Rapport de stage

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Study of phenomena around droplets impacting on a liquid surface

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Abstract

Although droplets are common objects that we can see everyday, their behavior remains a dramatic event. Many interesting phenomena happen whereas no one notice them. In this experimental study, a high-speed camera was used in order to get data and to describe, explain and predict what happens at the contact between a droplet released with no initial velocity, from a height varying from some centimeters to two meters, and a liquid surface. Distilled water, ethanol and silicone oil were used in order to have results to be compared. Relations between the observed phenomena and some dimensionless parameters were established for each liquid. A kind of repartition of the energy of the free-falling droplet after its impact was also drawn. In the analysis of each phenomenon, results of different researchers were considered to make interesting comparisons.

Resumé

Bien que les gouttes soient quelque chose de presque banal que l'on voit tous les jours, leur comportement reste quelque chose de spectaculaire en soi. De nombreux phénomènes intéressants ont lieu alors que personne n'en a conscience. Au cours de cette étude expérimentale, une caméra à haute vitesse a été utilisée afin de recueillir des données et de décrire, expliquer et prédire ce qu'il se passe lors du contact entre une goutte lâchée sans vitesse initiale, d'une hauteur variant de quelques centimètres à deux mètres, et un surface liquide. De l'eau distillée, de l'éthanol et de l'huile de silicone ont été utilisés pour obtenir des résultats complémentaires et comparables. Des relations entre les phénomènes observés et plusieurs paramètres adimensionnels ont été établies pour chaque liquide. Une sorte de répartition de l'énergie de la goutte après son impact a aussi été esquissé. Enfin, durant l'analyse de chaque phénomène, les résultats de différents chercheurs ont été considérés pour faire des comparaisons intéressantes.

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Introduction

Apart from being a phenomenon that is both interesting and beautiful, the impact of a liquid droplet on a surface is of practical importance in many natural and industrial processes. Raindrops enhance the soil erosion and they modify the interaction between the atmosphere and oceans. Drops are also used, through their impact, in many pyrometallurgical operations. Actually many processes are driven by droplets and especially by phenomena that are unseen to the naked eye and which account for a very special part of fluid physics.

As droplets are smaller than a river and larger than molecules their size is an intermediary one. This leads parameters that govern droplet evolution to be, at the same time, those which drive a river flow and those which characterize atom interactions.

Droplets have been studied since the end of the XIXth century. Rayleigh [1,2], Reynolds [3,4], Worthington [5] and Thomson and Newall [6] are the main researchers who studied it in that century. They examined the phenomena that may happen when a droplet falls onto a surface and more precisely, the impact of a liquid droplet onto a liquid pool. It has long been a problem of interest to physicists owing to its relevance in raindrops dynamics [7], production of ocean mist and airborne salt particles [8] and more generally vorticity generation near an interface through the formation of a vortex ring [9].

Depending on its impact velocity, a droplet may either bounce or float or coalesce when it hits the liquid surface [10].

When the kinetic energy of the droplet is small, the surrounding fluid is slowly expelled from the gap separating the two fluid masses as the droplet approaches the liquid surface. This fluid layer may remain enough time to make bounce the droplet. If the energy is larger, the layer of the surrounding fluid become too thin and Van der Wal forces become important: the two liquid interfaces coalesce [11]. Sometimes, the droplet floats: it remains at the surface without moving vertically but it coalesces within a finite time.

After the contact between the droplet and the liquid surface, some phenomena may occur. If the droplet is not very energetic, it will not even create a crater and, sometimes, when it coalesce, a smaller drop (the apex droplet) is released from the bigger one. Their size can be more or less predicted as it may depend on the Ohnesorge number [12].

Then, for quite low energetic droplets, vortex rings stop and a jet may appear resulting from the crater collapsing . Some characteristics are assessed. It seems that they appear when vortex rings stop. Experimenting with mercury, Hsiao et al. gave a critical Weber number value for the creation of the jet [13]. Their results matched with those obtained by Rodriguez et al. in 1985. The maximum height of the jet seems to depend on numerous parameters and not only in the case of a liquid jet but also with a jet made with granular solids. Thoroddsen and Shen plotted the maximum height of a granular jet as a function of the Reynolds number times the Froude number [14] whereas other researchers like Fedorchenko and Wang established a link with the Froude number [15]. Moreover, instabilities may create secondary droplets which pinch-off from the jet. Hallett and Christensen found a ratio between surface tension and inertia that may characterize this detachment [16].

For droplets with high energy, small droplets may be ejected from the edge of the crater. This phenomenon is called splash. Some researchers predicted the crown shape [17], although results linked with this work are those which characterize the splash apparition. Wang and Chen experimented with three liquids with different physical properties and found different critical Weber number. Other researchers also found a splash/nonplash boundary depending on the Ohnesorge number and on the Reynolds number [18].

Interesting phenomena also occur when the droplet does not coalesce. When it bounces, the ratio of its velocity after impact to its velocity before impact called restitution coefficient may be predicted. Through theoretical and experimental approaches, it seems to be linked to the Stokes number [19]. A limit for non-bouncing was also established linking the Stokes number to the capillary number.

During the training period that I did, as a second year student at ENSEEIHT, at the Microgravity laboratory of the "Universitat Politènica de Catalunya", I studied all these phenomena. I made experiments with three liquids: distilled water, ethanol and silicone oil. All of them have different physical properties and allow therefore making interesting comparisons. For each of these liquids, I run the same experiment: releasing a droplet from different heights and then observing, with a high-speed camera, its impact on a liquid surface at different impact velocities. I first studied each liquid separately, determining the relation between the Weber number, which is one of the main parameters for droplet evolution, and observed phenomena. I also tried to estimate how the energy of the free-falling droplet is dissipated, and each phenomenon was accurately studied. I compare each result with other liquids and I finally compared my results with those I found in the literature.

I. Laboratory context

My internship took place in the Microgravity laboratory of the "Universitat Politècnica de Catalunya". This university is divided into several campus around Barcelona, Spain, and I worked in the Castelldefels division. The university is specialized in architecture, engineering, merchant seamanship, economics, health sciences and applied mathematics. About 40000 students study there each year. More than a basic university, it is a very important pole of research in the Spain as there are more than 3500 research staff, 2564 sponsoring and collaborating companies and 84 cooperation and development projects in UPC.

The laboratory where I worked was originally created to determine the role of gravity on some physical processes like material science or fluid physics and to test and develop the design of space systems for space hardware. My work did not consist in studying something concerning microgravity but maybe, my results will be used in a further study. These are several projects currently being undertaken in this laboratory:

- Bubble jet impingement
- Vibrations in two phase systems
- Multibubble sonoluminescence in microgravity
- Characterisation of a bubble injector for space application

II. Experimental set up

The experimental set up is quite basic but it allowed to observe the main interesting phenomena. Image software used were very useful but their use brought some errors.

II.1. Presentation

All the experiments where run with the same system (Figure 1). I made a droplet fall into a transparent cubic Plexiglas container (1), with inner dimensions 100mm*100mm*100mm and half-filled with a liquid (about 55 to 60mm deep). Droplets were released by a syringe filled by the same liquid (3) that can be moved vertically. The size of the syringe hole is about 1mm which provides droplets with a diameter close to 2mm. At the upper end of the syringe, the piston was removed in order to let the liquid in contact with the ambient air. This creates a pressure gradient in the syringe and droplets are released at the bottom very regularly.

To record the contact of droplets with the free-surface, I used a MotionXtra HG-SE high-speed camera (2) connected to a computer with the software REDLAKE Imaging Studio, which allowed to record videos on the computer. The camera can provide 32000 fps (frames per second) videos but I recorded only 2000 fps videos in order to be able to keep large field and long enough videos. The exposure time was set to 500µs. As the common light frequency is 50Hz, a backlight (5), composed by a 126 LED plate connected to a continuous power supply, was used in order to correctly enlighten droplets. A diffusion film (4) was also put between the container and the plate in order to diffuse the light emitted by LEDS.

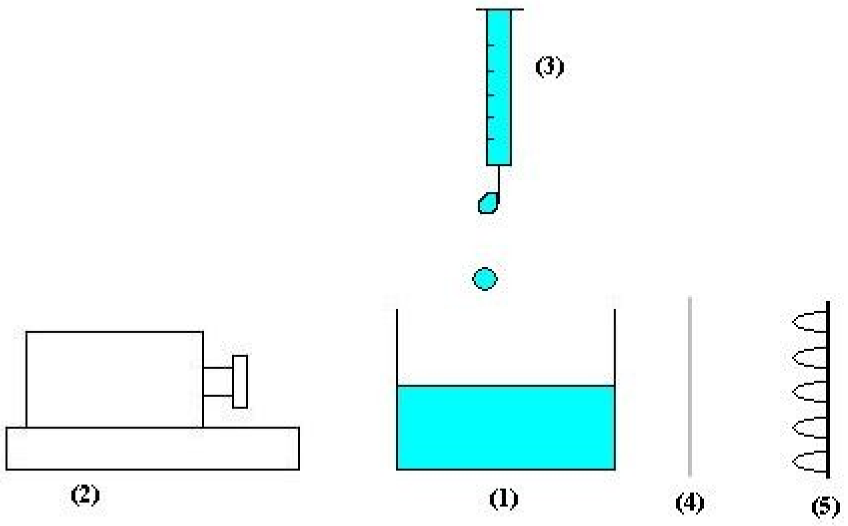

Figure 1: Drawing of the experimental set up: (1): half-filled recipient; (2):high-speed camera; (3): syringe; (4): diffusion film; (5): backlight.

II.2. Videos

The resolution of the videos recorded was generally 320*256 pixels, and the length of one pixel varied from 0.05mm to 0.1mm. This size allowed to see both horizontal and vertical phenomena like the formation of a crown around the crater and the splash that follows it or the formation of a vertical jet and the droplets that it can release. I used two different softwares to create and analyze videos. The first one, REDLAKE Imaging Studio, was used to shoot videos and to keep only the interesting frames. I needed a second one, ImagePro-Plus to make measurements on videos. Indeed, this software has a lot of interesting abilities. It may track an AOI (Area Of Interest), which can be for example a droplet, calculate its area or position. It also has many tools to measure distances between two points like diameters or velocities which can be understood as the distance run by the droplet between two frames.

II.3. Parameters

I used three different liquids: distilled water, ethanol and silicone oil. Table 1 shows their most relevant physical properties. Droplets were released from different heights from 5cm to nearly 2m. Table 2 shows the range of values of diameter, velocity and dimensionless number I used. Actually, they concern only studies with the droplet I made fall and others studies like the bouncing one have other values.

	Density ρ (kg/m3)	Viscosity μ (Pa.s)	Surface tension σ (N/m)
Water	1000	0.0010	0.0730
Ethanol	810	0.0012	0.0220
Silicone oil	960	0.0480	0.0207

Table 1: Physical properties for each liquid

	D (mm)	Velocity (m/s)	$Re=\rho DV/\mu$	$St=\rho DV/\mu$	$We=\rho DV^2/\sigma$	$Fr=V^2/gD$	$Oh=\mu/\sqrt{\sigma\rho D}$ (10^{-3})	$Ca=\mu V/\sigma$
water	1,7 - 2	0,82 - 4,52	1425 - 8484	1425 - 8484	16 - 525	39 - 1108	6,50 - 6,7	0,011 - 0,062
ethanol	1,8 - 2	1,05 - 4,45	1389 - 5507	1389 - 5507	81 - 1372	55 - 1075	2,6 - 2,8	0,059 - 0,249
silicone oil	1,71 - 1,74	0,99 - 4,46	34 - 153	34 - 153	78 - 1562	58 - 1134,5	258 - 260	2,31 - 10,58

Table 2: Values of drop diameter,velocities and dimensionless parameters for each liquid

The dimensionless number are often used in fluid physics. The Reynolds number (Re) is the ratio of inertia forces to viscous forces. The Stokes number (St) is the ratio of the same entities, but it may include some added mass effect. In my case, it is the same as Reynolds number. The Weber number (We) is the ratio of the inertia forces to the surface tension forces. The Froude number (Fr) is the ratio of the inertia forces to the gravity forces. The Ohnesorge number (Oh) is the ratio of viscous forces to the square root of inertia times surface tension forces. The Capillary number is the ratio of the viscous forces to the surface tension forces. In all these definitions and in all the expressions in the Table 2, ρ is the density of the liquid droplet, μ its dynamic viscosity, σ its surface tension, D is the diameter of the falling droplet and V is its velocity before impact.

II.4. Measurements

Using a wide range of heights, I was able to record all the commented phenomena, except with silicone oil. For each record, I always measured the velocity at impact and the diameter of the falling droplet, and when it happened:

- the potential energy of the vertical jet when it reaches its maximum height, assessing its weight by dividing the jet in parts where its diameter was the same
- the diameter, the velocity of droplets released by the jet and the height where I measured this information in order to assess a global energy which is the sum of the potential and the kinetic energy of each droplet
- the diameter and the velocity of all the droplets released by the splash, in order to obtain a global kinetic energy of droplets released by the crown

In order to calculate the potential energy of the jet, I separated the vertical column in three or four parts where the diameter of the column did not change very much. Then I just had to calculate the potential energy of each volume assimilated as a cylinder, assess their distance from the liquid surface and to add these energies. I obtained a potential energy close enough to the real one as the approximation of cylinders is quite a good one.

When I studied other phenomena like bouncing, I used these same videos but I did not use the droplet I made fall. Therefore, what I measured depended on the video but it was often diameters, height and velocities.

II.5. Drawbacks

However, the biggest problem I had to face was the measurement precision and the error that it may engender. Here, errors are not easy to assess. During the video treatment, droplet positions were determined by the software Image-Pro Plus. As the light was not exactly uniform, the software could have made little errors but these errors could have been increased when I subtracted lenghts to calculate velocities. But the error can hardly be greater than one pixel, and so the error is less than few percents. Nevertheless, the result concerning the value of the droplet ejected by the crown global energy is not very precise. First, this phenomenon occurs in three dimensions. Thus, droplets which are released at the front or at the rear are blurred and are not in the focus plan of the camera: a pixel there, is not as many millimeters as a pixel in the focus plan of the camera. What is more, the size of many droplets released this way is only 3 pixels or less. For one droplet, doing a mistake of 0.5 pixel brings an error of more than 15%. As there are sometimes 20 droplets leaving from the crown, adding their energies may make errors be canceled or get worse. But fortunately, this splash global energy is more than 10 times less than the other energy measured and the error made on the study of the splash does not change the validity of the other results.

III. Phenomena presentation

I studied five phenomena, more or less linked together. Some appeared at the contact between the released droplet and the liquid surface. Others, like apex droplets and bouncing, appear with the contact of a secondary droplet (created by the one initially released) and the liquid surface. This difference is due to the different energy contained in them.

III.1. Vertical jet

With all liquids, the first phenomenon which occurs is the vertical jet (Figure 2). Actually, the crater generated by the impact of the droplet collapses, and creates a rising column of liquid. Many authors separate this entity with something called vortex rings, which is indeed vorticity generated around the crater. They all agree saying that when one occurs, the other one does not. One of the first proposing a critical limit for these two phenomena were Rodriguez and Mesler [20]. They proposed a limit with the Weber number and said that for $We=U*\sqrt{(\rho D/\sigma)}$ greater than 8, vortex rings are not formed, and so, vertical columns are. As I worked with an other definition of the Weber number which is $We= U^2\rho D/\sigma$, the limit that it gives is We=64. Since then, this value has been confirmed by many other researchers like Hsiao et al. [13] or Liow [21]. Manzello and Yang [22] assessed the influence of temperature on this critical We and, for ambient temperature, the value they found was close to 60.

Vertical jets are also studied through measuring their maximum height. Even if it is not with liquid, Thoroddsen and Shen [14] run experiments with granular jets and found quite comparable results. They plotted the jet maximum height versus Re*Fr which were dimensionless numbers of a falling sphere. Fedorchenko and Wang [15] worked with a liquid, and plotted the jet maximum height versus the Froude number of the falling droplet.

Some researchers have also analyzed the velocity of the jet. Bartolo et al. [23] found unusual curbs plotting the ratio of the jet velocity to the velocity of the falling droplet as a function of the droplet velocity.

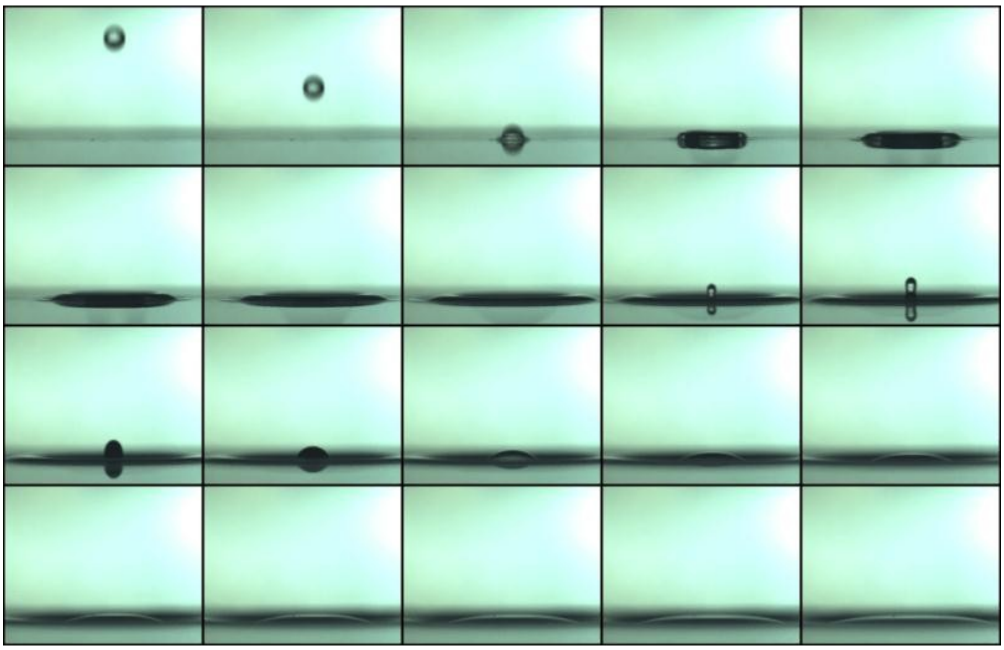

Figure 2: Example of jet without secondary drops. 2,5 ms separate two frames (from left to right and up to down).

III.2. Ejection of droplets

The vertical jet I just talked about is not always stable. In some cases, when instability occurs, some droplets may pinch-off from the top of the liquid column. I saw that, at quite low We, some very small droplets were ejected from the jet just after it was created. At greater We, the size of ejected droplets is about the size of the droplet I made fall, and they are ejected when the jet is higher. As I have not enough information usable for the very small droplets, I will only speak about the biggest one.

As I said, the instability caused by the falling droplet may bring one or more new droplets to be ejected (Figure 3). During my experiments, I was able to see more than three droplets released from one single jet. Sometimes, droplets interact between themselves. Even if image quality is not good enough to notice it, after being ejected, the second and the third secondary droplets bounce one onto the other in Figure 3. But as they are created by an instability, for droplets released from the same height, the impact can result in a different number of ejected secondary droplets.

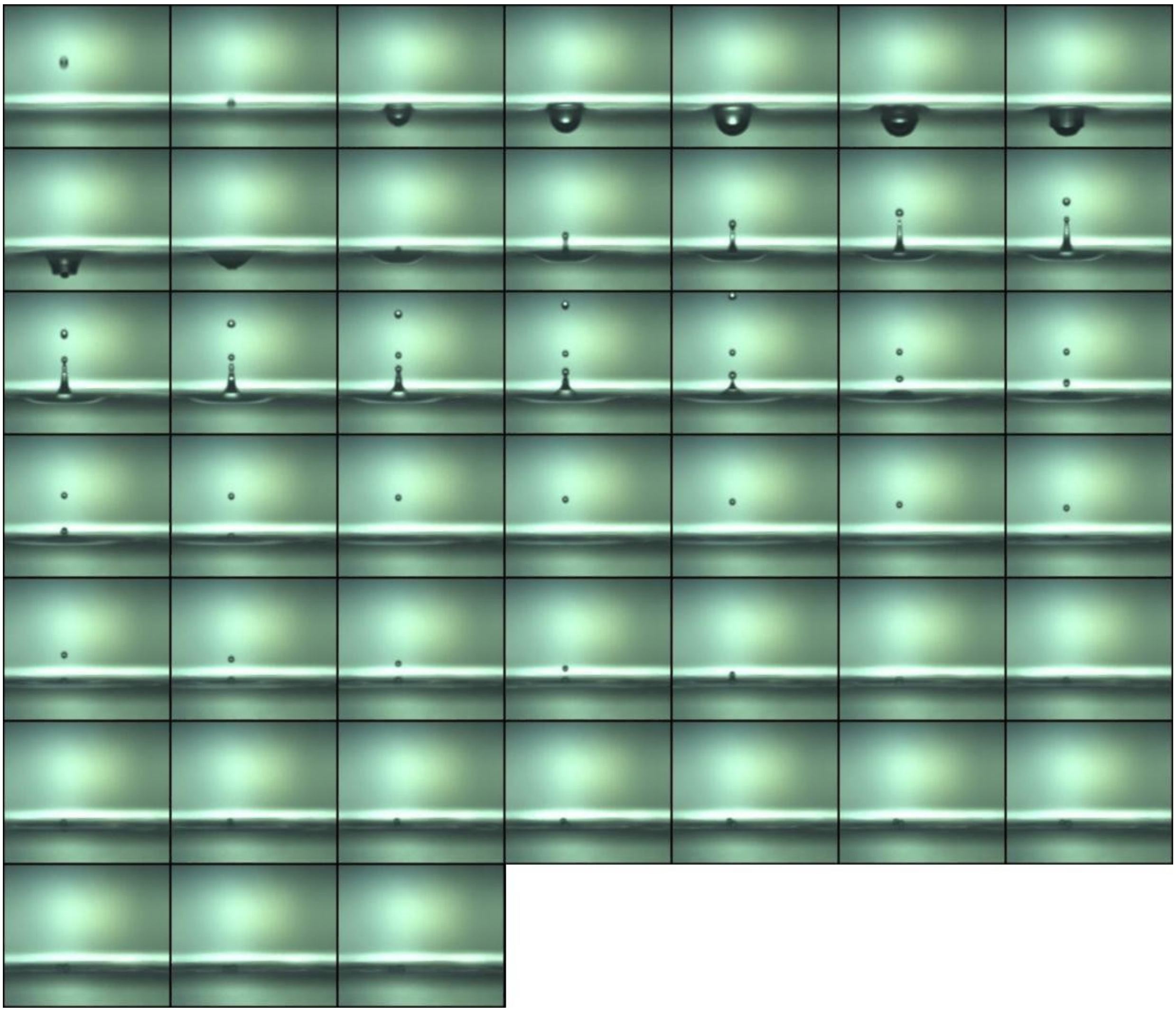

Figure 3: Example of ejection of multiple droplets. 3 ms separate two frames (from left to right and up to down).

Nonetheless, some authors tried to predict when these secondary droplets may pinch-off from the jet. Hallett and Christensen [16] calculated the ratio L of kinetic energy to surface energy. They found that droplets are ejected from the jet when L=7. According to them, this ratio seems to be linked to the Weber number and equals We/3. However, Rein [24] corrected this value and proposed that the ratio should be equal We/12. This brings to a critical We for the droplet separation of 84.

III.3. Splash

When a droplet with large enough energy impacts the liquid free-surface, there may occur a splash (Figure 4). Actually, this phenomenon takes place before (before in time, not before in energy) the crater collapsing, just after the droplet touches the surface. At the contact of the droplet, a crown is formed around the impact point. Very often, an instability brings this crown to eject very small droplets. Their size and velocities may vary a lot, and their number is hardly definable even if it seems that it increases when the falling droplet energy gets greater.

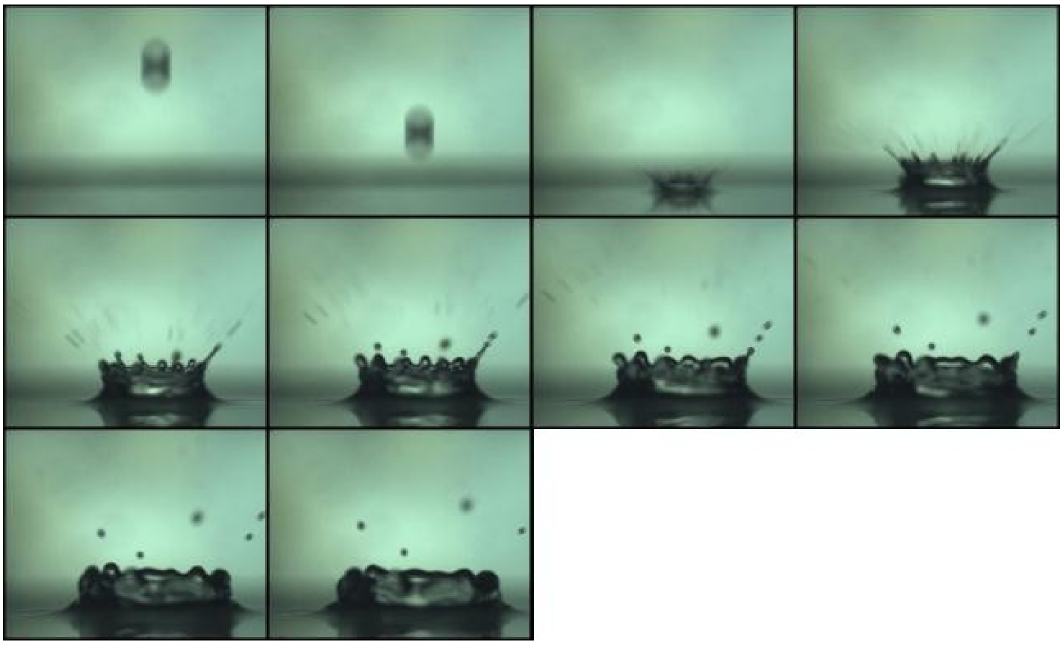

Figure 4: Example of splashing. 1 ms separate two frames (from left to right and up to down). The oblate aspect of the drop is due to the too long shutter time. The drop is spherical.

Furthermore, this is one of the most studied phenomena. Many researchers try to predict how the crown will behave. As I did not have enough time and as my videos were not precise enough, I was not able to study things like crown shape or energy of crown. I only focused my study on determining a critical limit for the apparition of the splash and to determine the energy of these ejected droplets. In 1984, Hallett and Christensen noticed that, with water, a crown appears for We>180 [16]. This is a different value of what Wang and Chen [25] found. They tried three different glycerol-water solutions with concentrations equal to 60%, 70% and 80%, and they found three different critical We which were respectively 400, 500 and 800. Some researchers think that the difference should come from the viscosity difference. This may justify the study made by Vander Wal et al. who plotted the splash/non splash boundary for thirteen liquids on a Oh-Re diagram [18], including therefore the viscosity.

III.4. Other phenomena

Previous phenomena were those I have been able to study increasing the height of the syringe, but there are others, that I was not able to study or that I studied but not directly with my falling droplets.

First, as everyone can see, when something falls into a liquid free surface, waves are formed. This still happens when a droplet impacts the surface. As the camera I used was on the free surface plan, I was not able to assess the volume contained in waves and so to assess the energy of these waves. Therefore, I did not study them even if they may be an important phenomenon.

Then, there are two other phenomena that can not be seen without a high speed camera. The first one is bouncing. Droplets I released didn't bounce but, as I said, droplets may create a jet and therefore, sometimes other droplets. These droplets, which are sometimes smaller and whose velocities are smaller too, may sometimes bounce. In Figure 5, in the middle frame of the third line, the secondary droplet is below the surrounding liquid surface but, some frames later, we see this droplet above the liquid surface. Actually, I counted a bounce when the droplet goes below the surface and then goes up again. Sometimes, it floats on the surface after.

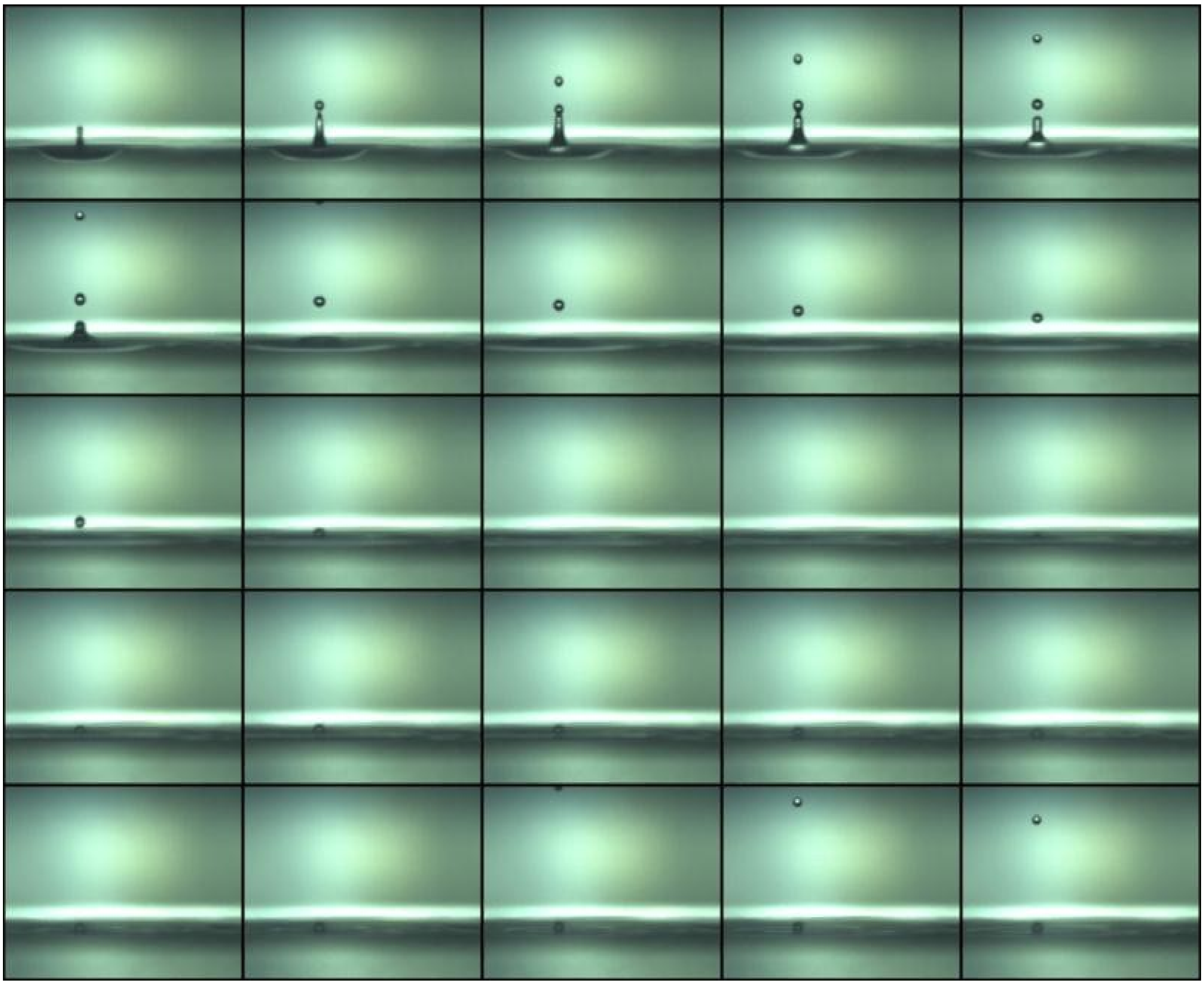

Figure 5: Example of bouncing. 5 ms separate two frames (from left to right and up to down).

The two main aspects that are observed with bouncing droplets are if there is bouncing or not and what is the restitution ratio which is the ratio of the velocity of the bouncing droplet after impact to its velocity before impact. Legendre et al. proposed laws for these two issues [19]. They found that a droplet will not bounce if $St^* < 2\ln(1/\sqrt{Ca})$ where St^* is the Stokes number of the droplet including its added mass and Ca is its capillary number. They also proposed that the restitution coefficient ε may be a function of St^* with $\varepsilon=\exp(-\beta/St^*)$.

The second phenomenon did not occur often. Sometimes, when a droplet coalesces, a smaller droplet is ejected from the first one (Figure 6). These droplets are called apex droplets. I tried to study them and to compare to the results of Aryafar and Kavehpour [12] who plotted the ratio of the smallest diameter to the biggest one versus the Ohnesorge number of the largest droplet.

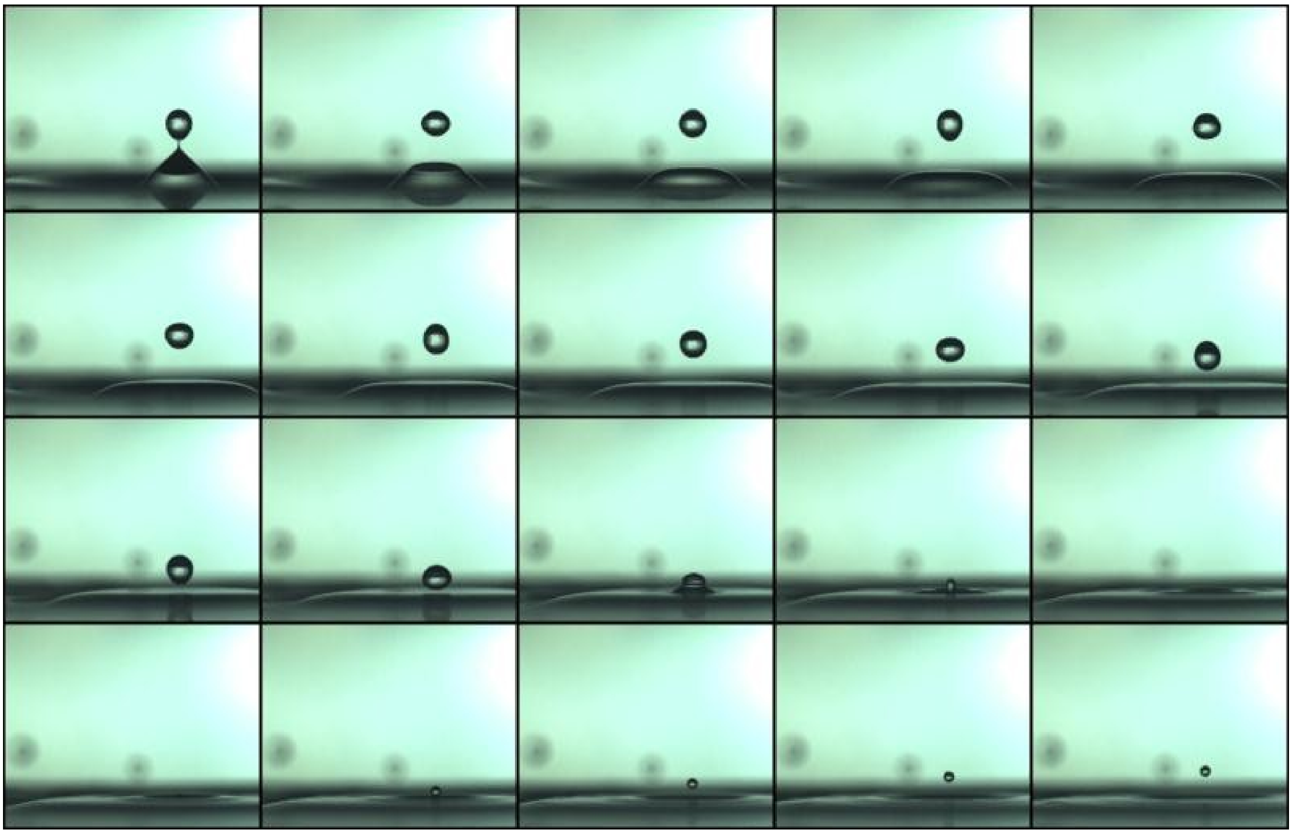

Figure 6: Example of apex drops. 2,5 ms separate two frames (from left to right and up to down).

IV. General results

For each liquid, I tried to obtain comparable result in order to make interesting conclusions afterwards. I managed it with water and ethanol but results with silicone oil are not numerous.

IV.1. Water

This chapter deals with distilled water which is the first liquid I experimented with. It sums up all the global results I had and especially the importance of the Weber number and the repartition of the energy of the free falling droplet.

IV.1.a. Evolution with We

The first experiments I made were with water. I released water droplets from 5.5cm to 172cm above the water free-surface. Focusing on assessing the Weber number of each record and on determining which phenomenon happens, I have been able to observe some correlations between the Weber number and these phenomena. This has lead me to the following observations :

- Until We=43, the surface is just slightly disturbed.
- From We=43 to We=57, the surface is disturbed and a kind of jet appears
- From We = 57 to We=93, there are small and quick secondary droplets which result from an instability in the rising column
- From We=93 to We=113, there is one jet with sometimes small quick droplets or sometimes one big secondary droplet or sometimes nothing.
- From We=113 to We=131, there is only one big secondary droplet(and of course a jet)
- From We=131 to We = 179, there is a splash at the contact and there is still one big secondary droplet
- From We=180 to We=525, there is still the splash and one big secondary droplet, in most cases, there is also another secondary droplet and in few cases there is a third one.

IV.1.b. Repartition of energy

I measured potential and kinetic energy for the primary droplet, for secondary droplets, for the jet and for the splash. I calculated the sum of these two energies for each one of these entities. Then I calculated the ratio of these sums to the initial droplet energy and I plotted them as a function of the Weber number of the initial droplet. The initial energy I used is the kinetic energy of the primary droplet at arrival because it is much bigger than the potential energy, and so nearly the same as the real droplet energy. The vertical jet seems to be the most energetic phenomenon (Figure 7). It is important to note that this histogram is made to show the different ratios and that a fit can not be directly done as the Weber number axis is not uniformly graded.

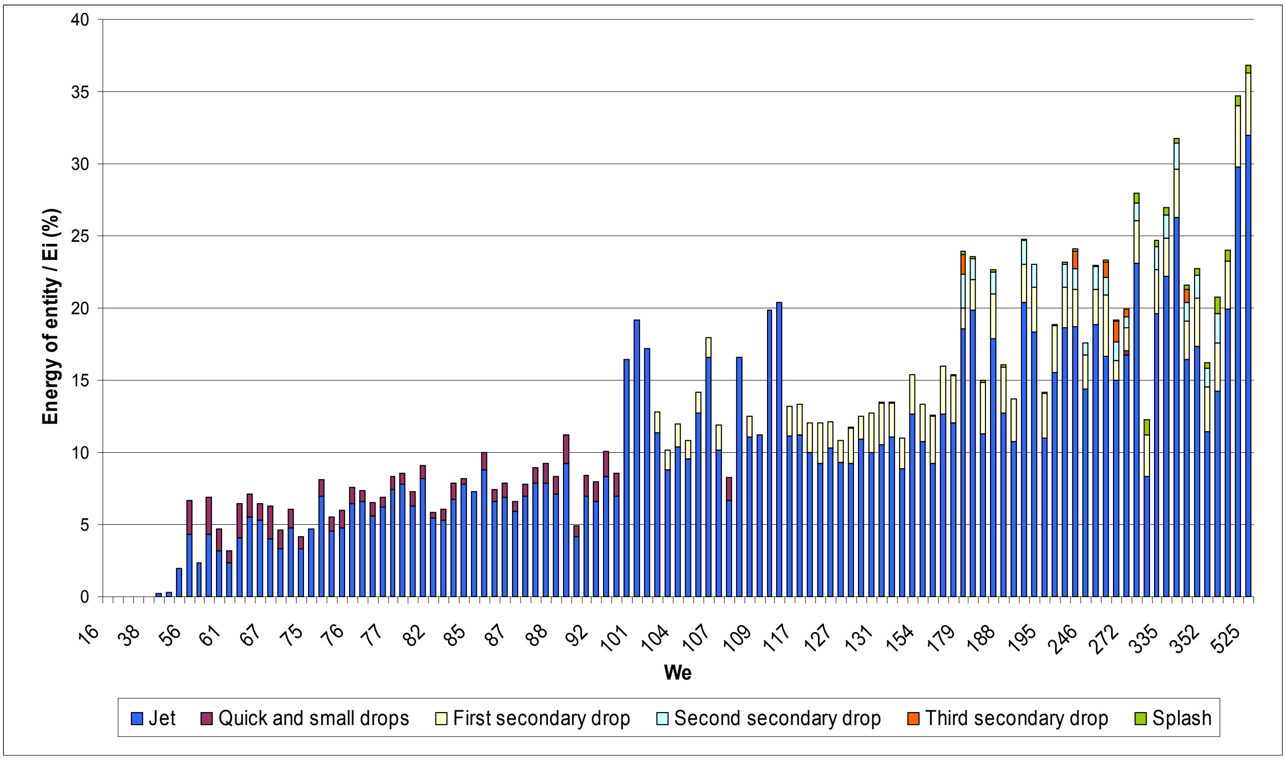

Figure 7:Ratio of the energy of each entity to the initial energy versus the Weber number of the initial droplet.

Using this data, I have been able to assess which percentage of the initial energy (Ei) is not used by the jet, the splash and by secondary droplets. Actually, this can be understood as an estimation of the energy dissipated (Ed) in the oscillations of droplets, in the cavity formation and in surface waves. Actually, data bring strangely to a linear relation between Ei and Ed (Figure 8). The correlation number R, which equals 0.9814, shows that the relation is strongly linear. The slope of the line is about 0.70. Thus, on average, there is only about 30% of the energy of the free falling droplet which is given to the splash, to the jet and to the secondary droplets and about 70% that it dissipated between droplets oscillations, crater formation and surface waves.

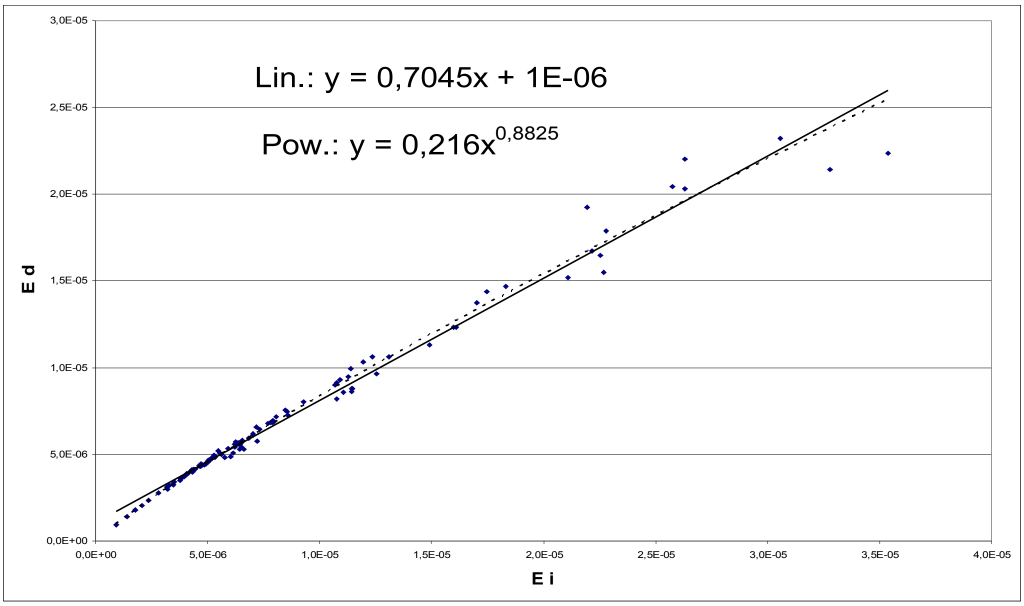

Figure 8: Ed versus Ei with linear (Lin.) and power (Pow.) regressions

However, the main drawback of this linear approximation is that this curve does not match the origin point. Indeed, if there is no droplet or droplet without energy this one will obviously give no energy. This is the reason why I tried to use a power regression (Figure 8). I obtained $Ed=\alpha*Ei^{\beta}$ with $\alpha=0.216$ and $\beta=0.8825$. β is quite close to 1 which shows that a linear regression is quite a good approximation.

IV.2. Ethanol

I tried a second liquid in order to see if the results I had with water may be comparable with the results of a liquid with different physical properties. This second liquid, ethanol, has slightly lower density and considerably lower surface tension than water. As for water, I tried determine the correlation between the Weber number and phenomena that occur and, moreover, to plot some energies as a function of the primary droplet energy.

IV.2.a. Evolution with We

I made the same experiments as with water but making only about fifty videos. I released droplets from 13cm to 190cm above the ethanol free surface. I tried then to observe which phenomenon occurs for which We:

-Until We=112, the surface is slightly disturbed and we can not even see a jet

-From We=112 to We=237, there are sometimes small and quick little droplets and always a jet

-From We=237 to We=290, there are the jet and one big secondary droplet

-From We=290 to We=711, there are the jet, one big secondary droplet, always a second secondary droplet and in many times a third secondary droplet

-From We=711 to We=1372, there are the same things as before with a splash

Comparisons will be made in the chapter IV.4 but we can already notice that critical We values are different from those in water.

IV.2.b. Repartition of energy

Results concerning the repartition of the energy are quite interesting and may be close to those with water. As we can see (Figure 9), the repartition looks like in the water experiment and the jet is still the most energetic phenomenon. The diagram is still used to show ratio values and the Weber axis is still not uniformly graded.

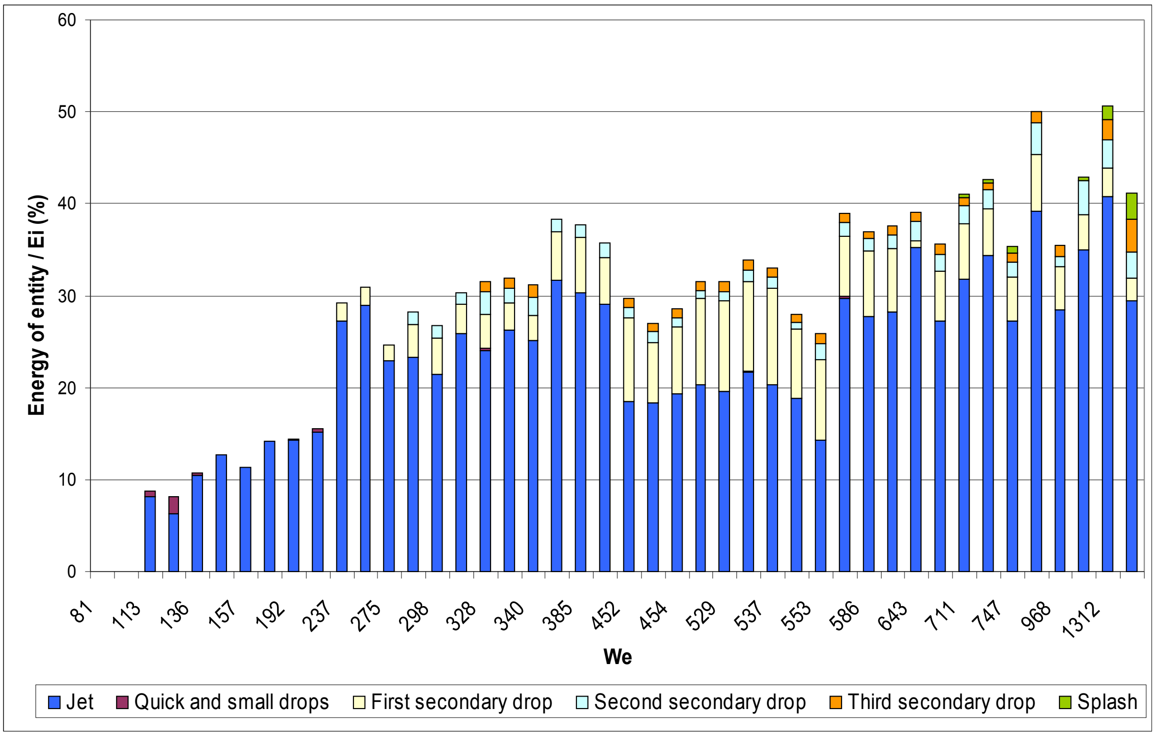

Figure 9: Ratio of the energy of each entity to the initial energy versus the Weber number of the initial droplet.

Around We=500, there is a decrease of the energy of the jet. In the meantime, there is also an increase of the energy of the first secondary droplet. This value of We accounts certainly for a case where the jet transfers more energy to the droplet it releases and therefore, at the beginning, the energy of the first secondary droplet and on the jet are certainly the same. Thus, it would be more interesting to consider the energy of the jet plus the energy of first, second and third (and other) secondary droplets as they seem to be originally the same.

Then I used in an other way this data and I made the same regressions as with water (Figure 10).

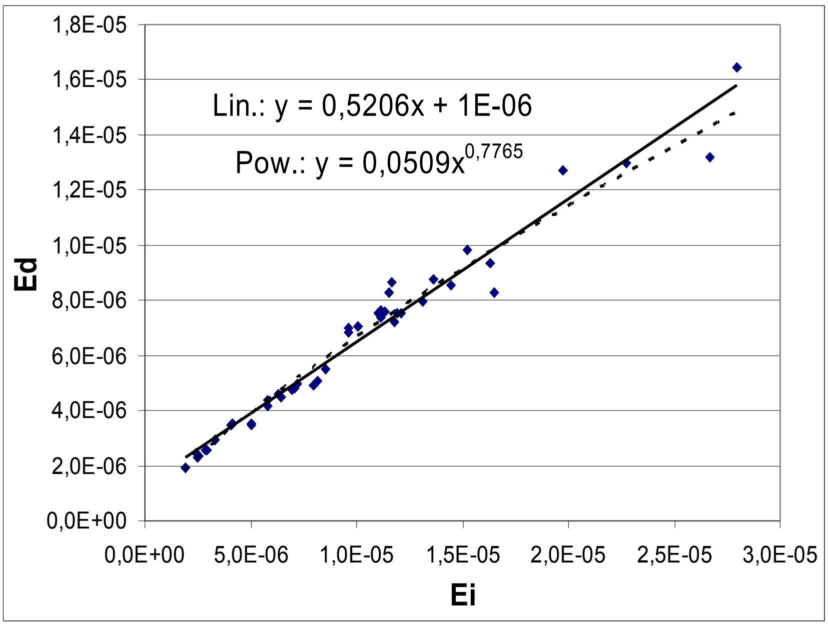

Figure 10: Ed versus Ei with linear (Lin.) and power (Pow.) regressions

But some figures change. The linear approximation seems to be still a good one. The correlation number is close to 0.97 but the slope is 0.52 whereas with water it was 0.70. That means that 48% of the energy of the free-falling droplet is redistributed among the jet, secondary droplets and the splash and 52% of the initial energy is dissipated between droplets oscillations, crater formation and surface waves. But there is still the problem of the origin point non matching. So, I fitted a potential curve and its equation is $Ed=\alpha*Ei^{\beta}$ with $\alpha=0.0509$ and $\beta=0.7765$ (Figure 10). β is still quite close to 1 but the linear regression with ethanol is worse than the one with water even if both remains still good approximations.

IV.3. Silicone oil

In order to confirm or infirm some of the assumptions I could have made before, I made experiments with a third liquid, silicone oil. The main difference between it and the two other liquids is its viscosity which is ten times bigger. Results with the silicone oil are quite surprising. Until We=484, there is nothing, the free surface is nearly not disturbed. We must reach We=1180, to see a kind of jet. And even at We=2000, there are no secondary droplets and no splash whereas, at this value, with the two other liquid, there would have been several secondary droplets and a splash. We can imagine that releasing droplets from a higher point would have allowed these phenomena but I was not able to release droplets from higher than 2m above the liquid pool in my laboratory.

IV.4. Comparison

I analyzed mainly the difference between water and ethanol results. The first obvious observation is that critical Weber number are different. What is more, with ethanol, the second and third secondary droplets occur before splashing whereas with water they occurred after. This brings me to say that the presence of one, two or three secondary droplets depends on instabilities and do not depend on the Weber number, even if instabilities may depend of this dimensionless parameter. That is to say that, supposing that there is a critical Weber number for apparition of one secondary droplet might be relevant, but doing it for the apparition of the second secondary droplet or the third for is not. Moreover, as critical Weber number are quite different, we can easily affirm that a parameter distinct from surface tension and from inertia must be important in this study.

Concerning the repartition of energy, for both liquids, the jet is much more energetic than other phenomena, especially splashing. For both, making a linear fitting in the graphic Ed-Ei seems to be relevant, at least in order to have a good approximation of the ratio Ed/Ei. Besides, this ratio is not the same for the two liquids and it requires further investigations to explain it.

Even if the silicon oil experiment did not give a large amount of results, it helps us to confirm the fact that We is not the only important dimensionless parameter. Indeed, as the main difference the silicone oil and the two other liquids is viscosity, we can imagine that viscosity must be considered to have relevant results. This may also explain the difference between critical Weber number between water and ethanol even if their viscosity are more or less the same.

V. Phenomena analysis

The aim of this chapter is to present results for each phenomenon and to compare them for all liquids. Some results extracted from literature are also written in order to have some references.

V.1. Vertical jet

In this paragraph, the main objective was to find correlation for the maximum height of the jet. A precision concerning my experiment is written not to be confusing. Some other results like with the Weber number are also given.

V.1.a. Critical Weber number

At first, the vertical jet looks like a big disturbance on the liquid surface but then it is more like a rising liquid column. Many researchers tried to define when this phenomenon appears. Rodriguez and Mesler [20] opposed the jet to vortex rings created around the crater made by the droplet. They found a limit We of 64 which has been confirmed afterwards by some scientist like Hsiao et al. [13] or Liow [21]. Other researchers like Manzello and Yang [22] looked for this limit We for different temperatures. For ambient temperature they found a value close to 60. This is close to some of my results. Indeed, with water, a rising column appeared at We=57. But this good correspondence is worse for ethanol (appearance for We=112) and even more for silicone oil (at We=2000 there is a jet but it has not a rising column shape).

V.1.b. How to measure the maximum height of the jet?

Researchers also study vertical jets through other parameters. Some try to determine the diameter of the jet and other try to determine its maximum height. I tried to find comparable results with the latter ones.

At first sight, measuring the maximum height of the jet seems to be very simple. Watching the frame where the jet is at its maximum and measuring its height seems to be sufficient. It could be. But which height should we measure? Actually, the main question is, should we count secondary droplets as a part of the jet or not? Indeed, as I said that at the beginning, the energy of secondary droplets is the energy of the jet we should maybe measure the height before droplets are released in order not to lose some information of the jet. But actually, after the first secondary droplet ejection, the jet generally keeps rising. And this may also be true with the second secondary droplet. All this is quite controversial and images on Figure 11, which are extracted from only one video show different cases:

-Frame 1 (23,5ms after droplet impact) : we can measure the height just before the first droplet is ejected, and therefore we will not lose any part of the jet.

-Frame 2 (24ms after droplet impact) : we can measure the height just after the first droplet is ejected, considering that ejected droplets are not the same objects as the jet.

-Frame 3 (38,5ms after droplet impact) : we can measure the height just before the second droplet is ejected, counting or not the size of the droplet-to-be.

-Frame 4 (44,5ms after droplet impact) : we can measure the height just before the third droplet is ejected, and therefore counting the size of the future droplet.

-Frame 5 (45ms after droplet impact) : we can measure the height just after the last droplet is ejected, and therefore counting only the jet, without secondary droplets.

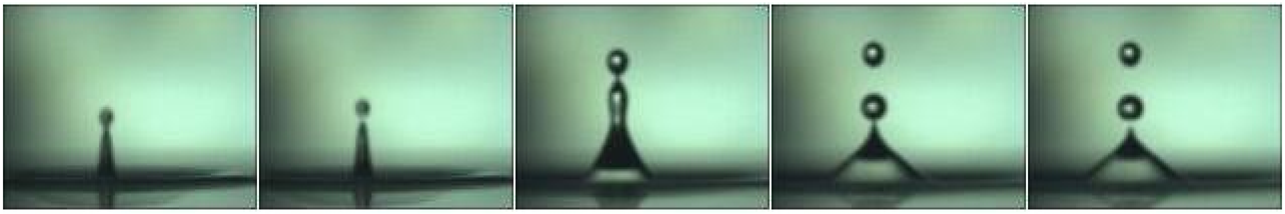
Figure 11: Example of ambiguities for the jet maximum height measurement

Obviously, there are many possibilities. I decided to measure the height of the jet after several droplet ejections. For instance, with this video, as in the two first cases the jet is still rising, I decided not to choose these cases. I also decided not to choose the fourth and the fifth cases because, globally, the jet falls, and when this third droplet is ejected, the jet has a triangular shape and not a rising column shape. So I finally used the third case, counting, as the maximum height of the jet, the maximum height reach by the rising column and, if necessary, droplets when they are still linked to it.

V.1.c. Results on the maximum height

Thoroddsen and Shen [14] made experiments with a solid sphere falling onto granular solids. Doing this, there is also a jet and they plotted its dimensionless maximum height versus Re*Fr where the Froude number was different from mine and equaled U/√(gD). They obtained the following relation: $H/D=\alpha*(Fr*Re)^{\beta}$. α is only a constant and β=1.19 is the important parameter of this relation. Doing the same regression (Figure 12), I obtained for water β=0.74 and for ethanol β=0.59. The power regression seems to be a good one, but β is quite different. This can certainly be explained by the difference of entities.

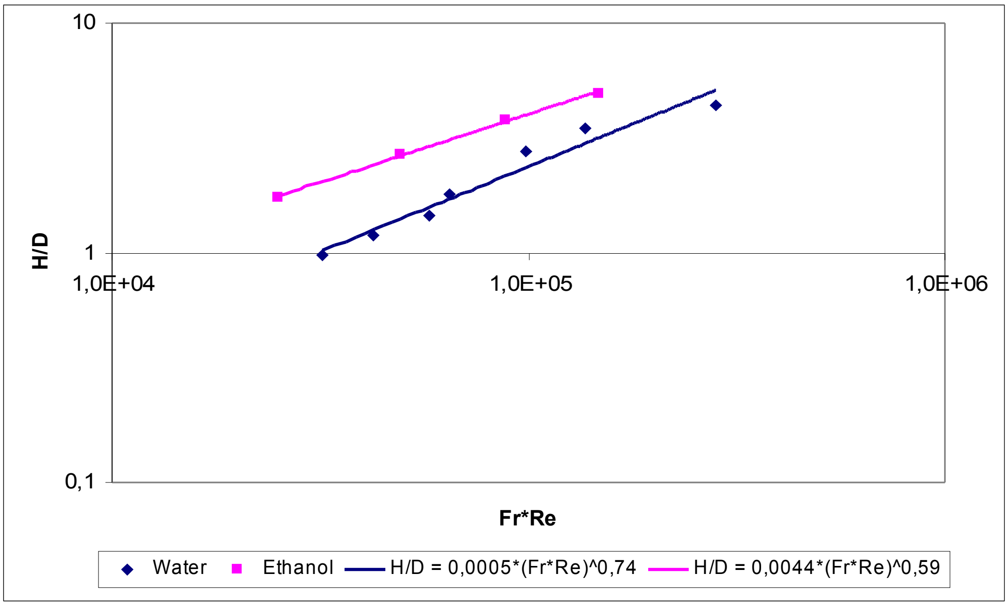

*Figure 12: Jet maximum height as a function of Fr*Re. Here, Fr=U/√(gD).*

Thus, as results were quite different, even for my two liquids, I tried to plot the same results but replacing Fr by We (Figure 13). Indeed, surface tension which appears in We is an important parameter for liquid and is not for solids. Moreover, as I wanted to keep the same formulation as these authors, I changed my definition of We (just for this experiment) and took We=U*√(ρD/σ). This provided me better results. Now, ethanol and water data seem to correspond themselves whereas using the Froude number, they were different.

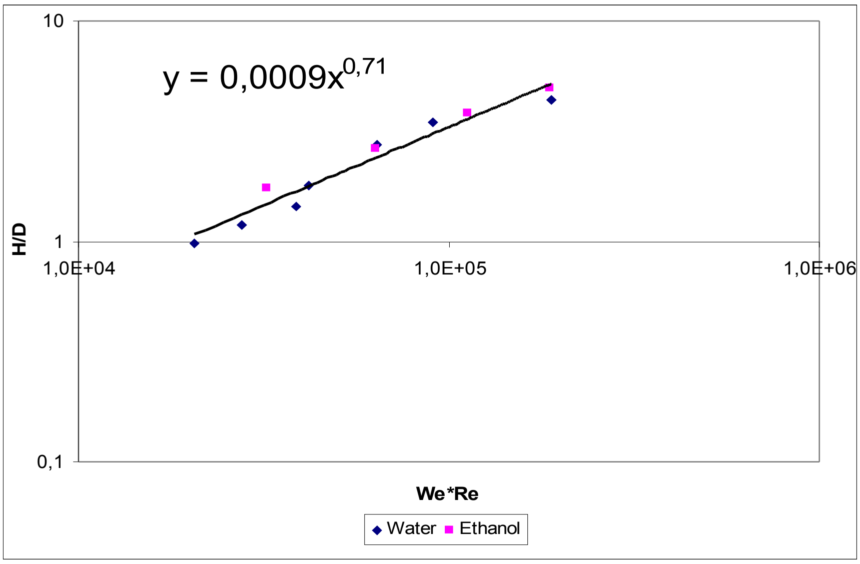

*Figure 13: H/D as a function of Re*We with We=U*√(ρD/σ)*

Here, in this log-log diagram, the power fit seems to be a very good one as we can use the same for water and ethanol data. This gives $H/D=0{,}0009*(Re*We)^{0,71}$.

I also tried to do the same fits using my normal definition of We which is $We=U^2\rho D/\sigma$ and this also gave corresponding data for water and ethanol. Using a power fit again, this gave $0{,}057*(Re*We)^{0,44}$

Still studying the jet maximum height, Fedorchenko and Wang [15] plotted the dimensionless maximum height versus Fr for liquid droplets impacting on a liquid surface. The liquid used was a blend of glycerol and water. They obtained some points which almost perfectly matched their theoretical prediction which was $H/D=1.43*Fr^{0.25}$ (here the definition of Fr is the same as mine). My results are not the same as the power of the Froude number is 0,58 and 0,78 for water and ethanol respectively (Figure 14) but power regressions seems to be the good one.

Several explanation may be given. First, the viscosity of the liquid they used is different from mine and, as they tried only one liquid to confirm their results, maybe using other liquid would have given other results. Then, in their theory, they neglected the role of gravity supposing that only surface tension is important. Actually, this hypothesis is relevant for small droplets such as in my experiment, but according to the droplet viscosity, the fact that surface tension is the most important parameter may certainly be more or less true. It would be interesting to run exactly their experiment again, using new liquids, in order to confirm or infirm their theory.

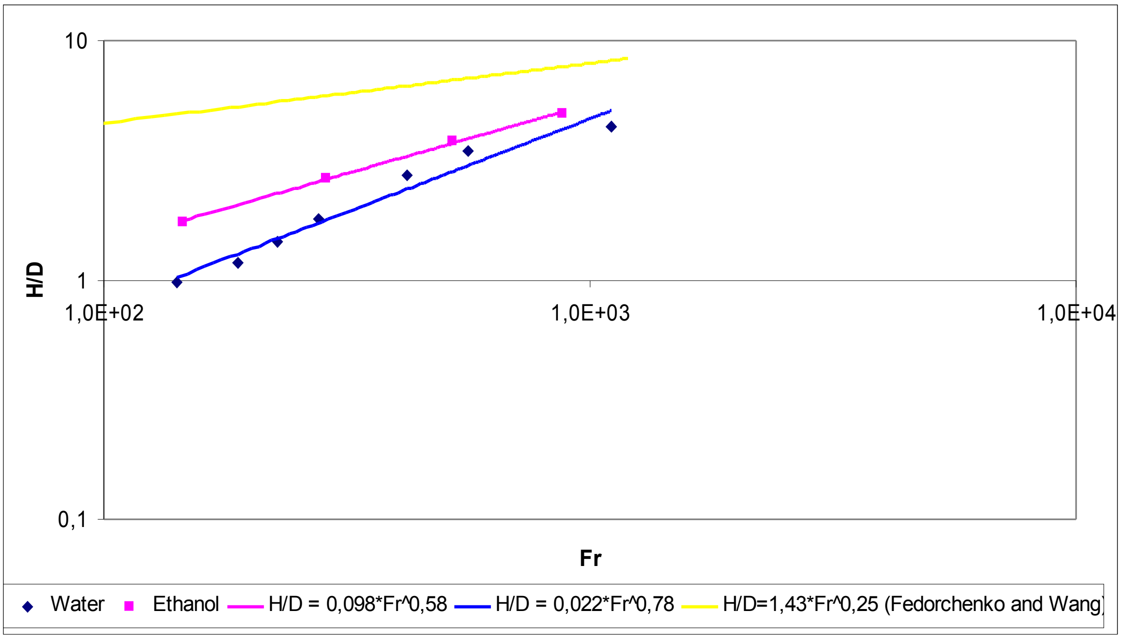

Figure 14: Jet maximum as a function of Fr

V.1.d. Jet velocity

Bartolo et al. [23] found different behaviours concerning the velocity of the jet. They plotted the ratio K, which is the ratio of the velocity of the jet Vj to the velocity of the impacting droplet Vd, as a function of the droplet of the impacting droplet Vd. At low droplet velocities, K seems to rise until K=30 for Vd=0,45m/s. Then it decrease and increase again till K=15 for Vd=0,65. After that, the greater Vd the lower K. Their diagram stopped at nearly Vd=1m/s with K equaling several unities.

When I had a jet, the velocity of my droplets were at least 1,5m/s. It seems that their diagram is also efficient for higher Vd (Figure 15). Indeed, the highest K I had was far below the last K these researchers had. The trend they observed in their experiment seem to be confirmed for higher Vd as the general behavior for my data is a decrease of K when Vd increase.

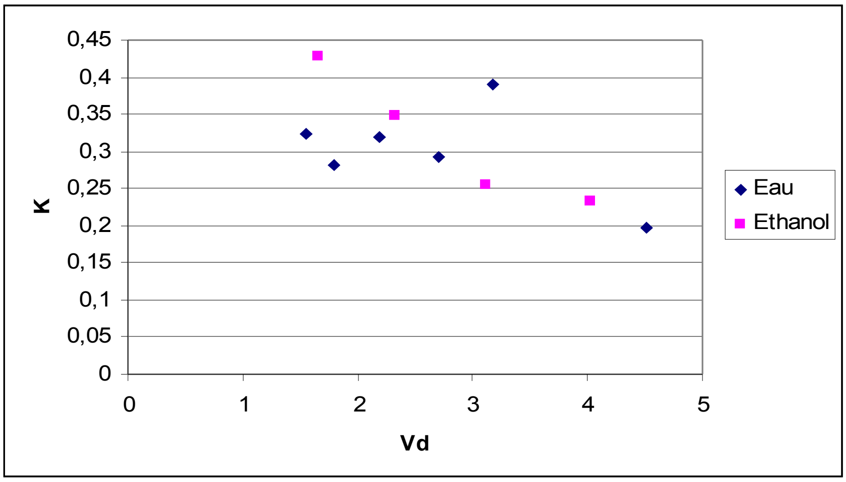

Figure 15: Ratio of the velocity of the jet to the velocity of the falling droplet versus the velocity of the falling droplet. Velocities are in m/s.

V.2. Splash

As for the vertical jet, some results linking dimensionless parameters to this phenomenon are given. The importance of viscosity is also highlighted.

V.2.a. Critical Weber number

The splashing phenomenon does not appear at low We. As we have seen in the chapter IV, splashing occurs at different We for each liquid. For water it appeared at We=131, for ethanol at We=711 and for silicone oil, even if at We=1200, it still did not appear. This certainly means that there is more than two parameters (inertia and surface tension) that govern the splashing phenomenon. This is what was found by Wang and Chen [25] who tried three different glycerol-water solutions (60, 70 and 80%) which had different viscosity. Splashing critical Weber number they found were respectively 400, 500 and 800. They supposed that it was due to viscosity changes.

V.2.b. Do two liquids with the same viscosity have the same critical We for splashing?

In order to answer this question, I used the results of Wang and Chen [25]. Table 3 shows the viscosity values of the liquids used by them and of the silicone oil used by me.

	Dynamic viscosity μ (Pa.s)	Density ρ (kg/m3)	Kinematic viscosity ν (m 2 /s)	Splashing We
glycerol-water 60%	0.01	1150	9.39E-06	400
glycerol-water 70%	0.02	1180	1.91E-05	500
glycerol-water 80%	0.06	1200	5.01E-05	800
silicone oil	0.05	960	5.00E-05	>2000

Table 3: Physical properties of the liquid used by Wang and Chen and of the silicone oil

If we focus on the dynamic viscosity we can see that the value for the silicone oil is between the value of glycerol-water 70% and the value of glycerol-water 80%. Therefore, we could easily suppose that the critical We for the silicone oil would be between the critical We of the two other liquid. But this hypothesis is wrong as 2000 is much larger than 800. The same thing can be noticed with the kinematic viscosity.

Indeed, the kinematic viscosity of silicone oil is nearly the same as the glycerol-water 80% one whereas their critical We are different. To conclude, two liquids with the same viscosity may not have the same critical We for splashing.

We must also notice that the value of 2000 for the critical We for splashing for the silicone oil is certainly much lower than the real one because, at We=2000, the jet just appears and there is not even one secondary droplet. This point reinforces the fact that, for two liquid with the same viscosity, the critical Weber number for splashing may be different.

V.2.c. More sophisticated splash/non splash boundary

Some authors tried to establish a boundary for the appearance of the splashing phenomenon. Vander Wal et al. [18] used thirteen liquids, defined the splash/non splash boundary for each one and tried to fit results on a Oh-Re diagram. They obtained potential relations like $Oh*Re^{\alpha}=\beta$. They determined values of α and β for the case of droplet impacting on a dry surface and droplets impacting on a thin film of liquid. For each case they compared their experimental results with their assumptions.

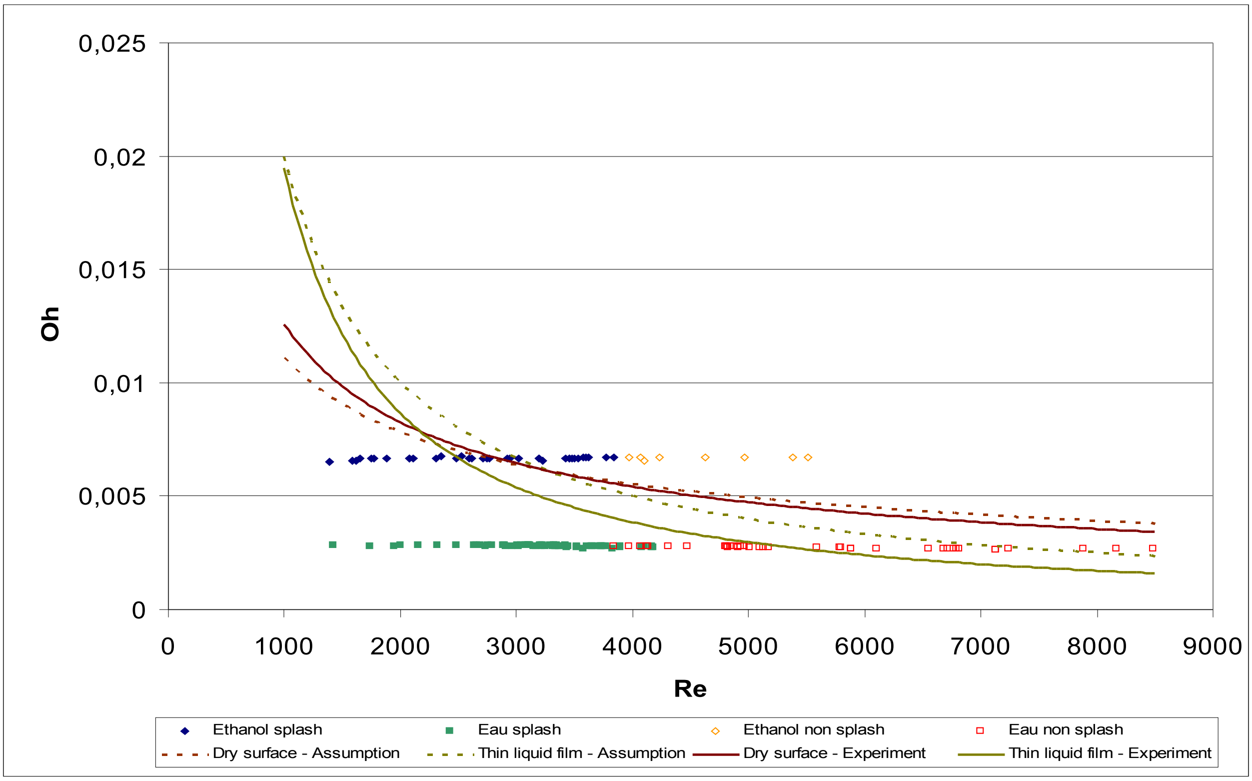

Figure 16: Comparison between my result concerning water and ethanol and the results of Vander Wal et al.

Figure 16 represents my experimental results concerning splashing for water and ethanol and shows where there was splash and where there was not. The results of these authors are also plotted in order to compare them with mine. Dashed lines account for assumptions and solid lines account for experimental results. Above these curves, these researchers noticed splash and, below, they did not.

Our data do not really match. However, the results of these researchers are not for a droplet impacting a deep liquid pool. For both of their cases, the influence of the wall (immersed or not) was present. This can explain some differences. Moreover, at high Re, the line for the thin liquid film is lower than the line for the dry surface. We can imagine that a good approximation for my experiment, where there is even more water, could be a line even lower. This line would probably match my water results. Indeed, for ethanol the line could hardly match its splashing/nonsplashing boundary unless the potential curve gets "vertical" for higher Reynolds number. This is also a trend less obvious but visible with the results of Vander Wal et al. which could be imagined.

V.3. Other phenomena

This chapter deals with the phenomena different from the two previous ones. As we saw that droplet ejection is fairly linked to the vertical jet, I let it in this chapter. Phenomena which did not appear with the droplet I released like bouncing or apex droplets are also contained in it.

V.3.a. Droplet ejection

As now I consider droplet ejection as a part of the jetting phenomenon, I only make a small chapter concerning it. Droplet ejection results from instabilities in the vertical jet. According to the jet energy, two or more droplets may be ejected. The size of these droplets seems to be linked to the time when they are ejected. If they are ejected just after the jet birth, droplets are small and if they are released when the jet is well formed, their size equals more or less the size of the free-falling droplet. Even if instabilities are not really predictable, some researchers proposed a critical Weber number for droplet ejection. Hallett and Christensen [16] assessed the ratio between kinetic energy and surface tension energy which are necessary to eject droplets. They linked this ratio to the Weber number and therefore, they obtained a limit We. Rein [24] corrected their expression and said that the critical We for droplet separation is 84. Concerning my experiments, I obtained a critical We of 103 for water but 237 for ethanol. Differences can be explained in many different ways but there are not enough experimental results to draw conclusions.

V.3.b. Apex droplets

Apex droplets are a surprising phenomenon which occurs when a droplet coalesces. Nevertheless, studies on this phenomenon are not numerous. Aryafar and Kavehpour [12] measured the diameter of the big droplet and the diameter of the smaller droplet that the big droplet creates. Then they plotted the ratio Ri of the second diameter to the first one as a function of the Ohnesorge number. They had data from Oh=0.005 to Oh close to 1. For Oh<0.1, Ri seems to equals 0.5. Then, for higher Oh, Ri decreases. Even if it occurred with water and ethanol, I do not have many results. The only ones I have are for Oh<0.1 and I have less than ten points. As I have some droplets that create apex droplets which also create other apex droplets, I separate these cases. For the first formation, Ri equaled 0.4±0.05 and for the second Ri=0.57±0.03 whereas they both have the same Ohnesorge number. This difference could be explained by the difference of size for droplets. Nervertheless, my values of Ri globally equal 0.5±0.1 and are in agreement with the results of Aryafar and Kavehpour.

V.3.c. Bouncing droplets

Legendre et al. [19] made an interesting theoretical analysis of the droplet bouncing phenomenon. One of the main results they had was a relation, between the capillary number and the Stokes number, which creates a limit, more or less restrictive, for this phenomenon. Actually, if the relation $St^* < 2\ln(1/\sqrt{Ca})$ is satisfied, a droplet will not bounce. But this relation does not mean that, if it is not satisfied, a droplet will bounce. It is just a lower limit for St*. Here St* which corresponds to the Stokes number of the droplet plus its added mass is the same as St (only the droplet) because the liquid droplet is falling into air. I tried to exploit as many videos as possible but it was not very easy because droplets do not bounce very high. Results I obtained were not very conclusive. It would have been useful if I had obtained droplet bouncing which satisfied the relation $St^* < 2\ln(1/\sqrt{Ca})$ which would have given a counterexample of the relation. But, here, I just had bounces with number of Stokes which are two orders of magnitude higher than the limit St, and it does not provide very interesting results concerning this relation. For instance, I had a bounce with a droplet whose Ca=0.0182 and St=387 whereas the Stokes number given by their relation would be 4.

Researchers also measured the coefficient of restitution ε which is the ratio of the droplet velocity after bouncing (V2) to the droplet velocity before bouncing (V1). Richard and Queré [26] made experiments with a water droplet falling onto a super hydrophobic solid surface. They plotted values of ε as a function of the velocity of the droplet before it bounces. The diameter of their droplet was 1mm and its velocity was below 1m/s. For very low velocities (until V1=0,2m/s), ε increased from 0,7 to 0,9 and decreased for higher velocities until 0,7. They explained that even if the rebound is perfect, ε did not equal 1 because of the energy dissipated in droplet oscillations. In my experiments, droplets which bounces where secondary ones, and their diameter varied from 0,6 to 1,7mm and their velocities were always below 0,6m/s. I plotted the ε values as a function of V1 values (Figure 17). As bounces were not very high, it was very difficult to make good estimations of velocities. This may explain why data seem so uncoordinated. However, we can still notice that values are always below 0,5 which agrees with the fact that water droplet will bounce more easily on a hydrophobic surface than on water which is obviously hydrophilic.

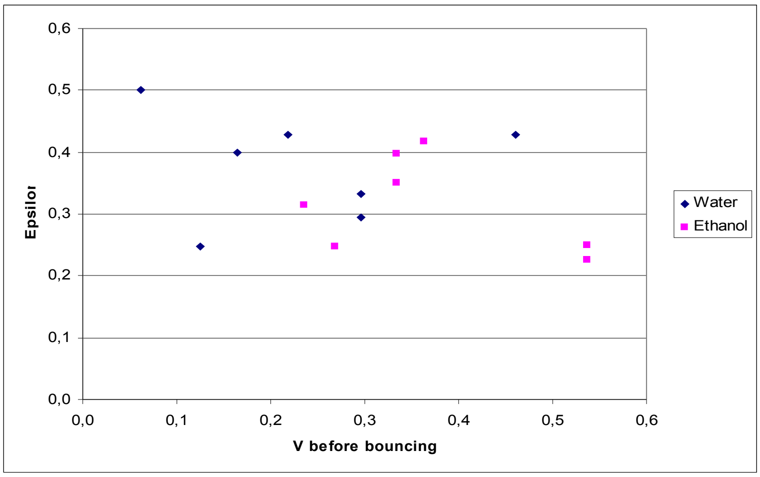

Figure 17: Ratio of velocities after and before bouncing versus velocity before bouncing. Velocities are in m/s.

Nonetheless, in order to have better results, I tried to modify the definition of ε . As ε equals the ratio of two velocities, it can be understood as the square root of the ratio of kinetic energies. Ideally, the potential energy of the droplet when it reaches its maximum height equals the kinetic energy at the surface height. As oscillations and other phenomenon ensure us that this is not true during experiments, I supposed that the ratio between this kinetic energy and this potential energy is equal to a constant value during the bounce instead of saying that it is equal to 1. Thus, calling 1 entities before bouncing and 2 entities after bouncing, we can write that

$$\frac{Ec_1}{Ep_1}=\frac{Ec_2}{Ep_2}=cste \qquad \frac{Ep_1}{Ep_2}=\frac{Ec_1}{Ec_2}=\varepsilon^2$$

So, with my assumptions, ε^2 could be also equal to the ratio of potential energies, which can be simplified as the ratio of the maximum height after bouncing to the maximum height before bouncing. As it is only an assumption, even if ε is close to this new parameter, let us give a new name to it:

$$\varepsilon_h=\frac{\sqrt{h_{max,1}}}{\sqrt{h_{max,2}}}$$

Plotting ε_h as a function of velocity V1 (Figure 18), results are really better. I tried to fit these results with a power regression. ε_h seems to be proportional to $V1^{-0,42}$.

Still with the restitution coefficient, Legendre et al. [19] evaluated the influence of the Stokes number on it. They fitted results with an exponential curve. They obtained ε=exp(-β/St*) with β=35. To compare my results with theirs, I modified the writing of this expression in order to have a linear relation. The relation I used is Y=aX with Y=ln(ε), X=-1/St and a= β. As I had seen that ε_h gave much better results than ε, I used ε_h. Results with ethanol were really uncoordinated and I was not able to fit results with any curve. This the reason why I fitted only water droplet bounces (Figure 19).

Actually, the exponential model for ε_h seems to be a good one. Moreover, the value of β I found is quite close to the value these researchers found. Mine equals 45,57 whereas their, with ε equals 35. Nonetheless, even if results seems to match themselves easily it would be interesting to understand why results with ethanol do not.

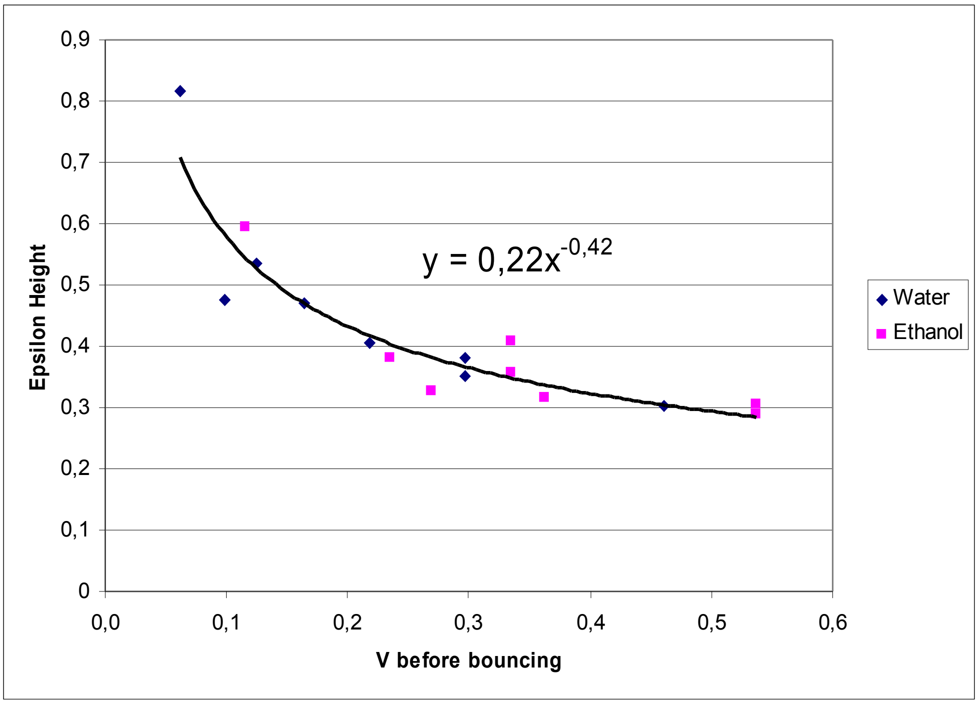

Figure 18: Square root of the ratio of maximum height after and before bouncing versus velocity before bouncing. Velocities are in m/s.

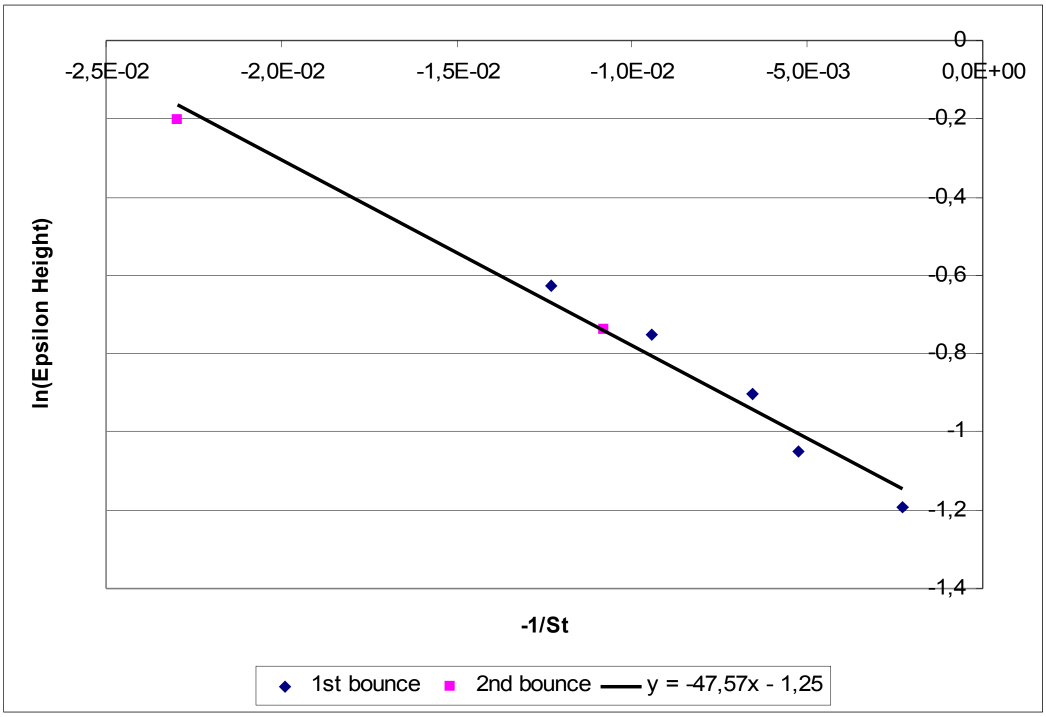

Figure 19: Linear fitting of ln(ε_h) versus -1/St

VI. Conclusions

VI.1. Scientific conclusion

Through all this report, main results are summarized.

The analysis of phenomena happening for each liquid allowed to set up interesting links between the Weber number and these phenomena. These links are different between water and ethanol and much more different with silicone oil. However, this shows that the Weber number is not the only parameter that governs these phenomena.

The energy of the free-falling droplet seems to go mainly into the liquid bulk. Even if the vertical jet is the most energetic phenomenon I studied, much energy is dissipated into surface waves, crater and crown formation. With water, about 70% of the initial energy was dissipated into the liquid bulk whereas it is 52% for ethanol.

The vertical jet gives interesting results. For experiment with liquids, power regressions linking the height of the jet and the Froude number or the Froude number times the Reynolds number seems to be good ones. Nonetheless, results with ethanol are different from the water's one. Replacing the Froude number by the Weber number, results get really better as ethanol and water fits seem to be equal. Concerning the velocity of the jet, I managed to add a part to the diagram of Bartolo et al. [23] showing that the jet velocity keep decreasing for droplet velocities bigger than 1m/s.

The ejection of droplets seems to be a phenomenon that depends on the vertical jet. The repartition of the initial energy showed that initially, the energy of the ejected droplet is the energy of the liquid column. The critical Weber number found by Hallett and Christensen [16] or Rein [24] is different from mine, but this is certainly linked with the different viscosities.

Critical Weber number for splashing were always different, even in liquids with same viscosities. The splash/nonsplash boundary of Vander Wal et al. [18] did not exactly match my results. This is certainly due to the fact that they experimented with thin liquid films. Through my results, it can be deduced that, experimenting with as many liquids as they did but with droplets impacting on a liquid pool would bring a regression that would follow the behavior they obtained with dry surfaces and thin liquid films.

When droplets did not coalesce, apex droplets or bouncing happened. Results with apex droplets are not very rich. They just confirm Aryafar and Kavehpour results [12]. Concerning bouncing, the relation given by Legendre et al between the ratio of velocities and the Stokes number seems to also work replacing this ratio by the ratio of maximum heights. In this experiment, doing this allowed to have really better results and to make fewer mistakes. This was also true when I plotted this ratio as a function of the velocity of the droplet before the bounce, where results with water and ethanol really well matched.

Finally, all the results I obtained during this internship might be useful. Even if sometimes I obtained results that just confirm others that I found in research articles, generally I had results complementary with theirs. I also succeeded in founding some results that I did not found in literature. I especially obtained clear descriptions of relations between Weber number and all the observed phenomena and I also showed how the energy of the falling droplet is divided, assessing the percentage that is dissipated into the liquid bulk.

VI.2. General conclusion

This internship was a real opportunity. From an experimental point of view, I discovered a very interesting phenomenon that I have been able to study with high-tech material. I have had to learn new software and to learn how to use a high-speed camera which has made me develop some way of working and therefore develop my autonomy. During all my internship, I had to take a lot of initiatives and especially during my experiments in order to keep them short enough and to have interesting result in the same time.

Concerning my results, I succeeded in obtaining usable results. A lot of them were comparable with some articles I found and I have also been able to bring some new results like the repartition of energy and the evolution with We which were not done before.

One of the main difficulties in this internship was working with research articles. All along the training period, I improved my way of searching information on articles, looking more precisely abstracts and references. I also managed to be aware of the different definitions that may be in articles. Some words are used with different meanings. The definition of dimensionless parameters was also often different in many articles.

Finally, I discovered what is the researcher work with its drawbacks, when sometimes too much freedom brings you not to really know which way you have to follow and all its advantages, from the free schedule to the constant possibility of using all our imagination.

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Other information:

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