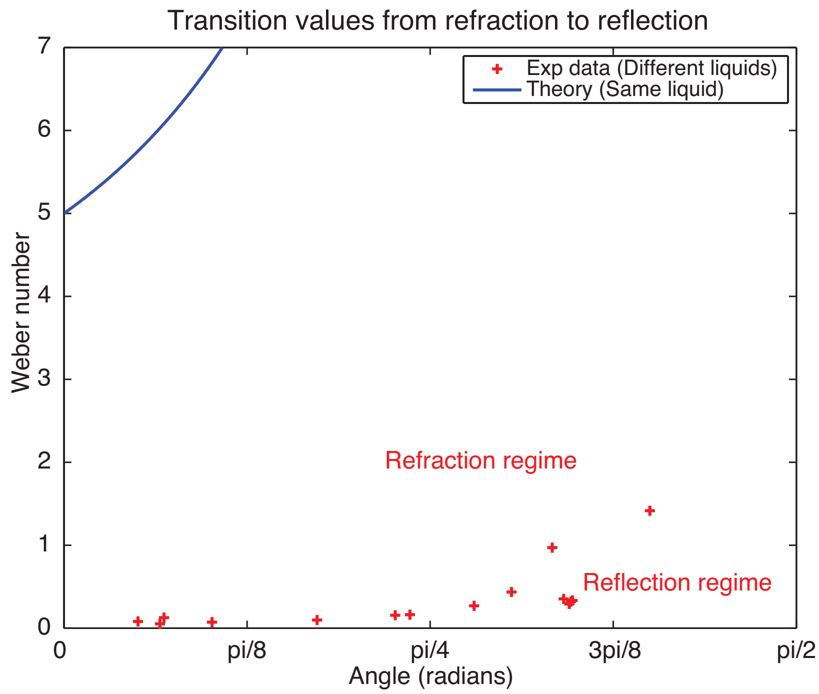

Figure 18: The angle and We number at which the transition from refracted jet to reflected jet occur. Theoretical line is equation (21) (from [1]) which is derived for jet and film of the same liquid.

The data points were taken when the jet transitioned from refracted to reflected. All experiments done at values above the data points will give a refraction, and all experiments done at values below the data points will give reflection. When getting very close to the transition value the phenomenon in Figure 19 was observed, refraction and reflection simultaneously.

The theoretical line in Figure 18 does once again not fit with the data. It is not strange that since this theory is derived from the same basis as the theory in Figure 17. This is a second indication that a completely new theory needs to be developed to describe what happens when a water jet interacts with a soap film.

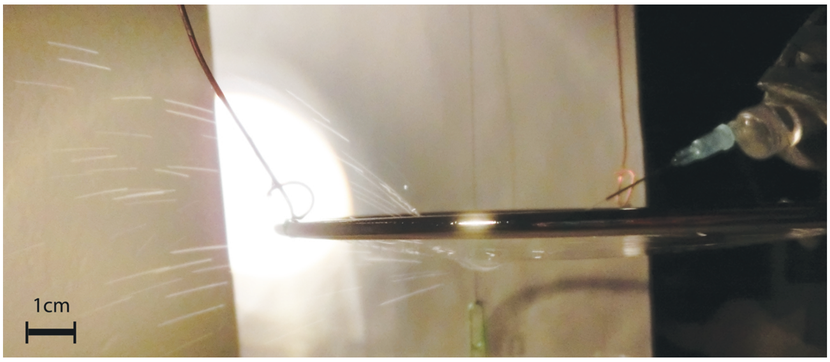

Figure 19: Jet is partly reflected, partly refracted. Right in the transition zone.

When looking at the wetting between the jet and film we find that there is not total wetting. In Figure 20 we can see that there is a contact angle of approximately 35°. Total wetting was assumed in the theoretical description of the phenomenon, but including the partial wetting does unfortunately not improve correlation.

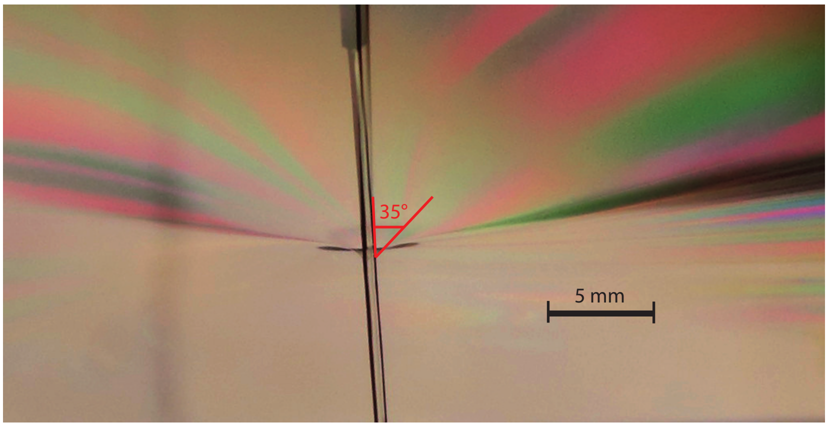

Figure 20: A closeup of the incoming jet, film and outgoing jet. An angle between the jet and film can be seen and is measured to be $\sim 35°$.

The contact angle is difficult to measure when having a tilted jet. Therefore no consistent measurements of the contact angle were done during the experiments. This is another reason why the partial wetting was not included in the theoretical description.

7 Discussion

This thesis is a continuation of the research previously done by Kirstetter *et al.* on the interaction between soap films and thin liquid jets of the same liquid [1]. We demonstrate that the theory suggested in said article is not applicable if the jet and film are not of the same liquid.

One trouble might be the small angle approximation, but earlier work using this approximation shows excellent agreement when using the same liquid in jet and film [1]. If the deviation between the theory and our experimental data had been large for large angle and small for small angles this might have been the problem.

Previous research [1] on soap jets interacting with a soap film reports refraction, absorption and a transient reflection region. For a water jet interacting with a soap film we instead find refraction, reflection and a transient absorption region. They report that a jet which is initially reflected will quickly be absorbed by the film [1], while we find the opposite: a jet that is momentarily caught in the film will escape and be reflected. This could perhaps be explained by the fact that the surface of the soap film is hydrophobic, or even superhydrophobic, since this behavior is similar to water jets bouncing on superhydrophobic surfaces [9]. It could also in part be caused by the glycerol in the film solution. The glycerol makes the film slightly more rigid, and is added because we want the film to have a long lifetime.

Since the reflected jet is unstable, either due to film vibrations or that the jet velocity is too low [9], it is not possible to measure the reflection angle. The reflected angle would be interesting to measure to find the energy lost in the collision with the film. This could be used in developing a model for the phenomenon.

In Figure 12 and Figure 13 we see the lifetime of the soap film as a function of the jet speed. If there was no mass transfer between the jet and soap film we would expect the lifetime of the soap film to be independent of the jet speed. If there were no mass transfer, as in the Kaye effect, the soap film would only break through natural drainage. The Kaye effect is however dependent on a viscous substrate and the soap-water-glycerol mixture used to form the soap film in our experiments can probably not be considered viscous, meaning the effect observed is not the Kaye effect [8].

The contact length in the Kaye effect increases with increasing speed of the jet, and therefore also with increasing viscous friction. But the Kaye effect is a reflection phenomenon and we need an explanation for why the refraction does not behave as it does for having same liquids in the jet and film. For refraction we assume that slower speed gives longer contact length. This can be seen in Figure 16 when comparing A and B. The contact length between the jet and film is important for viscous friction. Lower jet speed gives longer contact length, which increases the friction. This could explain why the data points in Figure 17 have a very steep increase in index of refraction when the We number goes towards zero. This very steep increase is not present when the jet and film are of the same liquid, indicating that it is a liquid dependent effect.

Noblin *et al.* [10] have demonstrated that it is possible to build a pressure controlled container for obtaining constant jet velocities. This is the only way to freely choose the liquid in the jet. It would be very interesting to see what happens when an oil jet impacts a soap film. Since a soap film is hydrophobic on the surfaces an oil jet might get stuck on the surface for low velocities. It is also possible that we would need much higher jet speeds to get through the film since the jet has to pass through the water lamella. Oil and water are immiscible and this could cause problems for the phenomenon.

If our research is representative for interaction between jets and films of different liquids we expect to find different amount of refraction depending on which liquids are used. We find refraction but only noticeable for very low velocities (around 0.06m/s) where the jet almost breaks up in drops. But if small refraction of low velocity water jets is of interest this is a very useful technique. It might be possible to change the liquid properties to find optimal combinations for different jet speeds and refraction angles. For example the relative surface tension, hydrophobicity and perhaps even viscosity could be altered to find which film liquid fits best for which jet liquid to get the desired amount of refraction.

8 Conclusion

The interaction between soap films and water jets have not been studied previously, and the results found are different from the interaction between soap films and soap jets.

This thesis finds that a water jet which impacts a soap film can do two things, either penetrate the film and exit at a slightly different angle than the incident or experience total reflection by bouncing off the film. When the jet penetrates the film and gets refracted the refractive index is very small compared to using the same liquid for both jet and film. This is thought to depend primarily on the hydrophobicity of the soap films surfaces but also on the only partial wetting between the jet and film.

The hydrophobicity is also thought to be the cause to why we find refraction and reflection as opposed to refraction and absorption for jets and films of the same liquid [1].

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