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APPENDICES: "MEASUREMENT OF THE FLUID AND FLOW PROPERTIES OF A SOAP FILM CHANNEL"

FH Bielefeld
University of
Applied Sciences

EPI GIJÓN
Universidad de Oviedo

Iván Vallejo Pérez
FH BIELEFELD AND "ESCUELA POLITÉCNICA DE INGENIERÍA DE GIJÓN"
Supervisor teacher: Prof. Dr.Tobias Böhm
Second supervisor teacher: Prof. Dr. rer. nat. Martin Petry
Support teacher: Dipl.-Ing. Heinz-Wilhelm Tiemann

1. APPENDIX I: "METHODS FOR MEASURING THE VISCOSITY OF OUR MIXTURE"

In this Appendix I, we are going to explain all the methods that we used to determine the viscosity of our soap mixture as well as the reasons why those methods where not finally used.

1.1. Method 1: Marble experiment for determining the dynamic viscosity

This first method can be performed as an own experiment, for that we can use one of the tubes of the laboratory (full of the mixture till one point), a marble and a timer.

The procedure is the following:

1. Obtain the initial information from the mixture and the marble
    a. Making a previous measurement of the mass of the amount mixture that we are using and the mass of our marble
    b. Values of the density of our mixture and obtain the volume and density of the marble
    c. Value of the height where we have the fluid
2. Leave the marble on a free fall in our mixture and measure the necessary time that it needs to reach the deepest part
3. Obtain the falling velocity of our marble
4. Formula for obtaining the dynamic viscosity

$$\mu_{mix} = \frac{2 * g * {r_{marble}}^2 * (\rho_{marble} - \rho_{mixture})}{9 * v(free\ fall\ marble)}$$

Several tries were performed with the two smallest marbles (1 mm and 2 mm of diameter).

Reason why we do not use this method: extremely high velocity that does not make possible to see the marble falling neither to perform the measurement

1.2. Method 2: Viscometer

Using a viscometer to produce a more professional, direct and accurate measurement.

Reason why we do not use this method: there is no viscometer that we can use in order to make the measurement.

1.3. Method 3: Simplification in order to obtain both viscosities

In this final method, the idea is to use directly the value of the viscosities of the water, because, from the quantities that are used in order to produce the mixture, we can see that the water has a greater contribution in comparison with the other two substances. For that reason and using a simplification, we can also say that the viscosities of our mixture is equal to the viscosities of the water that we use in our experiment which are the following

Kinematic viscosity

$$v_{mixture} = v_{water} = 1.0034\ mm^2/s$$

Dynamic viscosity

$$\mu_{mixture} = \mu_{water} = 1.0016\ mPa \times s$$

Reason why we do not use this method: although the main component in the mixture is water, we can not say that the viscosity of the mixture is going to be exactly the same as the viscosity of the water.

1.4. Method 4: Rotative viscometer

This apparatus measures the viscosity of a fluid by the rotation of a disc or a cylinder which is submerged in the fluid that we want to test. The disc or cylinder rotates at a known angular velocity. The instrument makes a measurement of the torque required in order to perform the rotation of the disk or cylinder.

Once we have all those values (the angular velocity, the torque that has been measured, and the characteristics of the disc or cylinder that we have used), we are able to obtain the value of the viscosity.

Reason why we do not use this method: there is no viscometer that we can use in order to make the measurement.

1.5. 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*.

Although this method is already explained in the main report, we are going to make a more detailed explanation of it.

1.5.1. 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 a fixed volume with initial and final mark for making the time measurement

Figure 1 Equipment for the capillarity experiment

The equipment is connected as it is indicated in the photo, for that, we have some fluid in our Petri plate and by means of pressure difference and the suction made using the syringe at the other side, we can filled the tube above the initial mark of the volume. The equipment is joined with the plastic tubes in order to have all the system closed, nevertheless we have to take into account that the valve allows us to open or close the system in order to be able to continue with the further suction till the fluid is above the initial mark.

1.5.2. 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 and in a detail way:

First step

First we have to filled 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 open so that the fluid goes down through our tube with the fixed volume and through the capillarity tube till it reaches again the Petri's dish. The objective is to measure the time that is needed by the fluid to go from the initial to the final mark of our tube.

First step

First we have to fill our tube with the liquid from which we want to obtain the value of the viscosity, for that we have to pour our liquid in the Petri's dish, so that the capillarity tube is introduced in the fluid and we must ensure that the free surface of the fluid is always (during we are doing the measurement) above the extreme part of the tube.

In order to filled our tube, we have to make a repetitive process that takes into account the syringe and the valve as main elements which are used on the process. The valve, as we have said before, allow us to connect the whole circuit but also allow us to connect either the syringe or the capillarity tube to the air, where we have the atmospheric pressure.

The valve is closed so that the syringe and the capillarity tubes are joined, and then we have to pull from the syringe in order to make suction on the capillarity tubes, once we have done it, we have to change the valve to an open situation between the syringe and the capillarity; in that way, the syringe is connected to the air (at atmospheric pressure), and the capillarity tube is closed, in that way, we are able to throw out the air that we have in the syringe to the atmosphere.

Then the valve is closed again and the process is repeated until the capillarity tube is filled to the initial point, or even it is better if we fill a little bit more that the minimum volume, in order to have a margin for making the time measurement.

Second step

Finally, once the system is filled with our fluid, we can allow the fluid to flow and measure the time needed by it to go between both references. In order to make possible the fluid to flow, we need to open the valve between the syringe and the capillarity tubes but in this situation what we do is to make the capillarity tubes to be connected with the air (at atmospheric pressure) and the syringe is closed. The syringe must be attached to the bottom part so that it is extended till its maximum length allowed by the system

The measurement of the time is made by means of a hand-working timer with a high precision which allow us to obtain the final parameter of the experiment. Also, as we have two different capillarity tubes, with different lengths and different diameters, we can perform the experiment with both tubes.

1.5.3. Corrected *Hagen-Poiseuille* equation

From the results that we obtained at the experiment, that are results of time, we want to obtain the viscosity of our mixture, and for that we have the following equation that relates both terms:

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

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 (it is not constant), so in order to make an approximation, we use the mean value.

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

1.5.3.1. Determination of the radius of the capillarity tubes

In order to perform the measurement of the radius, we have used an object micrometre, we are going to explain more or less how it works:

An object micrometre is an apparatus that has an own scale for making the measurements, in that way, you have to perform the measurement in the scale proposed by the apparatus and then "translate" this values to the real metric scale. In order to "translate" this values, we have a reference ruler (from 0 to 2 mm) that allow us to obtain a direct relationship between a value in the scale of the apparatus and the metric scale; in that way you only have to use this direct correlation in order to "translate" all your measurements.

The object micrometre that we used has two different lenses (5:1 and 10:1), so that you can use the lens that better fits with your object. In our case, we had to use each of the lenses for each of the capillarity tubes.

As we have two capillarity tubes, we will give them a name now, so that we can be more clear referring to them:

Capillarity tube 1	**The one whose length is: $l_1 = 290\ mm$**
Capillarity tube 2	**The one whose length is: $l_2 = 293\ mm$**

Then the results obtained in the object micrometre in the determination of the diameters with the specification of which lens we used for each measurement are (in the apparatus scale):

Situation	1st extreme	1st extreme (90º from the first measure)	2nd extreme	2nd extreme (90º from the first measure)
Capillarity tube 1	5.9 (x10)	6 (x10)	6 (x10)	6 (x10)
Capillarity tube 2	4.4 (x5)	4.5 (x5)	4.4 (x5)	4.4 (x5)

Now we have to determine the relation between the scale of the apparatus and the "real" scale; from the comparison between the scale and the reference ruler:

Type of lens	Measurement in the "apparatus scale"	Measurement in the "real scale" in mm
5:1 (x5)	5.3 (apparatus scale)	2 mm
10:1 (x10)	8 (apparatus scale)	1.4 mm

Finally the results obtained once we translate them from the scale of the apparatus and the real scale are:

Situation	1st extreme mm	1st extreme (90º from the first measure) mm	2nd extreme mm	2nd extreme (90º from the first measure) mm
Capillarity tube 1	1.0325	1.05	1.05	1.05
Capillarity tube 2	1.66	1.698	1.66	1.66

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 figures):

$$d_1 = 1.05\ mm$$
$$d_2 = 1.67\ mm$$
$$r_1 = 0.53\ mm$$
$$r_2 = 0.84\ mm$$

1.5.3.2. Results of the measurements

In this experiment what we will obtain are the time needed by the liquid to go from one to the other marks that are present in the tube with a fixed volume.

In order to check if the system works properly, we have performed a previous checking by using a fluid from which we know the viscosity, in this case, we have used water. Then we have obtained some results measuring the viscosity of the water and the viscosity of our mixture, we are going to see both values.

I Viscosity of the water

First of all we are going to make a table of the know parameters and then we can make the measurements of the changing parameters, those which have changes even if we use the same fluid in both capillars.

Constant parameters

$\mathrm{V} = 1 \times 10^{-4}\ m^3$

$l_1 = 0.29\ m$

$l_2 = 0.293\ m$

$r_1 = 0.53\ m$

$r_2 = 0.84\ m$

In this case we have performed a measurement of the density of the water in the conditions where the experiment where performed (and also a measurement of the temperature of the water in order to know those conditions):

$\mathrm{T} = 20.1\ ℃$

$\rho = 1002\ Kg/m^3$

I.I Capillarity tube 1

The characteristics heights of this tube with water are:

$h_1 = 0.586\ m$

$h_2 = 0.389\ m$

Then the values of the times that are obtained are:

t_1	t_2	t_3	t_{mean}
223.7 s	**224.1 s**	**223.7 s**	**223.8 s**

Solving the equation of the dynamic viscosity:

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

I.II Capillarity tube 2

The characteristics heights of this tube with water are:

$h_1 = 0.586\ m$

$h_2 = 0.389\ m$

Then the values of the times that are obtained are:

t_1	t_2	t_3	t_{mean}
43.1 s	**43.9 s**	**43.8 s**	**43.6 s**

Solving the equation of the dynamic viscosity:

$$\mu_2 = 1.012 \times 10^{-3}\ Kg/m \times s$$

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 measured for the water:

$$\mu_{water} = 1.0235 \times 10^{-3}\ Kg/m \times s$$

The value of the dynamic viscosity of the water measured with more precise instruments at a temperature of 20°C is:

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

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 mixutre

First of all we are going to make a table of the know parameters and then we can make the measurements of the changing parameters, those which have changes even if we use the same fluid in both capillarity tubes.

Constant parameters

$V = 1 \times 10^{-4}\ m^3$

$l_1 = 0.29\ m$

$l_2 = 0.293\ m$

$r_1 = 0.53\ m$

$r_2 = 0.84\ m$

In this case we have performed a measurement of the density of the soap mixture in the conditions where the experiment where performed (and also a measurement of the temperature of the mixture in order to know those conditions):

$T = 20.6\ ℃$

$\rho = 1009\ Kg/m^3$

II.I Capillarity tube 1

The characteristics heights of this tube with water are:

$h_1 = 0.585\ m$

$h_2 = 0.386\ m$

Then the values of the times that are obtained are:

t_1	t_2	t_3	t_{mean}
265.9 s	**265.6 s**	**266.3 s**	**265.9 s**

Solving the equation of the dynamic viscosity:

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

II.II Capillarity tube 2

The characteristics heights of this tube with water are:

$h_1 = 0.584\ m$

$h_2 = 0.387\ m$

Then the values of the times that are obtained are:

t_1	t_2	t_3	t_{mean}
48.8 s	**48.7 s**	**49.0 s**	**48.8 s**

Solving the equation of the dynamic viscosity:

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

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 considered as the dynamic viscosity of our mixture.

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

2. APPENDIX II: "SURFACE TENSION MEASUREMENT"

2.1. Experiment 1

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 less accurate measurement. (Check the main document chapter 5.6.1. "Experiment using the ring method (Du Nouy method)" for further information).

This experiment is really unprecise, it is just used in order to have an initial idea of the value that we are going to obtain in our measurement.

In order to perform this measurement we will use the two capillarity tubes that we have already used to measure the viscosity, a small recipient and a ruler.

Measuring the distances that the liquid flows through the capillary in a long period of time (because we have to wait till the forces are stabilised), we can determine the surface tension of the fluid.

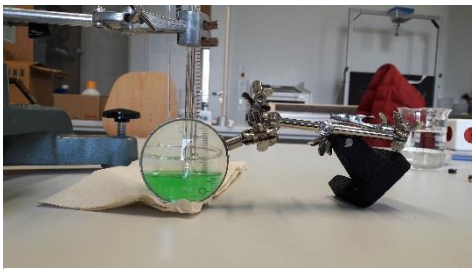


Figure 2 Equipment for the surface tension measurement

The physical explanation of the experiment is the following: the pressure forces that make the fluid go up inside the capillarity tubes are finally equal to the weight, the pressure and the friction forces, at this point the height of the fluid is stabilised and we can obtain the surface tension of the fluid.

The surface tension is related with the height and the radius of the capillary in the following way (in this equation we are not taking into account the angle that appears between the fluid and the capillarity tube, considering it as 90° in order to simplify the calculation):

$$\gamma = \frac{1}{2} \times \rho \times g \times r \times h$$

2.1.1. Checking the experiment using water

The experiment is firstly performed using water in order to determine the precision obtained in the measurements because the data of the surface tension of water is already known:

$$\gamma_{water\ expected} = 0{,}073\ N/m$$

Using both capillarity tubes, the results of the height of the water in the tubes are:

$$h_1 = 25\ mm$$

$$h_2 = 13\ mm$$

Taking into account the values of the diameters of the capillarity tubes that we already have from the viscosity measurement:

$$d_1 = 1{,}05\ mm$$
$$d_2 = 1{,}67\ mm$$

Thus, the final results obtained from the experiment for the surface tension of the water are:

$$\gamma_1 = 0{,}1\ N/m$$
$$\gamma_2 = 0{,}11\ N/m$$

The conclusion is that the experiment is not the most precise but it can give us a good approximation to the value of the surface tension of our mixture

2.1.2. Experiment with our mixture

Once we have checked the approximate validity of our experiment using water, we will use the experiment for obtaining the surface tension of our mixture. The results of the height of the mixture in the tubes are:

$$h_1 = 1\ mm$$
$$h_2 = 5\ mm$$

Taking into account the values of the diameters of the capillarity tubes that we already have from the viscosity measurement:

$$d_1 = 1{,}05\ mm$$
$$d_2 = 1{,}67\ mm$$

Thus, the final results obtained from the experiment for the surface tension of the water are:

$$\gamma_1 = 0{,}00259\ N/m$$
$$\gamma_2 = 0{,}00206\ N/m$$

The surface tension obtained is a much lower than the one of the water, and as we checked later with the “Du Novy” experiment we can obtained a better measurement for both fluids.

Reason why we do not use this method: lack of accuracy.

3. APPENDIX III: "METHODS FOR MEASURING THE FLOW RATE"

In this Appendix III, we are going to explain all the others methods that we used to determine the flow rate of our soap mixture in the channel. Those methods here explained were finally not include on the final report or were improved before its inclusion.

3.1. First idea for measuring the flow rate:

By means of direct measurement from the flow that goes through the first controlling element (open-close valve) and the deposit. The velocity (and also by direct relationship, the flow rate) depend only on the height between the exit of the nozzle and the free surface of the fluid (because as there is no pump on the system, the flowing movement is dependent only on the difference of heights)

3.2. Second idea for measuring the flow rate:

1. Measure the initial weight of the stone (dry stone)
2. Use an element in order to pick the mixture that falls under the stone
3. Open the system during a determined period of time (around 10-20 seconds)
4. Close the system after that time has passed
5. Measure the final weight of the stone (wet stone):
   The difference between the initial and final values of the weight of the stone, gives us the amount of mixture that is on the stone. For obtaining the volume we can use the weight of the mixture and its density.
6. Obtain the final value of mixture picked by the element used to pick the mixture
   Summing both values (the one of the direct and the one of the indirect measurement) we will obtain the total amount of mixture that was poured
7. Using a chronometer we can know the flow rate of the mixture through the nozzle

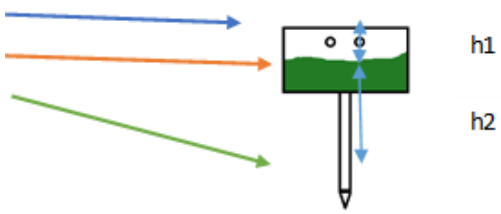
Reason why we do not use this method: difficulty in the measurement and the result should be the same that the one which was finally used.

3.3. Theoretical determination of the flow rate

The theoretical analysis of the system allows us to understand the reason why the flow rate changes when the deposit is becoming an empty deposit.

First of all, when we start the analysis we have to consider and use three different points on our design:

- Point 0: the free surface of the liquid in the deposit
- Point 1: the point where the fluid enters the tube
- Point 2: the point where the fluid enters the nozzle



Using the energy equation between the points 0 and 2:

$$\frac{{v_0}^2}{2g} + z_0 + \frac{P_0}{\rho g} = \frac{{v_2}^2}{2g} + z_2 + \frac{P_2}{\rho g} + \sum h_{linear} + \sum h_{singular}$$

In this equation, we can make the following simplifications:

$v_0 = 0$; as it is the free surface

$z_0 = h_1 + h_2$; where $h_1(t)$ and $h_2 = cte$

$P_0 = 0\ (P_{atm});\ P_2 = 0\ (P_{atm});$ as both are opened to the atmosphere

$z_2 = 0; considered\ as\ ground$

The linear and singular have not a great influence in the analysis

The final equations will be:

$$v_2 = \sqrt{2g(h_1 + h_2) + 2g(\sum h_{linear} + \sum h_{singular})}$$

$$Q = v * Section$$

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.

4. APPENDIX IV: "MODIFICATIONS OF THE CHANNEL"

This appendix includes the calculations that were made for the first pump that finally broke. In order to see the actual working parameters, see chapter 6.3.3. of the main document.

4.1. Calculating the parameters of our recirculating system with the first pump

The methods used with the first pump in order to perform this measurement are the following:

4.1.1. First attempt: previously determination of the power of the system to determine the power of the power supply-pump

In order to adjust the recirculating flow rate we only are able to select the voltage (and the current) given by the power supply. Using this consideration, we have to obtain the efficiency of the power supply-pump connexion and then from the circuit we can obtain the power needed in the power supply

4.1.1.1. Experiment to determine the efficiency of the pump

The experiment is made by constructing a circuit where we have all the variables to make the energy analysis, except the efficiency of the pump: fixed amount of water, fixed heights, fixed losses (estimated by theoretical analysis), fixed flow rate. The result is:

$$\eta_{pump} = 2{,}03\%$$

4.1.1.2. Determination of the power needed by the power supply

From the circuit that we construct in the recirculation, we have the following theoretical analysis whether we consider losses or not:

I Considering NO losses

$$H_{pump} = 1{,}9\ m\ in\ column\ of\ the\ mixture$$

$$Power_{minimum\ needed\ by\ the\ pump} = 0{,}13\ W$$

II Considering losses

In this case we have consider that we have 5 elbows and silicone that is the material of the tubes (ε=0,0015[mm]):

$$H_{pump} = 2{,}9018\ m\ in\ column\ of\ the\ mixture$$

$$Power_{minimum\ needed\ by\ the\ pump} = 0{,}1435\ W$$

Considering that the pump does not uses the whole amount of power that it gets, so that it has an efficiency, and once we already have the efficiency of the pump we can obtain the power needed from the power supply:

$$Power_{minimum\ needed\ by\ the\ power\ supply} = 6.41\ W$$

$$Power_{minimum\ needed\ by\ the\ power\ supply} = 7.07\ W$$

From this initial attempt we can say that the first pump that we are working with and the power supply will be able to afford the recirculation.

4.1.2. Second attempt: using the valve fabrication information

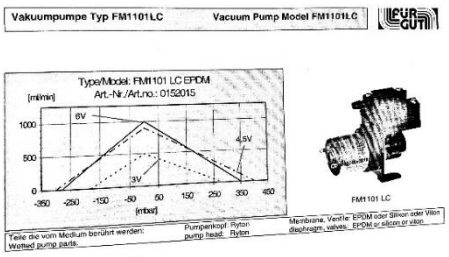


Figure 3 First valve fabrication information

Another way in order to have the same flow rate in the recirculation system as in the pouring system, is using the graph of the performance of the pump. Using the hydraulic jump that we need from our pump in order to create the circuit, we can determine from the graph which is the voltage needed in order to produce that movement of the water and also to obtain the maximum flow rate for the recirculation in this case.

$$\Delta P_{pump} = \rho_{mixture} \times g \times H_{pump} = 286796{,}79\ Pa = 286{,}72\ mbar$$

From the graph (at 4,5 [V]):

$$Q_{max} \approx 270\ mL/min$$

In this case we would not have exactly the same flow rate in our recirculating system as the flow rate of the film, but they will be really near. Our system will last about 20 min, starting with 0,8095 L in the upper reservoir and 0,2 L in the lower reservoir.

From this second attempt, we can assume that the recirculation is possible and will have good working conditions.

4.1.3. Third attempt: Determining by practice the correct recirculation rate of our system

4.1.3.1. Objective

The main goal of the recirculation system is to obtain the same value of the flow rate in the recirculation as the flow rate that we have for the soap film flow.

4.1.3.2. Controlling elements

The control of the recirculation system for this first pump, depends on two basic parameters that we can change:

- The voltage at the power supply element

  The power supply element is the one that controls the power given to the pump, in order to produce the movement of the mixture.

- The valve that is positioned in the recirculation pipe

  The use of a valve in the recirculation pipe to close it until we have the same flow rate in the recirculation than the one that is needed. The parameter that we are going to consider here is the number of turns of this valve.

4.1.3.3. Parameters that we take into account on the recirculation

In the calculation of the recirculation we have to take into account one more parameter, despite the two ones that are used as controlling elements, and it is the height of the fluid mixture in the lower reservoir, this height has a direct influence in the power given from the pump to the fluid, and thus, to the power needed in order to perform the movement of the fluid.

4.1.3.4. Results of the recirculation system

The first check that we have done is the maximum and the minimum flow rates for the recirculation system that we are able to control with those two elements. The conclusion in that initial study is that than the flow rate needed (the one equal to the flow rate of the mixture at the film) is below the maximum and the minimum flow rate that can be given by the recirculation system. For that reason, we have used the valve to reduce the flow rate given by the pump.

4.1.3.5. Measuring the recirculation flow rates

The measurements started using different values of the involved and controled parameters. Once we have stablished a value of the voltage and the opening of the valve, we have decided to measure with these conditions at different heights in order to obtain an estimation of the flow rate in the recirculation in between those parameters.

Voltage V	Nº of turns	Initial height m	Final height m	Volume L	Time s	Flow rate recir mL/s	Flow rate "medium" mL/s
5	7,5	0,45	0,4	0,05	100,5	0,49	**0,44**
5	7,5	0,4	0,35	0,05	87,3	0,57	**0,44**
5	7,5	0,35	0,3	0,05	98,8	0,51	**0,44**
5	7,5	0,3	0,25	0,05	107,2	0,47	**0,44**
5	7,5	0,25	0,2	0,05	97,6	0,51	**0,44**
5	7,5	0,2	0,15	0,05	110,6	0,45	**0,44**

We can see that the "mean" flow rate in the recirculation is not equal to the flow rate of the film (it is bigger), however those conditions allow us to last our film during the time that is needed to empty the lower reservoir and even more. From practice we have checked that it lasts at least 1 hour, which is a good way of presenting it to a class or in a conference. And theoretically the result would be:

$$t = \frac{V}{Q_{net}} = \frac{1000\ mL}{0{,}02\ mL/s} = 50000\ s = 13{,}9\ h$$

5. APPENDIX V: "THICKNESS MEASUREMENT"

5.1. 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 Å o 300 Å, 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, and 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.

5.2. Measuring the thickness of the film

5.2.1. 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.

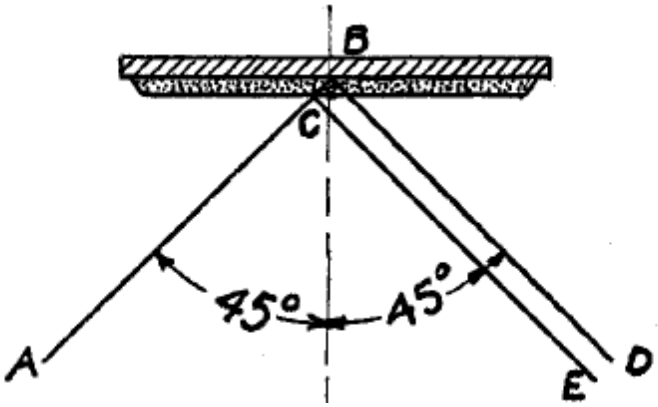


Figure 4 Reflection of the light in the film

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.

A very narrow beam of light, AB, is projected onto a metal surface at B at an angle of incidence of 45° whence the angle of the reflection, BD, will also be 45°. If now a uniform film of liquid is made to flow down the metal surface, the beam is reflected from the surface of the liquid at some point, C. Since the angle of incidence is unchanged, the reflection, CE, from the liquid surface is parallel to the reflection, BD, previously obtained from the metal surface. The distance between the two reflected beams can be measured, and is equal to the distance BC. The distance BC is the hypotenuse of a right triangle whose acute angles are 45°. One side of this triangle is perpendicular to the metal surface at B and is equal in length to the thickness of the film *h*. The latter dimension can, therefore, be accurately computed by multiplying the measured distance, BC, by the cosine 45° or 0.707. If an angle of incidence other than 45° is used, the calculations of the film thickness become more complicated. If the angle of incidence of the beam varies 1° from the desired angle of 45° an error of about 2 % is made.

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).

5.2.1.1. Description of the measurement with the metal piece separated from the film

Using this process in order to produce our measurement, we have to take into account that some of the conditions that must be fulfilled, can not be taken longer in our measurement, so that it is not going to be a precise measurement, but an approximation of the real value of the thickness of the film.

The narrow beam of light will be in our case a torch (flashlight) going directly to the film and crossing it in order to also be reflected by the metal sheet. The angle between the torch (flashlight) and the metal surface and the film will be of approximately 45° (as far as we can not produce a perfect position for our lighting element).

The light crosses the film and some of it is reflected, and then some of the light that reaches the metal sheet is also reflected, so that we can obtain both lighting rays in our lens and point with them into a blank sheet where we can obtain the distances between both rays. This distances is going to be the value of the reflection DE; that as it is explained in the theory, by means of the parallel comparison, is equal to the distance BC. This distance BC is the hypotenuse of the angle whose side is the thickness of the film and the distance between the film and the metal sheet, taking the value of $h+d$. (h = thickness of the film; d = distance between the film and the metal sheet)

Finally, once we measure the distance between the film and the metal sheet, we can obtain finally the value of the thickness of the soap film.

Problems that are presented on this measurement

1. Depending on the position where we used our lens, we obtained different values of the measurement.

Solution

The projector and receptor should be mounted with their centre lines in the same plane, and with the line bisecting the angle of their intersection perpendicular to the surface upon which measurements are to be made. When the surface is in a true vertical position, the centre lines of the projector light and the receptor of the light are in a horizontal plane and form an angle of 90°. This relation should be maintained for all measurements. The instruments, therefore, may be mounted in a fixed position.

2. In our experiment, the flow is not flowing in the metal sheet, we have our metal sheet at a distance *d* from the flowing film of soap.

Solution

From the conclusions of the original experiment, we can say that the distance between the incident ray over the film and the metal sheet that is behind the film is measured, and this value coincides with the value of the thickness of the film in the original experiment. However, in our experiment we do not have our film flowing in a metal sheet, but our metal sheet is placed at a distance *d* from the soap film.

Taking into account this explanation we have to measure the distance between the final point of our film and the metal sheet *d* and subtract this value to the one that we obtained performing the original experiment, so that we can obtain the value of the thickness of our film.

5.2.1.2. Results of the first process of measurement

The result obtained for the distance between the points DE and thus, the distance between the points BC is of 61 mm and *d* = 42 mm; then the value of the thickness of the layer is of:

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

Taking into account the errors in the measurements, such as in the position of the angle and the other measurements, we obtain it by means of the determination of errors in indirect measurements, that is, with partial derivatives:

$$h = BC \times \cos\alpha - d$$

$$\partial h = \frac{\partial h}{\partial BC} \times \partial BC + \frac{\partial h}{\partial d} \times \partial d + \frac{\partial h}{\partial \alpha} \times \partial \alpha$$

$$\partial h = \frac{\sqrt{2}}{2} \times \partial BC + 1 \times \partial d + BC \times \sin(\alpha) \times \partial \alpha$$

Considering the following errors in the specific measurements:

$$\partial BC = \pm 0.1\ mm$$

$$\partial d = \pm 0.1\ mm$$

$$\partial \alpha = \pm 1\ °$$

$$Error = \pm 923.53\ \mu m$$

Then the final approximate value of the thickness is:

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

5.2.1.3. Description of the measurement with the metal piece next to the film

Now in order to make the measurement we have attached the film to flow near the sheet metal element, then our *d* is nearly 0 and the value of the measurement is simply the value of the thickness of our film, with that experiment we obtained the following:

5.2.1.4. Results of the second process of measuring

The result obtained for the distance between the points DE and thus, the distance between the points BC is of 0.8 mm and $d \approx 0$; then the value of the thickness of the layer is of:

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

Then the final approximate value of the thickness is:

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

5.2.2. 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.

5.2.2.1. 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 are approximately around 1 mm, which is the value that we can expect due to the thickness of our string.

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.

5.3. Variation with respect the time

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 a 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.

For a laminar flowing soap film, a reasonably uniform film thickness can be achieved in the center of the channel (-20<x<20 mm) for a wide range of injection rates 0.04<J<0.4 g/s. The fractional variation $\delta h/h$ in that region is well under 10%.

We noted that as J increases, the average film thickness increases and, at the same time, there is a gradual change of the thickness gradient $\delta h/\delta y$, varying from 0.4 to 0.8 mm/m for low to high injection rates. The presence of this thickness gradient is a result of a residual acceleration of the film, which causes the film to stretch along the flow.

Achieving a high velocity with a steady-state flow is important for many 2D experiments; it can be realized only for soap films much longer in length than those in our current setup

5.3.1. Formula

Experimentally, such films have been studied with regard to their thinning rate by a large number of workers. Theoretically, the starting point used to be the Reynolds equation, based on the Navier-Stokes equation under the conditions pertaining to 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. This pressure, ΔP, consists of the capillary pressure in the surrounding Plateau border and the disjoining pressure in the film, caused by the London-van der Waals and electrostatic interactions between the film surfaces.

Good agreement between thinning rates and the Reynolds equation has been found only for very small films, e.g. with *R* < 50 urn. For larger films, increasing deviations between experimental and theoretical values for the film rate have been reported.

Finally analyzing the formula given, we can solve it by considering that the force per unit film surface area that causes the drainage is a function of the time, as far as we can see experimentally that the film has a variation of its drainage with the time or with the film thickness; taking into account both possibilities we obtain the following relationships between the thicknesses and its evolution.

5.3.1.1. Considering that ΔP = f(t)

$$\frac{1}{{h_{final}}^2} - \frac{1}{{h_{inicial}}^2} = 2653068.016 \times t \times \int_0^t \Delta P \, dt$$

5.3.1.2. Considering that ΔP = f(h)

$$-\int_{h_{initial}}^{h_{final}} g(h)\, dh = 1326534.008 \times t$$

Considering now that: $g(h) = i'(h)$

$$[i(h)]_{h_{initial}}^{h_{final}} = -1326534.008 \times t$$

As far as we do not know the relation that exists between ΔP and time or ΔP and thickness, we can only indicate the results in a formulation way.

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Section 3.3: Theoretical analysis from theoretical material from "Universidad de Oviedo"

6.4. Appendix IV: "Modifications of the channel"

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Section 4.1.2: Tables of efficiency of the pump and information about it

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6.5. Appendix V: "Thickness measurement"

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