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MEASUREMENT OF THE FLUID AND FLOW PROPERTIES OF A SOAP FILM CHANNEL

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ABSTRACT

This report describes the measuring and analysis of the fluid and flow properties of a soap film channel in order to be able to understand the behaviour of the channel and improve the performance of all the components. The soap film channel is a new equipment for analysing the fluid flow properties in a simplest way, using two dimensions and being able to see the flow through the channel.

The report starts with a general view of the history and development of the falling film flow channels, a description of a generic design to finally analyse the design that was developed in the previous years and the mixture that is used on this channel, which are the main focus of this document.

The study discusses the main properties and characteristics of the mixture such as: density, viscosity, refractive index, surface tension, and components percentages as well as an analysis of the flow rate and thicknesses of the channel and some modifications which were made to improve the working parameters of the channel.

Based on the research, the channel has been improved as far as new working configurations have been developed and the channel has new controlling elements in order to avoid the breaking of the film, which was one of the main problems of this channels and now is avoided.

1. HISTORY OF THE STUDY OF SOAP FILM CHANNELS

In the recent years, soap film channels have gained a more widespread usage in the experimental study of fluids. The concept of using flowing soap film in experimental work has been around since the late sixties. A pioneer of the use of soap film in this manor was Y. Couder, who developed one of the first methods for visualizing flows through the application of soap films and he was the first to give serious consideration to soap films as an experimental platform for 2D fluid dynamics. He wrote an exceptional paper introducing thickness and viscosity measurements of flowing soap films in 1964. His setup for studying flowing films was simple but effective enough to exhibit the potential of soap films as a means for studying two dimensional flows. His setup was basically a rectangular frame, which is inserted then removed from a soap solution to create a bubble. Following this, one would stick an object into the bubble and move the bubble against it to observe the flow past it. Findings on the stability of vortex streets, and on the coarsening of vortices in 2D turbulence were reported. This was sufficient for flow visualization but it had various drawbacks, including short observation time and the difficultly producing quantitative data.

Gharid later developed a water jet propelled soap film for flow visualization. It was a device where the film flows down a channel, like a conventional wind tunnel. With this design one draws a soap film from a solution reservoir, and then proceeds to run it along horizontal supports and onto a sheet of moving water.

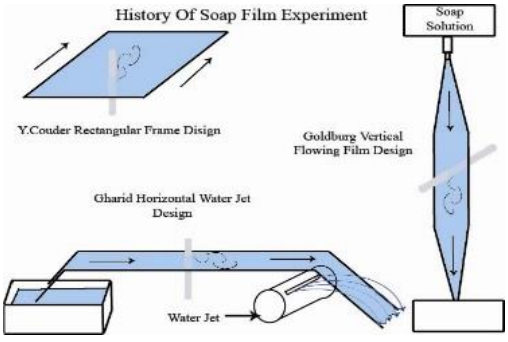

Figure 1 Development of the soap films channel experiments

In the mid- 90's; Goldburg, Kellay and others developed a gravity propelled soap film tunnel. It consisted of a reservoir of solution that dispensed solution through nozzle onto two steel wires and held under tension by a weight immersed in a lower reservoir. The wires are then separated to creating a bubble between them. In this set up there is little control over the flow speeds and the solution does not spread evenly over the guide wires creation non-uniform flow conditions. This bubble would flow down under the pull of gravity. This method produces fast flowing films that can attain speed up to several hundred cm/s. This method was then improved by using nozzles to spread the solution evenly across the wires. The method produces fast films, but there is little

control over the flow rate and film width. Moreover, the solution never spreads well after being injected from the holes, leading to a very no uniform film. This technique was the starting point for the new methods developed to study 2D fluids. The wire would come out of the nozzle then expand to the width of the test section and then contract into a lower reservoir. This arrangement is affected more by air drag because it produces faster flowing films.

Two-dimensional fluid dynamics in a *Taylor–Couette geometry* has also been explored using soap films. The method was developed by Wu and proved successful for measuring Batchelor scaling in the turbulent dissipative range. A variation of their apparatus was used to measure the viscosity of a soap membrane.

1.1. New apparatus (same design as ours)

The design currently in use by the recent studies is outlined in the figure. A typical element of solution will be followed during its downward trajectory. The fluid element starts in the upper supply reservoir (point a) where it is driven downward into the feed tube (point b) by a pressure head. A fluid metering valve (point c) sets the flow rate from the feed tube into the nozzle (point d). Two monofilament nylon guide wires (point e) splay from the nozzle. Thinner nylon pull lines (point f) are attached to the guide wires and hold them apart. As the fluid element is ejected from the nozzle, it stretches between the guide wires as it is accelerated by gravity in the expansion section (section I) of the channel. The element rapidly gains area due to vertical *y* and horizontal *x* stretching. In the test section (section II) the guide wires are parallel and the fluid element has reached a near constant *terminal velocity* due to the balance between gravitational and air drag forces. During this time the soap film is between 2 and 6 mm thick and travels between 0.5 and 4 m/s, depending on the fluid injection rate. At the bottom of the channel the element encounters the contraction section (section III) where the film thickness diminishes and the fluid slows in a process nearly the reverse of the expansion section (section I). The film finally drips from the guide wire tensioning weight (point g) into the bottom collection reservoir (point h). If the film breaks, one simply releases the tension on pull lines, allowing the weight to pull the guide wires together until they are touching. Once sufficient soap solution has dripped from the nozzle to wet the entire length of the guide wires, tension is reapplied to the pull lines, and a new film appears between them.

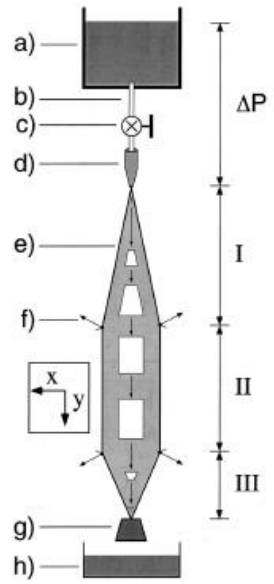

Figure 2 Actual soap film channel diagram

2. SETUP. WHAT IS A SOAP FILM?

The standard view of a soap membrane is a micrometre thick sheet of water covered on either side by surfactant soap molecules. Without the surfactant, the liquid sheet would be unstable and break up into droplets, because surfactants endow the film with an elasticity, against any local thinning that could lead to rupture. For a soluble surfactant, such as soap, molecules can reside both on the surface and inside the interstitial fluid sheet. Dissolved molecules can either be isolated or clustered into micelles, and can replenish the surface when the film is stretched slowly. The interstitial fluid layer can be as thin as 100 Å, which is the thermodynamically stable state.

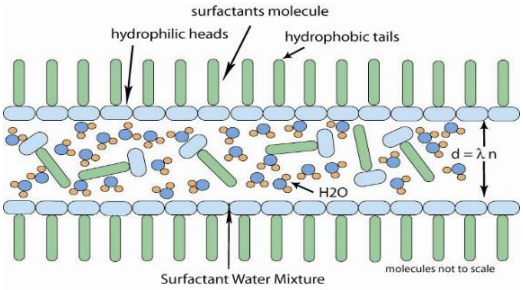

Figure 3 Setup of a soap film

The film is assumed to move freely as a composite slab, with soap molecules on either side, coupled to, and moving with the interstitial fluid. The film itself can be considered 2D to the extent that the film is typically 104 or 105 times wider than it is thick. Any interstitial fluid flowing perpendicular to the film will be greatly overdamped since the *Reynolds number* is much less than unity at micrometre length scales. The flow is therefore expected to be 2D for all practical purposes. As a result of its molecular composition, soap films are made of three layers; two layers of soap molecules separated by a layer of solution. This interior layer replenishes the outer layer when they thin due to evaporation and controls any local thinning that can lead to rupture. The distance between these layers is usually very small and on order of an integer multiple of the wave length of visible light. This allows interferences between light reflect off the top and bottom surface of the soap film.

This interaction between these two light waves cause destructive (dark colours) and/or constructive interference (bright colours) creating vivid colour variations. This interference changes depending on the thickness of the film, creating different interference patterns for different thickness variations. The thickness of the soap film is a scalar and can be thought as being concentration of substance in a fluid. Differences in the films thickness that arise when the bodies that inserted in the flow cause disturbances in the flow are analogous to the differences in concentration of fluid under the same condition. This property of soap films to display thickness variations as colour fingers allow for good qualitative observations and we will analyse it later in our soap film.

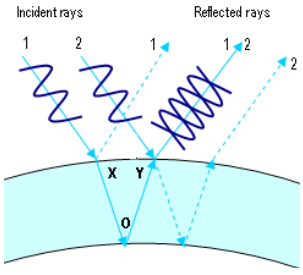

Figure 4 Light reflection in the film

3. WHAT DO WE USE THIS EXPERIMENT FOR?

The experiment is performed in order to deal with two basic problems in fluid analysis:

- Fluids flow is difficultly study experimentally (by eye): because of their transparent or uniform colour
- Fluids propagate in 3D: this experiment is a 2D application, reduces 1 degree of freedom
    - Simplify the conditions
    - Allow the comparison with simplified numerical computer models

Our method to do this experiment is to use flowing soap films, which are essentially the walls of soap bubbles which flow through a channel. Soap bubbles are very thin film, essentially a two dimensional surfaces, which when flowing behave as a two dimensional fluid. The colour variations on the soap film's surface (which represent thickness variation created by disturbances in the flow) gives soap film brilliant flow visualization ability; coupled with their two dimensionalities make soap films a formable tool for the study of fluids. Soap films provide a novel and inexpensive approach to investigating 2D fluid instability.

3.1. Why do we consider that the soap film is 2D?

Although soap films are 3D in their geometry, it would be reasonable to assume that for certain thicknesses the flow within the soap film is 2D in nature, as the length to thickness ratio is on the order of 105. Another notable mention is that the scales of coherent vortex structures should be large in comparison to film thickness. Also, an additional property that makes soap films ideal for 2D fluid dynamics experiments are their flow visualization potential.

3.2. Compressible fluid?

Although soap films are prime candidate for the study two-dimensional incompressible flow, soap films can also demonstrate properties analogues to compressible fluids. A flow is considered a compressible flow if the change in density of the flow with respect to pressure is non-zero and in general this occurs in *Mach numbers* approaching or exceeding 0.3.

Compressible flow is governed by the gas dynamics equations, and while soap does not travel at quite high speed, under some condition they can still behave in a manner consistent with the gas dynamics equations. The presences of wave propagation in soap films and their behaviour being consistent with gas dynamic equation can allow soap films use in conducting compressible fluid

dynamics experiment. Soap films have considerable potential for study two-dimensional fluid flow and growing implication for their use in experimental compressible fluid dynamics.

4. STUDYING OF A GENERAL FALLING FILM FLOW

In this chapter, we are going to explain how to make a general study of a flow film channel, including: the construction, the operation and the control of the channel, the reasons and the way to make the analysis.

4.1. Building a vertical falling film flow

A variety of ways to build long lasting vertically flowing films are outlined in this section. All the designs are variations of the basic construction diagram that we presented in the section 1.1 “New apparatus (same design as ours)”

The apparatus usually stands about 2 m tall and it is divided in four different stages. In the simplest case the upper fluid reservoir is hung from a hook in the ceiling or a structure (stage 1), the injection nozzle attached to it, and the pull lines operated by hand expands the channel gradually (stage 2) till the section of analysis where both guide wires are parallel (stage 3); finally, the channel is contracted and the mixture is collected again (stage 4). Reservoirs are located at both the top and bottom of the frame, and the solution can be recirculated between them using a pump. Recirculation saves potentially costly particles introduced into the solution for flow tracking, allows for runs of extended length with an essentially unlimited supply of solution, and can maintain a constant pressure head to eliminate changes in the mean velocity caused by a reduction in the amount of solution in the upper reservoir. To avoid contaminating the solution during the recirculation process, the materials that are wetted are either stainless steel or silicone. Wires for stretching the film are mounted on the frame sides, and the flow valve must be controlled for accuracy and repeatability.

In our design, we use a ring attached to the mixture wires by means of some pulling strings (white nylon wires), the same type that are used for the opening of the channel in the test section.

After the contraction section the fluid is collected in a lower reservoir. It can be recirculated to the supply reservoir with a pump. We can use both gear pumps and diaphragm pumps. Prolonged recirculation will lead to a thickening of the mixture as some evaporation occurs from the surface of the film, and can cause a build-up of dust and other contaminants. Nevertheless, some less contaminant materials, such as silicone tubes, can be used to decrease this contamination and dust in the mixture.

4.2. Materials considerations

Soap solution is surprisingly corrosive and prolonged exposure will corrode most metals including many stainless steels. To minimize corrosion problems, we recommend the solution come in contact only with anodized aluminium, teflon, glass, or surgical stainless steel. The fluid metering valve should also be very corrosion resistant. An alternative to a valve is to clamp the fluid feed tube partially shut. This method is effective though not as reproducible. A resilient tubing made of silicone or viton is recommended and the weight can be plastic coated, or can be avoided to be touched by the soap. The guide wires and pull lines are best made of monofilament fishing line or maybe also some varieties of nylon sheathed kevlar braids. There is also a great influence of our recirculation system where the best recommendation is therefore the use of the most inert materials possible.

4.3. Operation

The goals of operation are often to create a long-lived film having constant thickness and flowing with a uniform velocity. Steps:

1. Building the apparatus
2. Preparing the correct soap solution
3. Injecting the soap solution from a correct shape nozzle into a properly shaped channel
4. Check the ambient and operational conditions
5. Achieve the operational goals

This section will be used to describe the typical situations and their relation with the operational parameters.

4.4. Analysis of a vertical falling film flow

4.4.1. Flow control and channel geometry

The flow control is related with the behaviour and the operation of our channel. This changes in the behaviour can be seen by modifying the flow rate and analysing how the channel works.

A. **For very low flow rates**, the fluid in the film tends to separate symmetrically and cling to the guide wires, leaving a very thin film (<1 μm) in the centre of the channel. Thin films, moving at less than 1 m/s, often exhibit violent instabilities in the test section of the channel, this is due to the spontaneous generation of thin soap film at the point of contact between the film and the guide wire; this is called marginal regeneration. Interestingly, we

never observe marginal regeneration in faster flowing films, because the high shear rates near the guide wires may suppress the marginal regeneration instability.

B. **At slightly faster flow rates** the separation of fluid near the nozzle lessens and the marginal regeneration is suppressed. The film in the centre of the channel will still be thinner than the film near the edges.

C. **For medium flow rates** the separation disappears, is the optimal situation leading to uniform films in the test section where the film thickness varies by less than one quarter wavelength of light (≈0.1 µm) over its entire width.

   As an example from the experiment made by Rutgers, Wu and Daniel: for their 1 m long expansion section into a 5 cm wide test section, the optimal film thickness ranges between 2 and 5 mm with corresponding films speeds of 2–3 m/s. If such uniform films are essential to an experiment, the channel geometry can easily be adjusted to optimal conditions.

D. **For the highest flow rates** a thicker jet of fluid shoots down the centre of the channel and the interference fringes in the expansion section show a characteristic dip in the centre

   As an example from the experiment made by Rutgers, Wu and Daniel: it corresponds to a total change in thickness of 0.8 µm, which translates to a gradual ≈15% change in film thickness.

E. **For higher flow rates** the film becomes supersonic and unstable with respect to transverse undulations of the film. When the film speed exceeds the wave speed, shock waves appear and the film eventually breaks.

   Vertically flowing films in air are thereby limited to thicknesses of about 6 µm traveling at about 4 m/s.

4.4.2. Surface tension

The molecules near the surface of a pure fluid have a different environment from those in the interior of the fluid. A molecule in the bulk of the fluid will experience forces in all directions due to the surrounding molecules. The resultant force over a macroscopic time will be zero. Molecules near the surface of the fluid will experience a weaker force, from the gaseous region above the surface, as the density of the gaseous region is considerably smaller than that of the bulk fluid. Consequently, such molecules will experience, on average, a force pulling them back into the bulk of the fluid. This force will have the effect of reducing the area of the surface making the surface free to change its shape, as in the case of a water droplet which always takes up a spherical shape. It will also have the effect of reducing the density of the fluid in the region of the surface.

A soap solution consists of soap molecules and water molecules. Each soap molecule is formed form the metal salt of a long chain fatty acid molecule and becomes ionizes in solution. The

negatively charged ions near the surface experience an average force towards the surface while the positive charge ions will be dispersed throughout the solution. This is the energetically favoured configuration for the ions in the surface.

An important consequence of the variation in the environment of the molecules in the region of the surface of the fluid, in both pure fluids and soap solutions, is the presence of a macroscopic surface force localized within about one atomic thickness of the surface. For most purposes, it is justifiable to consider this as a surface tension, that is a force per unit length, σ, in a "membrane" of negligible thickness at the surface of the fluid.

A soap film consists of two such surfaces separated by a thin layer of fluid, which may vary in thickness from 2×10^5 Å to 50 Å (10 Å =1 nm). The largest thickness will occur immediately after the formation of a film. Once the film has formed it will commence to thin. Each surface is composed of soap ions which are separated, largely, by water molecules. The thickness of the film will decrease until a final equilibrium thickness is reached, providing the film does not rupture. Both surfaces of the film will have a surface tension associated with them.

The surface of any fluid will be in a state of uniform tension if the fluid surface satisfies the following conditions:

A. The surface tension must be perpendicular to any line drawn in the surface and have the same magnitude for all directions of the line
B. The surface tension must have the same value at all points on the surface

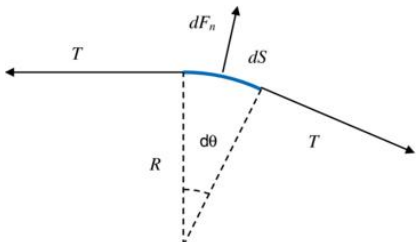

Figure 5 Surface tension in the film

In the case of a soap film, with two surfaces, it is convenient to introduce the concept of film tension: σ_g, which is the force per unit length of film and is equal to twice the surface tension. For thick films the surface tension will be equal to that at the surface of a bath of soap solution. However, for very thin films the value will differ from that for the surface of a bath of soap solution. The two conditions, (A) and (B), are satisfied by most fluids. For a soap film, however, it is possible that (B) will only be satisfied approximately. For example, consider the equilibrium of a section of a vertical soap film of thickness t, width l, and height h. Let the surface tension at the bottom of the section of film be σ_0 and that at height h. The vertical force at the top of the film is $2l\sigma_h$, the factor of 2 arises because the film has two surfaces. This force balances the force at the bottom of the film, $2l\sigma_0$, plus the weight of the film mg, where m is the mass of the film. If ρ is the density of the fluid in the film then $m=tlh\rho$. For equilibrium,

$$2l\sigma_h = 2l\sigma_0 + tlh\rho g$$

Hence:

$$\frac{\sigma_h - \sigma_0}{\sigma_0} = \frac{th\rho g}{2\sigma_0}$$

A thick film with a thickness of one micron (10^{-4} cm), a height of 10 cm, and σ_0= 30 dynes per cm has, from the previous equation, a variation in surface tension, $\Delta\sigma$, of about 1.5 per cent. In the thinnest films, typically 60 Å thick, this variation is reduced to 0.01 per cent. It has been assumed that the fluid, or soap film, is at constant temperature in **thermodynamic equilibrium**. Under these conditions it is found that the surface tension, σ, of a fluid surface depends only on the temperature. This is known as the **static surface tension**. The surface tension will differ from the static value if the fluid, or soap film, is not in thermodynamic equilibrium. An example of a common **non-equilibrium situation** occurs in a jet of water issuing from a pipe. The molecules at the surface of the water are not in thermodynamic equilibrium. The environment of the molecules at, or near, the surface will differ from that of a fluid in thermodynamic equilibrium. Consequently, the surface tension will differ from that in the static case. This is known as the **dynamic surface tension**.

Surface tension has been defined as the force per unit length in a liquid vapour interface. The concept can be extended to two phases of different fluids providing they do not mix; immiscible fluids. The surface tension between two liquid phases is called the interfacial tension, and that between a solid and a liquid the adhesion tension. There will also be a surface tension at a solid-gas interface.

The surface tension of a not associated liquid in thermodynamic equilibrium with its vapour has been shown empirically to be of the form:

$$\sigma = \sigma_0 \times \left(1 - \frac{T}{T_c}\right)^n$$

where: T is the absolute temperature, T_c is the critical temperature at which σ vanishes, and σ_0 and n are constants for each liquid. A typical value of n is 1,2. It is seen, from the previous equation, that σ decreases with increasing temperature, becoming zero at $T=T_c$.

4.5. Influence of the air in the experiment

The approximation that soap films are 2D is appropriate, however damping effect of the surrounding air on the development of turbulent vortices can be considerable at times. This can add to the damping effects on the films internal viscosity and complicate the determination of the *Reynolds number* which is essential for the understanding of the flow condition. If the air drag becomes substantial the flow can no longer be considered consistent with the *Navier-Stokes*

equations. There are ways to reduce the influence of air drag on the film, the use of slow moving and thicker films, rather than thinner and fast moving ones can reduce this effect. An extremely effective but expensive method for eliminating the influence of air drag is to enclose the apparatus in a vacuum chamber. Soap films are also relatively inexpensive and easy to implement in experiment without high precisions of measurement.

4.6. Soap solutions for films and bubbles (how long do they last?)

The similarity between the structure and behaviour of lipids and soaps has led to a resurgence of interest in the properties of soap molecules. The lifetime of pure soap films and bubbles is sensitive to the presence of impurities, dust particles, excess caustic alkali or excess fat. Consequently, special care is necessary in the preparation of pure soap solutions and the subsequent formation of films and bubbles. The stability and lifetime of films and bubbles are affected by the evaporation of water from the surface, the humidity of the surroundings, air currents, shocks and vibrations. Carbon dioxide in the atmosphere also diminishes the life of soap films. These factors can be eliminated by controlling the environment of the film or bubble. The pure soap film in a controlled environment should last indefinitely but bubbles contain gas at pressure higher than the environmental pressure. This gas will effuse through the bubble once the bubble has thinned significantly, with the result that the diameter of the bubble will decrease with time. The effect is greatest for the smallest bubbles which contain gas at the greatest excess pressure.

4.6.1. Longest lasting bubbles

Sir James Dewar produced a bubble of diameter 32 cm in a controlled environment which he kept for 108 days. During this period the diameter decreased by a few centimetres due to effusion. He also produced a disc of soap film, 19 Cm in diameter, which he kept for over three years. More recently Cook and Kuehner have described solutions that are particularly good for this purpose. Kuehner has obtained 20 cm diameter bubbles that last for 102 minutes in the open air.

4.7. Interference Phenomena Produced by Soap Films

Soap films and soap bubbles produce monochromatic interference fringes when exposed to monochromatic light and coloured fringes on exposure to white light. These interference phenomena occur when the thickness of the soap film is comparable to the wavelength of visible light.

A ray of monochromatic light striking the film is split into two rays. One of those rays results from reflection at the film surface and constitutes about 4% of the incident intensity. The other ray, which constitutes about 96% of the incident intensity, is refracted into the film. About 4% of the intensity of this refracted ray is internally reflected at the second face of the film and the remaining 96% cent is transmitted by the film. The ray reflected at the second face of the film is finally refracted at the first face of the film and emerges from the film in a direction parallel to the ray reflected from the first face. These two rays will have approximately equal intensity but differ in optical path length.

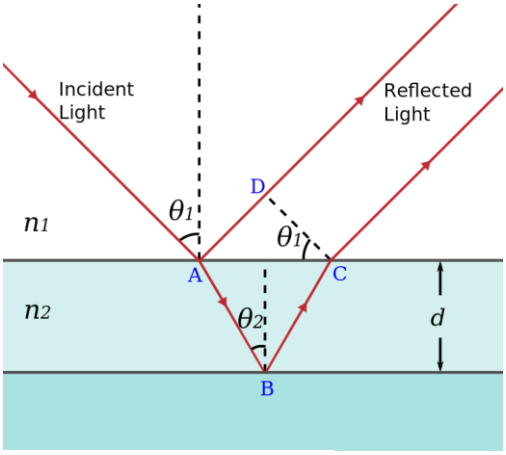

Figure 6 Interference phenomena

The former ray will suffer an optical path change of *(1/2) λ*, where *λ is* the wavelength of the light, due to the phase change of π on reflection from the first face of the film, which is the medium of higher refractive index. The latter ray will have an additional path length due to the additional path in the film and no phase change due to reflection at the second face. The two parallel rays will interfere. All incident rays on the film at the same horizontal level will interfere with the same phase, and path difference between the two split rays. Interference by incident rays at different vertical film heights will have different phase differences.

We obtain bright horizontal bands due to constructive interference. This occurs when the phase difference between the split rays is a multiple of 2Π. Dark horizontal bands, due to destructive interference, occur when the phase difference between the split rays is an odd multiple of Π.

The film eventually reaches an equilibrium thickness in which both faces of the film are parallel. In this state there is no variation in intensity over the surface of the film. This is called the common black film. It occurs, typically, at a thickness of 300A (30nm). A further decrease in the film thickness, to another stable equilibrium state with a thickness of about 50A, is often possible and is known as the Newton black film. Some films have only one equilibrium state, while others have two or more equilibrium states.

The intensity of a light beam, *I*, reflected from a soap film of refractive index μ, thickness *t*, for an angle of refraction ϑ, and a wavelength of the light λ; is given by:

$$I = I_0 \sin^2\left(\frac{2\pi\mu t}{\lambda}\cos\theta\right)$$

In order to study the interference produced by reflection and transmission from a soap film it is advisable to keep the film in a controlled environment in order to prevent the film rupturing. When a soap film finally ruptures it will break up into many small droplets. Most of the energy of the film is converted into kinetic energy of the droplets. This produces droplets with typical velocities of the order of 10^3 cm/s

From the relation between the thickness of the film and the intensity of the light reflected, it is possible to perform an experiment in order to relate the thickness with the colour that it is seen by the human eye. Extracted from another experiment, the relation is in such a way as follows:

First Order	Thickness in Å
Black	60
Silvery White	120
	—
Amber	—
Magenta	2010
Second Order	
Violet	2160
Blue	2500
Green	2900
Yellow	3220
Orange	3480
Crimson	3710
Third Order	
Purple	3960
Blue	4100
Blue	4280
Emerald Green	4660
Yellow Green	5020
Carmine	5420
Bluish Red	5780

Fourth Order	Thickness in Å
Grass Green	5970
Green	6340
Yellow Green	6820
Carmine	7460
Fifth Order	
Green	7900
Green	8420
Pink	8930
Pink	9450
Sixth Order	
Green	10000
Green	10440
Pink	11000
Pink	11500
Seventh Order	
Green	12100
Green	12650
Pink	13150
Pink	13700
Eighth Order	
Green	14200
Pink	15000

Figure 7 Light intensity - film thickness relationship table

5. STUDYING OF THE SOAP FILM MIXTURE

5.1. Type of mixture

This step is only a basic analysis of the mixture that we are using taking into account the percentages that we are using of each of the components of the mixture. First of all, we can say and classify our mixture as:

- Homogeneous: the components cannot be differentiated by eye.
- Liquid

If fact, it is a homogeneous mixture of liquids, which is called: solution. The solutions are formed by two or more substances which are physically different and which are distributed in different percentages in the mixture. A solution has always both a solute and solvent present. The solvent is the element that has a higher proportion in the mixture and usually it is liquid, in our mixture, the solvent is the water; on the other hand, the solute are the other elements present in the mixture, in our case, the solvent are the glycerine and the dish liquid (brand name: Fairy)

5.2. Actual composition of our mixture

In the mixture we have the following components:

- Volume of water = 91,32 % of the total volume
- Volume of dish liquid = 6,85 % of the total volume
- Volume of glycerine = 1,83 % of the total volume

With the information given from this contribution of each component to the final volume of the mixture, it is expected that most of the properties of our fluid are extremely near and related with the properties of the water. Each of the components have different contributions to the mixture: the water is the main component, the dish liquid creates the soap film and the glycerine increases the lifetime of the soap film.

5.3. Measuring density and temperature of the mixture and of the tap water

The density of our mixture can be approximated as the density of the water that we use in order to produce the mixture due to the proportions.

In order to perform the measurement we are using a densimeter. This equipment is able to measure at the same time the density (ρ) and the temperature of a fluid. The comparison between the theoretical and the practical values takes into account that the theoretical is done at 20°C and this

change in the temperature of the measurement can affect the precision of the measurement. The results obtained are the following

$$\rho_{mixture} = 1.007 \ \ Kg/l$$

$$\rho_{water} = 0.999 \ Kg/l$$

$$T_{mixture} = 26.8 \ ℃$$

$$T_{water} = 21.4 \ ℃$$

The temperatures are relatively close to 20°C, so that we consider that the measurements of the density are correct for our experiment.

5.4. Measuring the viscosity of our mixture

For measuring the viscosity we are only going to explain just the final method that has been used and in the appendix we include the other methods and the reasons why those were not used. (Appendix I: "Methods for measuring the viscosity of our mixture")

5.4.1. Method 5: Capillarity experiment in order to determine the viscosity

The final method used in order to measure the viscosity of our mixture is based on an experiment dealing with the capillarity, the measurement is made by making the mixture to pass through a capillary tube of radius *r* and a capillary element with a defined volume *V*.

Figure 8 Capillarity experiment setup

5.4.1.1. The equipment

The equipment used for this experiment is:

- Petri's dish (Petri's plate)
- Capillarity tubes of different diameters
- Plastic tubes
- Valve
- Syringe
- Tube of an fixed volume with initial and final mark for making the time measurement

5.4.1.2. Procedure

The measurement is performed in two basic steps that can be repeated in order to make several measurements and be sure of the final result obtained. Those two steps can be explained in a fast way (the one in the report) and in a detail way (it is included in the Appendix I: "Methods for measuring the viscosity of our mixture")

First step

First we have to fill the tube by using the syringe in order to have enough fluid in the system for performing the measurements.

Second step

Finally, the circuit is opened so that the fluid turns down through our tube with the fixed volume and through the capillarity tube till it reaches the Petri's dish. The objective is to measure the time the fluid takes to run the initial to the final mark of our tube.

5.4.1.3. Corrected Hagen-Poiseuille equation

In the experiment we measure the running time. From this we calculate the viscosity as follows:

$$\mu = \frac{\pi\, r^4\, t\, \Delta P}{8\, V\, l} - \frac{1.12\, \rho\, V}{8\, \pi\, l\, t}$$

where we have the following parameters:

r → is the internal radius of the capillarity tubes (as we have two tubes, we will have two values that we will obtain by means of an object micrometre)

t → is the time measured in the experiment (as we will perform the experiment three times for each capillarity tube, we will use the mean value between the three measurements)

$\Delta P = \rho g \bar{h}$ → where we have that $\bar{h}$ is the mean value of the heights of the marks with respect to the free surface of the liquid in the Petri's dish.

$$\bar{h} = \frac{h_1 + h_2}{2}$$

we use this mean value because the height is a function of time

h_1 → is the difference in height between the free surface of the liquid and the initial reference (used to start the timer), when we have our tube full of the liquid

h_2 → is the difference in height between the free surface of the liquid and the final reference (used to finish the timer), when we have our tube empty and all the liquid is in the Petri's dish

V → is the volume that we have at the tube with fixed volume

l → is the length of the capillarity tube

5.4.1.4. Determination of the radius of the capillarity tubes

In order to perform the measurement of the radius, we have used an object micrometre, see Appendix I for more information.

As we obtained several values of the same diameter (because we have two measurements from each extreme), we can obtain a mean value for those diameters and the radius (with 2 significant decimals):

$$d_1 = 1.05\ mm$$

$$d_2 = 1.67\ mm$$

$$r_1 = 0.53\ mm$$
$$r_2 = 0.84\ mm$$

5.4.1.5. Results of the measurements

In this experiment we will obtain the time the liquid takes to run from the first to the second mark as the tube with a fixed volume. From those values we are going to obtain finally the viscosity (for further information, see the Appendix I: "Methods for measuring the viscosity of our mixture")

I Viscosity of the water

Solving the equation of the dynamic viscosity:

I.I Capillarity tube 1

$$\mu_1 = 1.035 \times 10^{-3}\ Kg/m \times s$$

I.II Capillarity tube 2

$$\mu_2 = 1.215 \times 10^{-3}\ Kg/m \times s$$

I.III Dynamic viscosity of the water at 20°C

$$\mu_{real} = 1.003 \times 10^{-3}\ Kg/m \times s$$

From those results we can conclude that the values that we obtained are quite good in relation with the value of the dynamic viscosity of the water measured with more precise instruments, so that the experiment is going to make us able to obtain the dynamic viscosity of our mixture with a quite accurate value.

II Viscosity of the soap mixture

Solving the equation of the dynamic viscosity:

I.IV Capillarity tube 1

$$\mu_1 = 1.256 \times 10^{-3}\ Kg/m \times s$$

I.V Capillarity tube 2

$$\mu_2 = 1.215 \times 10^{-3}\ Kg/m \times s$$

From those results we can conclude that the values that we obtained are quite near so that we can perform a mean value between both which will be the value that we will consider as the dynamic viscosity of our mixture.

$$\mu_{mixture} = 1.236 \times 10^{-3}\ Kg/m \times s$$

5.5. Determination of the refractive index of our mixture

The determination of the refractive index of our mixture has been made by means of a laboratory experiment. Before performing the experiment, due to the high content of water in our mixture, we can assume that the value of the index would be close to the value of this parameter for water

(which is $n_{water} = 1.33$ using withe light); nevertheless we have developed an experiment in order to check this supposition.

5.5.1. Materials required

- Convex lens
- Mixture that produces the soap
- Plane mirror
- Retort stand
- Pointer
- Meter scale

5.5.2. Procedure

The experiment deals with four different steps in order to find the parameters needed to determine the refractive index of our mixture.

1. Determine the focal length of the convex lens (f_1)
2. Determine the focal length of the combination of convex lens and liquid lens (F) and the focal length of only the liquid lens (f_2)
3. Determine the radii of curvature of the lens (R)

   This radius of curvature of the lens has been determined by means of the use of a spherometer.

5.5.2.1. Spherometer

The spherometer is a device that can be used to determine the height of a lens, and from that value and the distances between the supports that form a equilateral triangle (the distance between two consecutive supports) we can obtain the radius of curvature of the lens.

$$R = \frac{a^2 + 3s^2}{6s}$$

where: a is the distance between two consecutive supports; s is the height determined by the spherometer.

$$R = 73.94\ mm$$

5.5.3. Results

The wavelength of the light used is very important in this experiment, in our case and in order to check the supposition we have made our measurements with white light.

$$f_1 = \frac{y_1 + y_2}{2}$$

$$F = \frac{y_1 + y_2}{2}$$

$$f_2 = \frac{F\, f_1}{f_1 - F}$$

Then for obtaining the refractive index we would have:

$$n_{mix} = 1 + \frac{R}{f_2}$$

$$n_{mix} = 1.3414$$

Refractive index of liquids varies from 1.33 (water) to 1.67 (mercury). This narrow range in the values of refractive index indicates that the variation in the velocity of light through liquids is small. Considering that our value, is almost equal to the one of the water, and taking into account that our mixed is made in a huge percentage of water, we can assume that our value is correct.

5.6. Determination of the surface tension of our mixture-air interface

Surface tension is the tendency of a fluid reducing its surface to a minimum. The surface tension is measured in the interfaces between two substances and in order to make the calculation we have used two different experiments, however, in this document we will only attach the results regarding the most accurate measurement. (See Appendix II: "Surface tension measurement" for further information)

5.6.1. Experiment using the ring method (Du Noüy method)

This experiment in comparison with the other that are explained in the Appendix II: "Surface tension measurement" uses a more precise equipment and for that, is the one selected in order to get as valid for our final result of the measurement. The materials used in order to perform the measurement are:

Figure 9 Surface tension measurement setup

- A ring
- Nylon thread
- Torsion dynamometer
- Beaker

The ring is attached to the torsion dynamometer which allow us to determine the value of the force that is needed in order to pull the ring out of the liquid where we submerged it. The surface tension can be calculated from the diameter of the ring and the tear-off force.

The measuring of the force is plotted in a graph, using a computer software that allow us to plot the force as a function of time. The curve is growing till a point where the force breaks down dramatically, after the fall the force is stabilised. This value after the stabilisation of the force is the weight of our ring, and the difference between the weight of the ring and the maximum force

measured by the apparatus before the breakdown, is the force needed to counterbalance the surface tension of the water upon the ring (in the table is shown as ΔF)

The surface tension is then obtained dividing the force measured by the doubled perimeter of the ring; the perimeter of the ring needs to be doubled since we have an outer and an inner surface.

$$\gamma = \frac{F}{Perimeter_{ring}} = \frac{F}{2\pi(r_i + r_a)} \approx \frac{F}{4\pi r_{innerfine}}$$

The data from the ring is:

$Mass_{ring} = 5\ g \rightarrow measured\ in\ a\ scale$

$Weight_{ring} = 52\ mN \rightarrow determined\ by\ the\ software$

$d_{outer} = 61\ mm$

$d_{innerfine} = 60\ mm$

$d_{innerthick} = 59\ mm$

$Inner\ perimeter_{ring} = 2 \times 2\pi r_{innerfine} = 18{,}85\ cm\ from\ its\ diameter\ measurements$

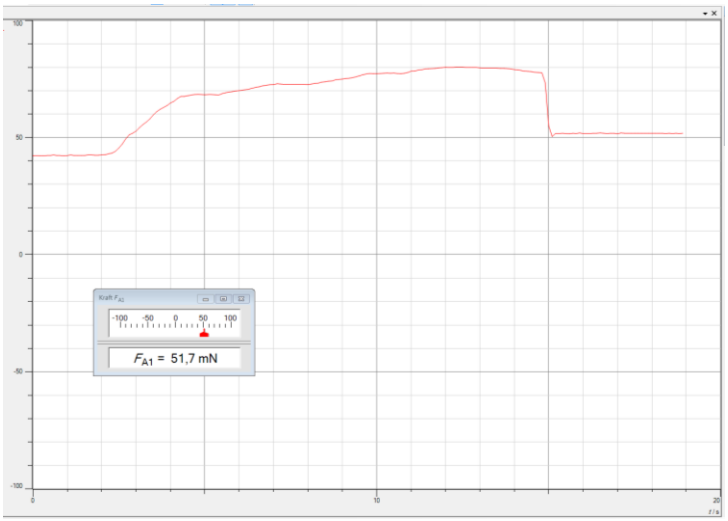

Figure 10 Surface tension experiment for the water

5.6.2. Checking of the experiment using water

First of all, in order to check how the experiment works, we are going to use water, because we know the values expected for its surface tension, and we can check if the experiment works correctly.

Nº of the attempt	Maximum force mN	Weight of the ring mN	ΔF mN	Surface tension mN/m	Expected surface tension mN/m
1	69,4	50,9	18.5	0,049	0,073
2	70,1	52,1	18	0,048	0,073
3	70,7	52,1	18.6	0,049	0,073
4	71,1	52,2	18.9	0,05	0,073
5	70,7	52,2	18.5	0,049	0,073

The result obtained for the water is not perfect in relation with the expected surface tension value, but it can be seen as a good approximation due to the small difference, about 0.03 mN.

5.6.3. Experiment using our mixture

Once we have checked the experiment we can make the measurement of the mixture using the same procedure as for water.

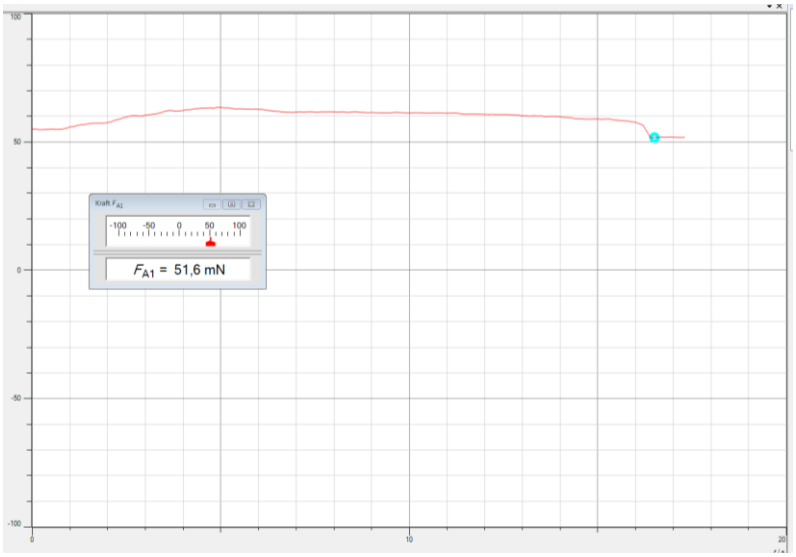

Figure 11 Surface tension experiment for the mixture

Nº of the attempt	Maximum force mN	Weight of the ring mN	ΔF mN	Force bubble generation mN	Surface tension mN/m
1	63,4	51,9	11.5	60,8	0,032
2	63,9	51,8	12.1	60,9	0,032
3	63,9	51,9	12	61,6	0,032
4	63,3	51,9	11.4	61,6	0,03
5	63,4	51,8	11.6	61,7	0,031

Then we can conclude that the value of the surface tension of our mixture is going to be approximately:

$$\gamma \approx 0{,}031\ mN/m$$

5.6.3.1. Special behaviour of the mixture during the experiment

The mixture has a different behaviour as the one that we can observed for the water. The mixture behaves as water till the point where the ring goes out of the free surface of the mixture, at that moment, the maximum force is obtained and a bubble is generated between the ring and the free surface. During the existence of the bubble, the force is stabilised till the point where the bubble is broken, then the graph drops dramatically till the final value of the force that is the value of the weight of the ring.

The diameter that is affecting the value of the surface tension is decreasing when the bubble is generated, as far as the diameter is no longer the diameter of the ring, but the contact diameter of the bubble that is in contact with the free surface of the mixture. This diameter can be estimated as far as the surface tension is constant because the interface is in every moment between the mixture and the air.

The consequence of this behaviour is that the force (and thus the surface tension) remains constant during the extraction of the ring, and while the bubble exists the surface tension can not be determined.

6. STUDYING OF OUR FALLING FILM SOAP FLOW

6.1. Materials used (in general)

In this project, we are going to use as initial materials those that are given from the previous two works on this concept. Also, we are going to add some other materials in order to obtain a better behaviour of the channel and different configurations and measurements. Then, we have already constructed the film soap flow channel completely, where we have the following elements:

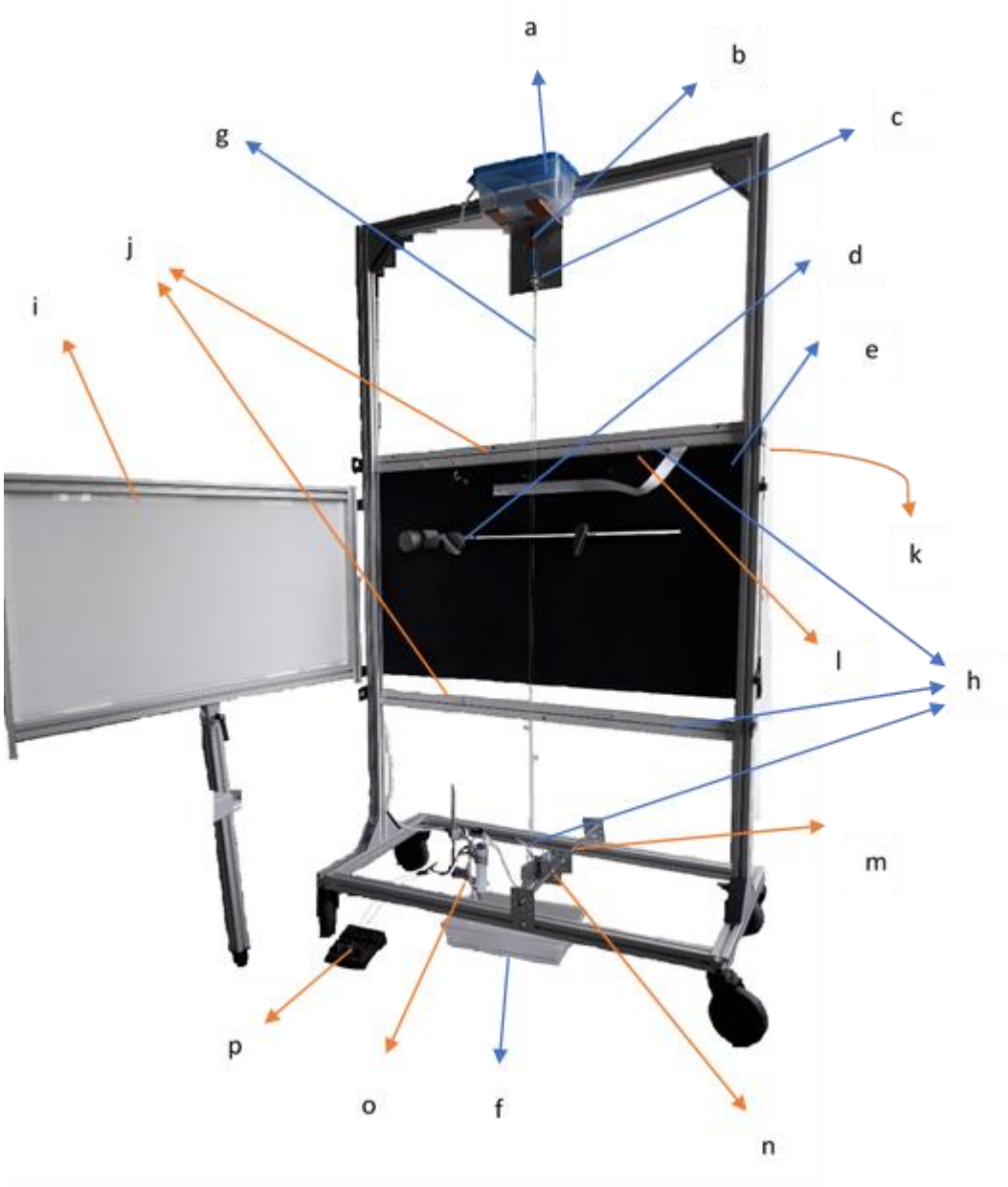

Figure 12 New channel design

a. Upper reservoir
b. Open-close valve (ON/OFF)
c. Regulation valve
d. Metallic elements
e. Black supporting element
f. Lower reservoir
g. Guide strings (yellow nylon strings) → used for guiding the soap
h. Pull strings (white nylon strings) → used for controlling the opening and subjecting the ring
i. Lighting system
j. White composite supporting beams
k. Backward hooks
l. Frontal hooks
m. Fastening element for avoiding oscillations of the bronze ring
n. Bronze ring
o. Recirculation system (pump, silicone pipes and syringe)
p. DC power supply

Including those materials, we have also some laboratory and mechanical elements and stuff to produce the mixtures and the final product of our project (the final mixture that we have to work with) and to perform the different measurements:

- Testing tubes
- Flasks
- Thermometer
- Densimeter

6.2. Analysis of the vertical falling film flow

6.2.1. Flow control

The control of the flow is made by means of the use of two valves. The *open-close valve*, which is positioned on a higher position and that we called *the open-close valve*, is used for allowing or not the flow, it has two working positions, ON or OFF. On the other hand, the *regulation valve*, which is called *the regulation valve* must be used at specific positions that allow us to obtain different flow rates, behaving in that way as a flow control valve.

The geometry of the channel can be explained using the previous years' works, in that sense and using our new modifications, we will be able to explain it properly in the future.

As an important point, we can explain that the different colours that are seen in the channel are not the real flow of the soap, those different colours are related with the different thicknesses of the channel at different positions and the angle of the light that gets through our channel.

In summary from the explanation that we will see in the film thickness analysis, there is an influence between the film thickness and the force that produces the drainage of the film, and from the film thickness and the velocity of the soap in the channel although the colours observed are not exactly the real flowing paths of the soap.

However, if (parts of) the observed thickness field associated with a soap film flow rotates like a vortex, say, we can trust that a rotating vortex indeed exists in the two-dimensional flow of the soap film although it does not have the same path as the one that we can see with the colours.

6.2.2. Determination of the flow rate

Further information in: "Appendix III: "Methods for measuring the flow rate""

6.2.2.1. Final result of the measurement of the flow rate

I Through the open-close valve

Using the usual measurements for the mixture, which allows us to obtain a final product with 1.095L (with 1 L of water, 0.020 L of glycerine, and 0.075 L of Fairy Ultra). Once we have made the mixture, we can perform the measurement to obtain the value of the flow rate.

1. Prepare the mixture
2. Let the mixture flow during a determined period of time (only through the *open-close valve*)
3. Measure the amount of mixture that flows
4. Determine the flow rate in m^3/h and $\mu L/s$

Only with the behaviour of the mixture flowing through first valve, we can measure the flow rate for a determined period of time. (Without considering the *regulation valve, which* modifies the flow rate of the system). Using this principle, we obtain the following values (we consider 10 seconds as our reference time for the measurement):

Nº of the attempt	Exact extraction time s	Volume of the mixture mL	Flow rate m^3/h	Flow rate µL/s
1	10.30	51	0.02	4951.46
2	9.88	49	0.02	4959.51
3	10.06	49	0.02	4870.78
4	10.20	48	0.02	4705.88
5	10.07	48	0.02	4766.63
6	10.08	44	0.02	4365.08
7	10.40	10	0.01	961.54

Conversions that we have to make:

$$v = \frac{Q}{Section}$$

$$Section = \frac{\pi}{4} * d^2$$

The diameter used there will be the diameter of the nozzle, which we know that is about: 2-2.5 mm. And the nozzle has a circular shape, due to that we must use this equation for obtaining its section.

As we can see in the theoretical calculation of the flow rate (Appendix III "Methods for measuring the flow rate"), the flow rate depends on the pressure head of the fluid in the upper reservoir. When the upper reservoir has less mixture, the pressure head diminishes and the flow rate is also lower.

II Through the regulation valve

The second valve is used, as we already know, to regulate the flow rate of the mixture through the nozzle. In order to check it, we will obtain the values of the flow rate measured as a function of the number of turns of this regulation valve. The turns start with the *regulation valve* completely closed, and the turns are opening the valve.

NOTE: In this experiment we maintain more or less constant the height of the mixture in the reservoir in order to have at every moment stationary flow and do not have great variations in the result due to variations in height between the measurements:

Number of turns	Time measured s	Volume measured mL	Flow rate µL/s
6	164,8	11	66,75
7	121,3	10	88,44
8	82,6	10	121,07
9	65,8	10	151,98
14	34,4	32	930,23
15	36,2	40	1104,97
16	37,8	52	1375,66
17	33,4	53	1586,83
18	26,7	52	1947,57
19	30,4	60	1973,68
20	22,3	46	2062,78
22	27,2	57	2095,6

As we can see, as far as we open the valve, the flow is increasing as it was expected.

For 12 turns, that is the number of turns used in the last year construction, we have performed several measurements in order to give a more precise value:

Time measured s	Volume measured mL	Flow rate µL/s
24,7	11,2	445,34
28,4	12,1	422,53
26,5	11,5	433,96

The mean value will be:

$$Q_{12\ turns\ of\ the\ regulation\ valve} = 433{,}95\ \mu L/s$$

The value obtained is different from the one obtained in the previous year, but there is an important reason: the flow rate changes as a function of the height of the mixture in the upper reservoir (as it is explained in the Appendix III). Then, if you measure the flow rate from the reservoir since it is full until it is empty, the flow rate that you will obtain will be an average of the flow rate along this time.

From the **theoretical calculation of the flow rate** we obtained the following **conclusion:**

Finally, we can say (as we obtained from the measurements), that the velocity and the flow rate of the fluid depends on the height of the fluid in the reservoir which changes with time.

6.2.3. Channel geometry

The dimensions of the channel are:

$$h_{channel} = 137{,}8\ mm$$

$$w_{channel\ short\ hooks} = 10{,}3\ mm$$

$$w_{channel\ medium\ hooks} = 22{,}7\ mm$$

$$w_{channel\ long\ hooks} = 38{,}1\ mm$$

6.2.4. Stationary flow?

Comparison between the flow variation with the deposit full with 1.095 L of mixture and when the mixture has been poured

The condition in order to have stationary flow deals with the variation between the maximum and the minimum values in the flow that we measure. As we have demonstrated, the value of the flow decreases with the height of the mixture in the reservoir, then we can obtain the value of this variation and the percentage of the variation to know if we can assume the flow as stationary or not.

Using the maximum velocity (at the highest position of the mixture in the reservoir) and the minimum one (at the lowest position of the mixture of the reservoir) we would have:

$$\%\ difference = \frac{Q_{min} - Q_{max}}{Q_{max}} \times 100\ \% = \frac{961{,}54 - 4959{,}51}{4959{,}51} \times 100\ \% = -80{,}61\ \%$$

The flow has a great variation, so that we cannot assume that the flow is stationary during the whole experiment. Nevertheless, maybe we can say that the flow is stationary if we stop the

measurement a few seconds before the reservoir is empty (when we have poured much more than the half of the mixture), in this situation we would have the following difference:

$$\%\ difference = \frac{4365{,}08 - 4959{,}51}{4959{,}51} \times 100\ \% = -11{,}99\ \%$$

In that case, we can assume that the flow is stationary in this experiment till some seconds before the reservoir is getting completely empty.

6.2.5. Effective viscosity of a soap film

Typically, the flow of a *Newtonian fluid* is characterised by the *Reynolds number*, which has the fluid viscosity as a key parameter.

The effective kinematic viscosity is commonly expressed as follows: (using the formula developed by Trapeznikov in 1957)

$$\nu_e = \nu_b + 2\frac{\nu_s}{h}$$

h is the thickness of the soap film and it is determined with different methods that we will analyse later.

The effective viscosity of the soap film is therefore comprised by the viscosity of the interstitial fluid layer ν_b and the contributions from the two fluid-air interfaces ν_s.

For thick films, the bulk contribution ν_b is the dominant value, whereas for thin films the terms that account for the surface will dominate ν_s. Generally ν_b is taken as the viscosity of water whereas ν_s depends on the chemical components in the soap.

6.2.5.1. In our experiment

In our experiment, the film thickness has great variations, then we will obtain results more related to the viscosity of water and also some results are related with the viscosity of our mixture and also bigger depending on the values of our thickness. As the results in the thickness measurements are not really accurate, neither will be our values for the effective viscosity.

We have used different experiments for determining the film thickness (see chapter 7: “Thickness measurement”, which is the reason why we obtained different values for the effective viscosity of our mixture. First of all we are going to take as references the theoretical viscosity of water and the practical one for the mixture from chapter 5: “Studying of the soap film mixture”:

$$\upsilon_b = \upsilon_{water} = 1{,}0034\ mm^2/s$$

$$\upsilon_s = \upsilon_{mixture} = \frac{\mu_{mixture}}{\rho_{mixture}} = \frac{1{,}236 \times 10^{-3}\ Kg/m \times s}{1007\ Kg/m^3} = 1{,}2274\, mm^2/s$$

I Experiment 1: Light reflection

I.I Measurement with the metal piece separated from the film

$$h = 1133{,}51\ \pm 923.53\ \mu m$$

$$\nu_{emin} = 2{,}20\ mm^2/s$$

$$\nu_{emax} = 12{,}69\ mm^2/s$$

I.II Measurement with the metal piece next to the film

$$h = 562{,}7\ \pm 923.53\ \mu m$$

$$\nu_{emin} = Not\ a\ reasonable\ value$$

$$\nu_{emax} = 2{,}66\ mm^2/s$$

II Experiment 2: Quick closing valve method

In this case we can use the maximum and the minimum values obtained in the measurement:

$$h_{min} = 680{,}77\ \mu m$$

$$h_{max} = 994{,}97\ \mu m$$

$$\nu_{emin} = 3{,}47\ mm^2/s$$

$$\nu_{emax} = 4{,}61\ mm^2/s$$

As we can see from an easy comparison between the values obtained for the mixture with our previous data and from our thickness measurements, the measurements of the thickness are not really accurate and we can not consider any of the values obtained as the real one.

6.3. Modifications of the channel

6.3.1. Adding the lights

The previous lighting system was not powerful enough in order to allow the visualization of the vortexes that are created due to the thicknesses changes in the channel. The improvement of the visualization is made by means of the use of new LED lights that are able to change the colour and allow us to see the film using a monochromatic light.

Monochromatic light over the film

Figure 13 Red monochromatic light over the film

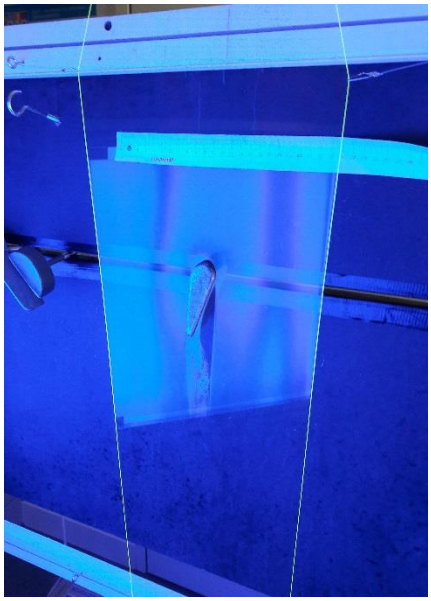

Figure 14 Blue monochromatic light over the film

The use of the monochromatic light allows to see only dark and bright lines over the film, which allows to improve the visualization of the different layers of the film. The performance of all the colours is not the same, and after analysing the performance of all the possible colours we have selected the red and the blue monochromatic lights as the best ones in order to see the behaviour of the film.

6.3.2. Substitutions in the lower part of the channel

At the beginning of the year, the tight behaviour of the channel was produced by means of the weight of a stone that was placed in the lower part of the channel; however, as it is an extremely rudimentary element and because of some problems that we will enumerate in the following list, we have thought about some alternatives to modify this part of the channel.

6.3.2.1. Problems that generate the stone and its solutions

- **Oscillation and breakage of the soap film:** when the strings are quickly separated to produce the soap film, an oscillation of the stone can be produced, which creates a problem as far as an instability in the soap film is created and this instability can break the soap film.
- **The stone does not allow the exact measurement of the flow rate or the recirculation:** due to its position, in the lower part of our channel, the flow of the mixture once it goes out of the space between both strings, reaches the stone and impacts against it. This makes possible that some part of the mixture is absorbed by the stone and it makes not possible to pick the whole amount of fluid (to make the measurement of the flow rate and the recirculation of our channel).

Our initial objective was to avoid the oscillation of the channel as well as improving the measurement of the flow rate and allowing the recirculation of our mixture. The ideas deal with the use of a fastening element (could be a bigger cylinder or an element made by beams), and adding a new and smaller weight element, that finally will be a ring.

6.3.2.2. Substitution of the stone by a bronze ring

In order to avoid the oscillation of the bronze ring, we have two main options:

- Fixing the ring in between of beams that will be attached to the main structure of the channel.
- Introducing our cylinder into a higher diameter cylinder which is going to be in the floor. In that way, it is not going to be possible to oscillate a lot in any direction, and we will be able to make the recirculation from that second reservoir to the upper one.

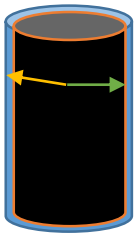

Figure 15 Initial design for the supporting cylinder

The only problem that may appear from this method is that the bigger cylinder cannot be fixed at the ground (because we want our system to be mobile), then we will need to positioned it at the beginning of the experiment.

As far as we want to use our actual collecting reservoir because it is transparent and allow us to control the amount of mixture in the lower part, we will use the first option. This solution will be explained in the next pages.

I Theoretical calculations

For the selection of the material of our ring has been considered the materials that were available in the workshop; we have selected an element made by bronze. The determination of the characteristics of the ring has been made considering the properties of the stone, mainly it's mass.

$$m_{stone} = 0{,}28\ Kg$$

The initial bronze cylinder has the following characteristics:

$$Initial\ length = 120\ mm$$

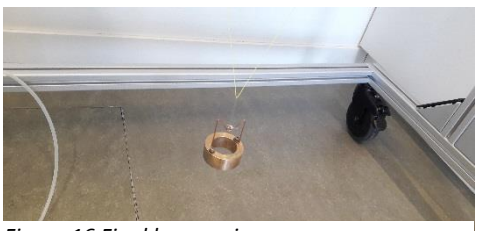

Figure 16 Final bronze ring

$$Initial\ weight = 1{,}085\ Kg$$

The objective is to obtain the final weight that is needed that is about *0,28 Kg*, and for that considering the density of bronze, we should cut the ring up to a length of:

$$Final\ length = 22\ mm$$

Finally, our element used for making the substitution of the stone will be made of bronze. This element will allow the dropping of the soap film and its recirculation because, as it is a hollow cylinder, the drops will go through it.

II Final result

The element made of bronze will be the one attached to our channel. In order to join it to the strings, we have used two screws and a filament for joining by means of the nylon thread.

The final value of the mass is about *0,287 Kg* due to those elements that we have to add to our bronze ring in order to attach it to the main structure.

6.3.2.3. Fastening element for avoiding oscillation

The fastening of our bronze ring will be done by using a new structure which is attached to the main construction of our project by means of screws. Using different designs and configurations, we have finally reached a good solution for this part of the channel, taking into account the following considerations:

This fastening element must be at a correct height in order to be able to control the oscillation of the ring in the different opening positions of the channel; the fastening element works as a wall, as far as it does not allow the movement of the ring in three directions due to its “V-shape”, making possible the crashes with the ring which diminish its oscillations.

I Components

The fastening element is made by three different parts:

- Plane sheet metal plates: are used to attach the fastening element to the main structure using screws.
- Screwed axis: main element that goes through all the others in order to join them using the nuts.
- Nuts: are the elements that fix the part to the axis using the existing pressure between 2 nuts.
- Fastening part:
    - The “U-shape” sheet metal plate that joins the V-shape element to the axis
    - The “V-shape” sheet metal plate that crashes with the ring in order to avoid its oscillations.

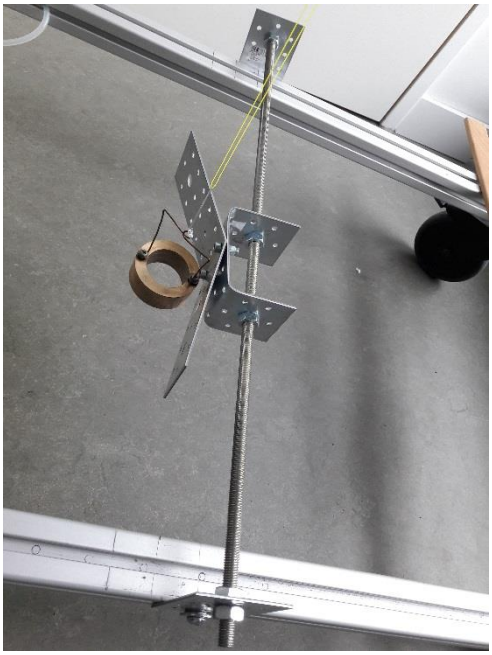

Figure 17 Fastening element for our bronze ring

6.3.3. Recirculation of the soap mixture

The analysis of the recirculation of our soap film channel has been one of the most difficult parts of the project. In order to explain its analysis, we are going to start with a little of theory that deals with the way of doing the recirculation in those types of channels.

6.3.3.1. Objective and conditions of the recirculation

The main objective of the recirculation of the flow of our film is to pick the soap that we obtain at the end of the film and put it again in the upper deposit by means of a circuit that must include a pump and some pipes of small diameter.

Recirculation saves potentially costly particles introduced into the solution for flow tracking, allows for runs of extended length with an essentially unlimited supply of solution, and can maintain a constant pressure head to eliminate changes in the mean velocity caused by a reduction in the amount of solution in the upper reservoir.

6.3.3.2. Materials that allow a better performance

The recirculation has better results when we use some kinds of pumps: gear pumps and/or diaphragm pumps. In our case the pump is a gear pump.

Prolonged recirculation will lead to a thickening of the mixture as some evaporation occurs from the surface of the film, and can cause a buildup of dust and other contaminants.

It has been demonstrated that the use of certain plastic or rubber types of tubing can, over time, release substances into the solution which causes it to turn turbid, and the film to rupture

incessantly it is better to use a system of pyrex containment vessels, teflon and silicone tubing. Main recommendation: use of inert materials

In our case the pump is a gear pump and the tubing system is made by means of silicone tubes of small diameter in order to reduce the head pressure needed by the pump.

6.3.3.3. Theoretical analysis of the circuit needed

Using the energy equation between the point 1 (the free surface of the mixture in the outer cylinder) and the point 2 (the free surface of the mixture in the reservoir), we are able to obtain the following relation between the power, the flow rate and the height of the pump (that in this case is equal to the difference in height between points 1 and 2):

$$Power_{minimum\ needed\ by\ the\ pump\ for\ affording\ the\ head\ difference} = \rho g \left(z_2 - z_1 + \sum h_{losses} \right)$$

And the power needed from the power supply must take into consideration the efficiency of the pump, the efficiency of the power supply, and the efficiency of the transmission between them.

$$Power_{power\ supply} = \frac{Power\ min.needed\ by\ th\ pump\ for\ affording\ the\ head\ difference}{\eta_{pump} \times \eta_{power\ supply} \times \eta_{transmission}}$$

6.3.3.4. Construction of our recirculation circuit

I Welding the materials

First, in the construction of the recirculating circuit will take place the welding of the materials that we need. Using an electronic board, we will join the motor to the power supplier (as an initial construction in order to be able to add some other elements or devices later). Using a welding of tin, we can join the elements all together.

Figure 18 Welding materials

II Joining the materials to our prototype

The recirculation system for our design will be constructed by means of a long line of transparent silicone tube that will join the lower reservoir in order to pick all the mixture after the film is created, the pump and the power supply that allow the recirculation, the syringe that controls the head pressure (only used in the final configuration with the second pump), the recirculation valve and the upper reservoir. The silicone tubes will be attached to the basic structure of our soap film flow channel, so that we can give them a certain position and we can hide them in order not to be seen from a frontal positon with respect to our channel.

III Calculating the parameters of our recirculating system

Finally, on this analysis, the objective is to obtain a recirculating system that makes us possible to have a non-stop loop of constant flowing soap along the film with a constant flow rate. For that, we want to obtain the same flow rate for the recirculating system as the one that we have on the pouring system (notice that the flow rate at the reservoir is almost constant till it is getting empty, so we can have stationary flow in our film).

In order to obtain the parameters of our recirculating system, we can perform different measurements and we can obtain it in different ways. In this document we will only include the final attempt with the correct pump, measuring the recirculation rates directly in our channel (in order to see the other three attempts with the first pump that finally broke, see Appendix IV: "Modifications in the channel" for further information)

6.3.3.5. Analysis of the recirculation with the second pump

The experience with the first pump was good in order to use only the experimental analysis with the second pump. Using this second pump, the objective, the parameters and the controlling elements are similar than the ones used with the previous pump. The only difference is that with this second pump we use a syringe as another controlling parameter of our recirculation system.

The parameters are the voltage given by the power supply, the number of turns of the valve that is attached to the recirculation pipe, the initial volume in the lower reservoir (which is always between 750 mL and 1 L), and in this case the new parameter is the final volume in the syringe when the recirculation is already working. The syringe ads pressure to the system in order to make easier the work of the pump.

This system is more difficult to control than the previous one, which is the reason why we have not achieved as good results as for the other. Nevertheless, the recirculation is enough in order to have the channel running during several hours.

In the following table, we are going to show the results obtained and the conditions needed for the recirculation:

Voltage V	Nº of turns	Final syringe volume mL	Volume mL	Time s	Flow rate recir mL/s	Flow rate "medium" mL/s
4	0	18	138	177,5	**0,78**	**0,44**
4	0	19	40	60,6	**0,66**	**0,44**
4	3,5	27	73,6	136,5	**0,54**	**0,44**
4	3,75	18	49	132,7	**0,37**	**0,44**
4	4	18	42,4	120,2	**0,35**	**0,44**

From 0 to 3.5 turns, the difference notice in the results is really low as far as the pipe is completely open till we reach 3,5 turns in the controlling valve. The *orange values* are correct in order to perform the recirculation using the medium configuration and allow a good behaviour of the channel during several hours.

I Procedure in order to have a correct recirculation

This new design of the recirculation system has the following basic steps:

1. Connect the inlet and outlet points of the pump to the inlet and outlet pipes.
2. Fill the syringe with our mixture and run the pump at 4 V
3. Connect the syringe to the optional vent of the pump
4. Introduce the mixture that is in the syringe in the system till the syringe has only a volume of about 20 mL

IMPORTANT NOTE: The recirculation system must be cleaned after each used, connecting the whole system and using it with water in order to clean the silicone pipes, the syringe and the pump.

6.4. New working positions

The basic idea of this modification is to have different widths in our channel in order to see the different behaviours of the channel in those positions and different colours in the film. Those positions are going to be called as: "*short*", "*medium*", "*long*". We have attached some new hooks at the backward of the channel in order to have three different working positions instead of only one as we had before.

In order to obtain a more symmetric behaviour of our channel we have made some modifications that are explained now:

- Same length in the four *pull strings* (white nylon strings) attached to the *guide strings*.
- Same height for the position of the black elements that support the strings: those elements are positioned at 119 mm from the lower supporting beam.
- New hooks and the same distances for the *hooks* in the *backwards* of the channel (that means that we have the same widths at both sides from the centre of the channel)
- Same position of the pins that connect the *pull strings* (white nylon strings) with the *guide strings* (yellow nylon strings) by using the *white composite supporting beams*

IMPORTANT: the pull strings (white nylon strings) that go behind must go through the frontal hooks in order to reach the backward part of the channel and once they are at the backwards of the channel, they must go below the black supporting element in order to have correct values of the opening of the channel

Controlling geometry elements

The objective of those elements is to maintain a fixed position of the safety pins along the yellow strings. Those elements have two main parts:

- White composite supporting beams (wood): is fixed to the main structure of the channel by two screws and is the support for the hooks.

- Frontal hooks: are attached to the composite supporting beams to be used as guide for the pull strings.

Design modifications

For each of the three possible working positions we are going to analyse some parameters concerning its correct functioning:

- Working values
  - Position of the *backward hooks* of the channel measured from the backward edges (symmetric)
  - Number of turns of the *regulation valve* to create the film
- Recirculation values
  - Parameters needed in the pump controlling system for allowing the recirculation
- Correct subjection of the bronze ring with the fastening element used to avoid oscillations

Positions	Working values	Working values	Recirculation values	Correct subjection
Subjection used with the backward hooks	Position of the hooks (mm)	Number of turns of the regulation valve		With the fastening element
Short	17	6	It lasts about 4 hours and 10 min. without recirculation	Yes
Medium	27.2	12	$V_{lower} \approx 750$ mL Voltage ≈ 4 V Turns ≈ 3,5 or 3,75	Yes
Long	38.6	14	$V_{lower} \approx 750$ mL Voltage ≈ 4 V Turns ≈ 0	No (too tight strings create correct subjection)

7. THICKNESS MEASUREMENT

7.1. Draining and thinning of soap films

A freshly formed soap film contained by a frame will, typically, have a thickness of the order of a micron (10^3 nm, 10^4 Å), but it may exceed this value by as much as a factor of a hundred. Once formed the film will commence to drain. Mechanisms such as convection, evaporation, and suction produced by pressure gradients, will cause water to drain out of the film and result in the thinning of the film.

If the film does not rupture these draining processes will continue until the thickness of the film has reached an equilibrium value. This is typically in the range 50 A o 300 A, which is the regime of destructive interference and blackening of the film when viewed by reflected light.

A freshly formed surface of a soap film reaches its equilibrium shape in the order of seconds. However, the thickness of the film reaches its equilibrium value in a time that is orders of magnitude greater than that for the surface. For the fastest draining films, of low surface viscosity, this will be minutes whilst films of high surface viscosity will take hours to drain to their equilibrium thickness.

If white light is used the interference pattern produced by the cumulative effect of interference, from each wavelength constituting white light, will give rise to colours in the film. The colour of each region of the film will be determined by its thickness. Consequently, the thickness of the film at any point can be determined from the colour of the film. The variation of thickness over the whole film, at any time, can be mapped from the colours in the film. This variation in thickness, over the surface of the film, as a function of time enables information concerning the draining and thinning mechanisms to be deduced.

7.2. Measuring the thickness of the film

7.2.1. Description of the experiments for measuring using light reflection

This procedure for measuring the thickness of the layer is based on obtaining the difference in length between the reflections of a narrow light point either in the layer and in a metal sheet positioned behind the film.

The method utilizes the well-established principle that some light is reflected from any surface, and that the angles of incidence and reflection are equal (both are angles of 45°). Parallel forward movement of the surface causes a proportional change in the position of the reflected beam. The position of the beam of light reflected from the surface will be likewise affected by introducing an interjacent flowing film of liquid.

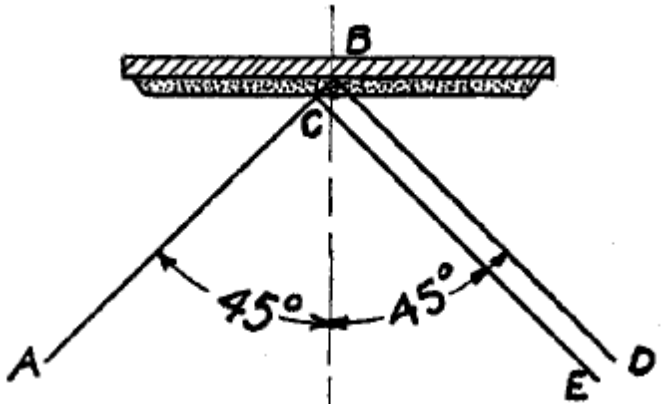

Figure 19 Reflection of the light in the film

For this first experiment, we are going to use two different configurations: with the metal piece separated from the film and with the metal piece next to the film (almost touching each other). In the main report, we are just going to display the results obtained in both experiments, consult Appendix V "Thickness measurement" for further information.

NOTE: These measurements were all performed for the medium aperture of the channel with its working parameters

7.2.1.1. Results of the measurement with the metal piece separated from the film

Then the final approximate value of the thickness is:

$$h = 1133{,}51 \pm 923.53\ \mu m$$

7.2.1.2. Results of the measurement with the metal piece next to the film

Then the final approximate value of the thickness is:

$$h = 562{,}7 \pm 923.53\ \mu m$$

7.2.2. Description of the experiments using the "Quick closing valve method"

The liquid volume *V* is measured in a channel with length *L* by quickly closing valve at the start and moving the reservoir at the end of the length.

The mean film thickness $h = V\pi/DL$ is determined. The complexity of method consists of the realization of instantaneous and simultaneous closure of the valve and movement of the reservoir. It is usually assumed that the part of the liquid volume associated with liquid drops is negligible.

7.2.2.1. Results

In order to obtain more precise values of the measurement, we have performed it several times in order to have a more accurate result. The procedure consists of positioning the reservoir in the end of the length of the reservoir at the same moment than the upper valve is closed.

V_{film} mL	$1,8$	$1,9$	$1,7$	$1,6$	$1,3$
h m	$9,43 \times 10^{-4}$	$9,95 \times 10^{-4}$	$8,9 \times 10^{-4}$	$8,38 \times 10^{-4}$	$6,81 \times 10^{-4}$
h µm	$942,61$	$994,97$	$890,24$	$837,87$	$680,77$

As we can see, the result is approximately around 1 mm, which is the value that we can expect due to the thickness of our string. The errors were not obtained for this experiment as far as the results obtained are not expected as extremely accurate.

All the experiments that have been performed for the thickness measurement have been made for the middle point of the backwards hooks, however, as the results are not accurate with our equipment, the results of the thicknesses for the short and long longitudes for the hooks can be approximated to a thickness of 1 mm.

7.2.3. Final analysis of the measurements

The results obtained with the different methods are quite different ones from the others, and looking at the chapter 6: "Studying of our falling film soap flow" (at the section 6.2.5.1) we can see that the results for the effective viscosity are not correct due to the lack of accuracy of the measurements about the film thickness. The results obtained here are only an approximation of the real film thickness, and allow us to understand how small variations in the thicknesses can produce great variations in the image that we obtain from the channel and its properties.

7.3. Time variation

The thickness of the film is affected by the flow that is performed in it, so that the thickness is varying all along the time, that means that for performing an accurate measurement we need to use a process using an spectrometer or a photodetector so that we can obtain this evolution along time. The thickness is also influenced by the interaction between the soap and the air that surrounds it.

This measurement is too precise and we do not have the equipment to perform it with a good final value. There is a formula based on the *Navier-Stokes* equation that explains the thinning of thin liquid films:

$$-\frac{dh}{dt} = \frac{2h^3}{3\eta R^2}\Delta P$$

where h is the film thickness, t is time, η is the bulk viscosity, R is the film radius (horizontal films formed with the usual technique are, at a good approximation, circular), and ΔP is the force per unit film surface area causing the drainage.

Further information about this formulation and the derivation of this formula in order to obtain the force that causes the drainage as a function of the thickness and the time, see Appendix V: "Thickness measurement".

8. VON KARMAN VORTEX STREET

8.1. Theory

In practise this phenomenon appears after a destabilization of the flow due mainly to the surface roughness of the cylinder. In numerical simulations, these details cannot be modelled, then the destabilisation occurs when the numerical error reaches a certain unknown threshold.
Before the destabilisation, the near wake of the cylinder, we observe too long opposite rotating swirls, which are not observed in practise because the destabilisation occurs immediately. Then the destabilisation happens and the Von Karman vortex street develops in the wake of the cylinder.

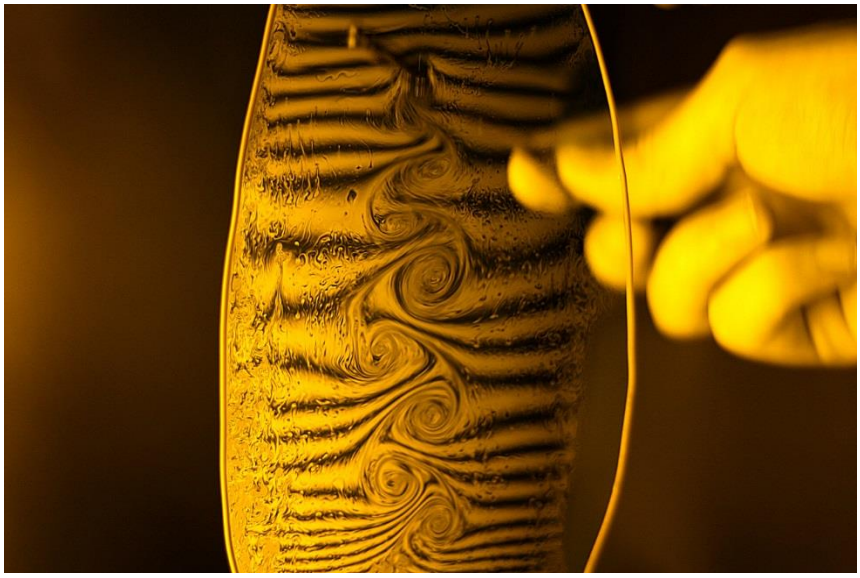

Figure 20 Visualization of a Von Karman vortex street in a film

8.2. Application in engineering

In low turbulence, tall buildings can produce a Karman street so long as the structure is uniform along its height. In urban areas where there are many other tall structures nearby, the turbulence produced by these prevents the formation of coherent vortices. Periodic crosswind forces set up by vortices along object's sides can be highly undesirable, and hence it is important for engineers to account for the possible effects of vortex shedding when designing a wide range of structures, from submarine periscopes to industrial chimneys and skyscrapers.
In order to prevent the unwanted vibration of such cylindrical bodies, a longitudinal fin can be fitted on the downstream side, which, provided it is longer than the diameter of the cylinder, will prevent the eddies from interacting, and consequently they remain attached. Obviously, for a tall building or mast, the relative wind could come from any direction. For this reason, helical projections that

look like large screw threads are sometimes placed at the top, which effectively create asymmetric three-dimensional flow, thereby discouraging the alternate shedding of vortices; this is also found in some car antennas. Another countermeasure with tall buildings is using variation in the diameter with height, such as tapering - that prevents the entire building being driven at the same frequency.

8.2.1. Problems caused by this phenomenon

- Even more serious instability can be created in concrete cooling towers, for example, especially when built together in clusters. Vortex shedding caused the collapse of three towers at Ferrybridge Power Station C in 1965 during high winds.
- Karman turbulence is also a problem for airplanes, especially at landing.

8.3. Visualization

The Karman vortex street in fluid dynamics refers to swirling vortices caused by unsteady flow separation as fluid flows over a body and occurs within the *Strouhal instability*. The *Reynolds number* is calculated and gives us a value of turbulence in the soap film channel. Next the *Reynolds number* for the cylinder that we have in our flow can be calculated as follows:

$$Re = \frac{d_{cylinder} \times v_{free\ flow\ stream}}{v_{mixture}}$$

where, *d* is the diameter of the cylinder, *v* is the velocity in the free flow stream and *v* is the kinematic viscosity of the mixture.

Depending on the *Reynolds number*, qualitatively different flows are observed. When the *Reynolds number* is small, i.e. $Re << 1$, viscosity dominates inertial effects. In this low *Reynolds number* limit, the flow is called creeping flow. The streamlines are symmetric fore-aft and left-right.

When the *Reynolds number* is increased to the range $5 \leq Re \leq 40$ the fore-aft symmetry is broken as separation of the streamlines takes place on the cylinder's lee-side and attached zones of recirculating fluid form. The left-right symmetry is retained, rendering the attached eddy on the left (right) side a positive (negative) sense of rotation. No complete theory exists for the steady flow field in this case, and experiments as well as simulations are needed to study this flow.

The third and perhaps most fascinating flow is found as *Re* is increased to the range $40 \leq Re \leq 180$. The flow is now unsteady as the eddies on the cylinder's lee side detach one after the other such that one eddy shed has the opposite sense of rotation compared to the previously shed eddy. As they are washed downstream, they form a vortex wake structure like a staggered grid of vortices. Here, the vortices on the left rotate counter clockwise and the vortices to the right rotate clockwise. This regime of *Reynolds number* is what Karl Hiemenz considered, and the wake type is indeed the von Kármán vortex wake. In this range of *Re* the vortex shedding is two-dimensional and laminar.

For higher Reynolds numbers, *Re ≥ 260* the flow is three-dimensional as turbulence becomes increasingly more dominant in the region of flow close to the cylinder. A few cylinder diameters downstream a vortex wake with a structure similar to the von Karman wake emerges from the turbulent flow, and therefore the Von Karman wake is ubiquitous in nature.

8.3.1. General considerations for obtaining the Von Karman vortex street

Conditions for having a Von Karman vortex street:

$$Re = \frac{d_{cylinder} \times v_{free\ flow\ stream}}{\nu_{mixture}} \in (40{,}400)$$

8.4. In our experiment

First of all we are going to analyse the main data that we can obtain initially from our experiment in order to determine if we can or if we cannot obtain the Von Karman vortex street with the cylinder that we have in our design, and in the case that we can we will explain the conditions and in the case that we cannot we will explain the reasons.

8.4.1. Data from our channel

$$d_{cylinder} = 0{,}05\ m$$

$$d_{injector} = 0{,}002\ m$$

$$h_{channel} = 137{,}8\ mm$$

$$w_{channel\ short\ hooks} = 10{,}3\ mm$$

$$w_{channel\ medium\ hooks} = 22{,}7\ mm$$

$$w_{channel\ long\ hooks} = 38{,}1\ mm$$

$$S_{channel} = w \times h$$

8.4.1.1. Medium hooks

For obtaining the section of the channel we can use either both thicknesses that we obtained from our different experiments:

$$Using\ h = 562{,}7\ \mu m \rightarrow S_{free\ flow\ stream} = 1{,}28 \times 10^{-5}\ m^2$$

$$Using\ h = 1{,}1\ mm \rightarrow S_{free\ flow\ stream} = 2{,}5 \times 10^{-5}\ m^2$$

The values of the velocities and the flow rate of the mixture is obtained as a function of the number of turns that has to be done to our control valve (the grey one). Using the initial conditions of the control valve, we use 12 turns of our valve. Then the velocity of the flow in the injector is:

$$v_{of\ the\ mixture\ in\ the\ injector} = \frac{Q_{injector}}{S_{injector}} = \frac{459{,}18[\mu L/s] \times 4}{\pi \times 0{,}002^2[m^2]} = 0{,}1462\ m/s$$

By means of continuity equation:

$$Q_{injector} = Q_{free\ flow\ stream}$$

$$v_{free\ flow\ stream} = \frac{v_{injector} \times S_{injector}}{S_{free\ flow\ stream}} = \frac{0{,}1462 \times \pi \times 0{,}002^2}{4 \times S_{free\ flow\ stream}}$$

As we have two values of the thickness:

$$v_{free\ flow\ stream} = 0{,}036\ m/s$$

$$v_{free\ flow\ stream} = 0{,}018\ m/s$$

Then the value of the Reynolds number is:

$$Re = 1464{,}79$$

$$Re = 732{,}40$$

Those values of the *Reynolds number* assure that the Von Karman vortex street is not possible to be created with those conditions because they are not in the valid range, we have two different options:

- **Reduce the value of the diameter of the cylinder**

  This option has the difficulty that we have to use or construct a new element for the cylinder, or to use another element that is not fixed to the main structure.

  Using 12 turns at the control valve:

  $$D_{cylinder} \leq 0{,}014\ m$$

  Using an element of this diameter (in this case we use the plastic element of the figure) and the actual configuration of the channel, we obtain our Von Karman vortex street, without any big problem of stability.

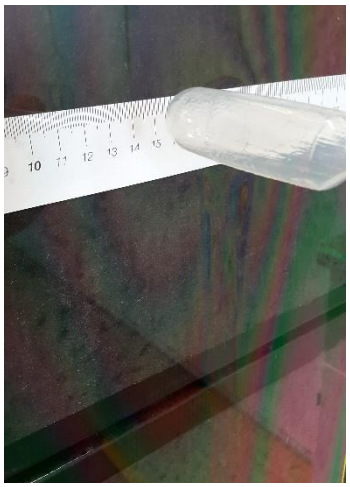

Figure 21 Von Karman vortex street in our channel with the initial lighting system

Problem

The vortex that is created is really small so that it can only be seen from a near position (not to show in a high class) and that with this small instability that is created, we can only create the first Von Karman vortex, and not a second one at some distance away from it.

- **Reduce the value of the velocity of the free flow stream, and for that we need to reduce the value of the velocity of the nozzle.**

  In order to reduce the value of the velocity, we need to close the control valve in order to reduce the flow rate. For that we want to obtain the flow rate needed in the injector in order to have a value of the Reynolds that allow us to obtain the Von Karman vortex street.

$$Re_{max} = \frac{d_{cylinder} \times v_{free\ flow\ stream}}{\nu_{mixture}} = \frac{0{,}05 \times v_{free\ flow\ stream}}{1{,}22741 \times 10^{-6}} = 400$$

$$v_{free\ flow\ stream} \leq 9{,}82 \times 10^{-3}\ m/s$$

$$Q_{injector} \leq 1{,}26 \times 10^{-7}\ m^3/s$$

$$Q_{injector} \leq 126\ \mu L/s$$

  In order to obtain the number of turns that are needed for obtaining the desired flow rate in the injector, we are going to use the table that appears in the chapter 6: “Studying our falling film flow channel”.

  Conclusion: using our actual cylinder of 5 cm of diameter and 8 turns, we can obtain the Von Karman vortex street.

  Problem

  This solution uses a very low flow rate, which creates an extremely instable film, so it is easily broken (impossible to take a photo). The film has stability problems on the boundaries, at the lower part of the channel in the points where the mixture is in contact with the strings.

Final solution for the medium hooks

Finally in order to be able to produce the Karman vortex street with the configuration of the medium hooks, we are going to use an element with a diameter lower than 14 mm (in order to use 12 turns of the regulation valve). The selected element is a new 7 mm diameter cylinder which is going to be introduce through the space where we have our metallic elements. The behaviour of the channel can be seen in the pictures:

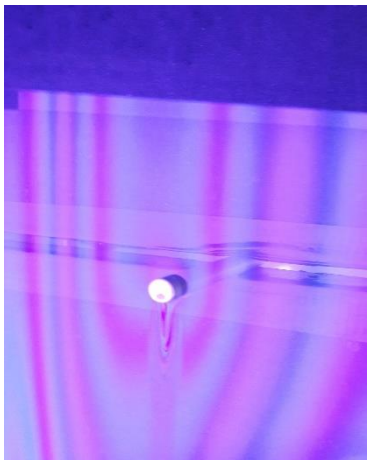

Figure 22 Von Karman vortex street in our channel with the violet light

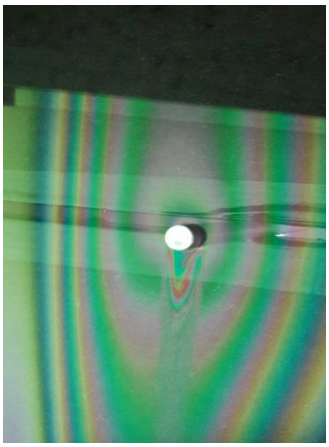

Figure 23 Von Karman vortex street in our channel with the green light

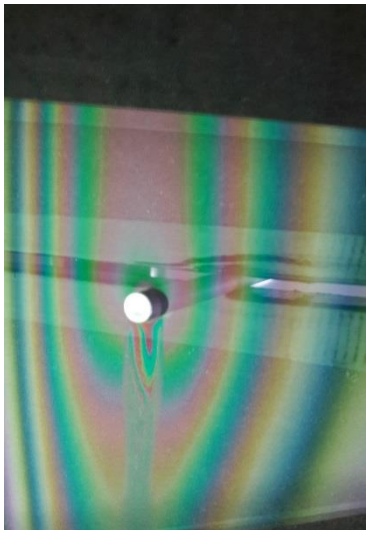

Figure 24 Von Karman vortex street in our channel with the green-blue light

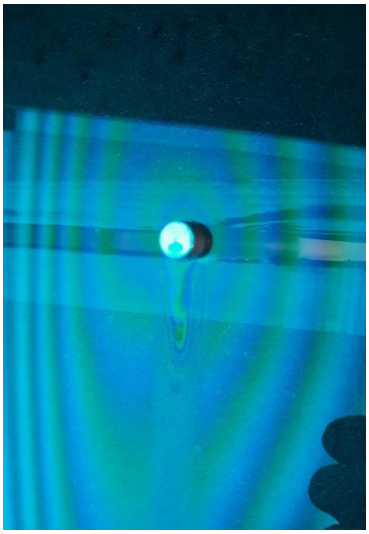

Figure 25 Von Karman vortex street in our channel with the blue light

8.4.1.2. Short hooks and long hooks

Using the cylinder that we have in our prototype:

	Thickness	$Q_{injector}$	S_{FFS}	v_m	v_{ffs}	Re	n° turns	Von Karman
Short	1 mm	66,75 µL/s	10,3 mm^2	0,021 m/s	$6{,}48 \times 10^{-3} m/s$	263,97	6	Yes
Long	1 mm	930,23 µL/s	38,1 mm^2	0,296 m/s	0,0244 m/s	993,96	14	No

For the short hooks we obtain our Von Karman vortex street with the cylinder that is in our prototype and 6 turns, however the film will break easily due to the instabilities.

For the long hooks we can not obtain this behaviour with the cylinder that we have in the metallic elements of the prototype, because the limit diameter is going to be:

$$d_{cylinder} \leq 0{,}02\ m = 20{,}12\ mm$$

As the figures obtained for the medium hooks configuration are going to be similar to those for the long hooks configuration, we can say that the photos above (that we take for the medium hooks and the new cylinder) can be used also to understand the behaviour of the long hooks configuration.

8.5. Final conditions for Von Karman vortex street

Backward hooks	N° of turns-regulation valve	$d_{cylinder}$
Short	6	≤ 50 mm
Medium	8	≤ 50 mm
Medium	12	≤ 14 mm
Long	14	≤ 20 mm

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