

OIL DROPLETS IMPACTING AGAINST HORIZONTAL SMOOTH SURFACES

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Abstract. *In many machining process it is a conventional practice to use mineral oils to help the metal cutting process. The oil-water emulsion promotes the heat exchange and maintains the quality of the cutting fluid. The shock of the oil flow against the machinery parts with relative movement, provokes the formation of small oil drops. These oil droplets spread on several machine surfaces in a relatively moderate impact velocity. The oil drop impact can form other very small droplets which are thrown in many directions in high velocity. In this work, a low cost high-speed photographic device was developed and applied to study a small oil drop falling against a horizontal smooth glass flat surface. The photographic apparatus is composed of an electronic circuit to control a photographic flash. This operates by a laser barrier, delay circuit to control the time and a SLR photographic camera. Captured Images of the oil drop in free fall permit to determinate quantitatively the drop velocity, dimensions and a qualitative analysis. The results obtained show clearly the possibilities to study the phenomena of the oil drop spreading on surfaces.*

Keywords*. Drop, drop impact, high-speed photography, image capture, image processing*

1. Introduction

The spreading process of a liquid drop on a solid surface is frequently encountered in many industrial applications, e.g. material machining, spraying processes and ink jet printing. Many industrial process such as spray cooling of hot surfaces, fire extinguishment by sprinkler systems, plasma coating, spray forming and pesticide spraying requires an understanding of the impact dynamics of the liquid drop on solid surfaces.

In machining process, for example, expensive cooling soluble oil is utilized to help in the metal cutting operations. This mineral oil flows in direction of the several parts of the machine tool and forms oil drops. These drops are shot in many directions with different velocities against the machine parts. Therefore, many small oil droplets are formed and dispersed is various directions in a relatively high velocity. As a result, the size of these droplets is variable and many remain in suspension around the machine environment. Thus, oil fog can be generated producing an inadequate work environment and a continuous loss of cutting oil. Because the presence of the oil fog, several types of the oil retention filters must be installed in order to minimize the atmosphere contamination.

A trap filter is a kind of oil retention indicated to this case, (Gonçalves & Vieira, 2000). All of different kinds of filters need of specialized care and provoke a continuous energy loss in ventilation ducts. In these aspects, the knowledge of the liquid droplet dynamics can be a useful tool to minimize the costs with cutting oil loss, to save energy and to promote a healthy work environment.

In many cases, the experimental studies of droplet of different liquids impacting against several surfaces are carried out utilizing high-speed cameras. These cameras can obtain the image captured up to millions of frames per second (*fps*). Unfortunately, high-speed cameras represent a device of high cost of acquisition and an expensive cost of maintenance. High-speed video cameras using magnetic recording media have many advantages when compared with chemical film cameras. For instance, minor maintenance cost is required. However, video-tape images present a limited resolution and a low signal to noise ratio (*SNR*). The final images obtained by a video system are poor in quality when compared with the images recorded through chemical pellicle media.

The objective of the present work is to develop a high-speed photographic device, utilizing a still photographic camera, in order to investigate the breakup of liquid oil drops on a surface at room temperature and atmospheric pressure conditions. Drop images in free fall have been captured in order to determine quantitatively the drop velocity and drop dimensions (the drops have been considered axisymmetric) and, additionally, several oil shock images have been captured in order to obtain qualitative information about the shock dynamics and spreading process and micro droplets formation.

2. High-speed image capture

Many engineering phenomena occur in a very small time period and a cinematographic register is a useful tool in the studies of these phenomena. Using a chemical-pellicle film in a cinematographic camera it is possible to generate good quality images. The conventional cinematographic cameras generally work in 24 fps. Several roll film formats are conventionally available for these cameras from the 16 mm size to professional format, i.e. 70 mm. Some conventional cinematographic cameras allow to execute the record in high frame rate, no more than 120 or 150 fps.

In several engineering applications, it is necessary to use a high-speed cinematography camera, i.e., an able equipment to record in several thousand of frames per second. Fukai *et al*. (1995) registered the use of a 16 mm high-speed camera of maximum speed of 6000 frames per second. They studied the deformation of a liquid droplet colliding with a flat surface.

High-speed cinematographic camera is a high-cost device, requiring a specialized operation due to the expensive special film rolls. The high-speed video camera is a way to reduce the costs. Unfortunately, video camera produces images of limited resolution and low SNR. Buch *et al*. (1998) used a *Kodak Ektapro* to capture digital images of the drop dynamics in 1000 fps (192×239 pixels) and for 6000 fps (only 32×239 pixels) obtained 8 bits of grayscale images. The major advantage of the digital image is the possibility to observe in many hours a high-speed video footage which reveals certain characteristics of the flow that certainly influence the interpretation of the results. However, the low resolution, high noise level and low contrast result a poor quality images.

The resolving power (*RP*) is a measure of the ability of a photographic material to record fine detail. General concepts of resolving power and its measurement are contained in ISO 6328-1982 and ANSI PH2.33-1983 standards. These standards define RP specify values of the number of lines per millimeter that can be separated visually (resolved). The photographic image of a test object with a multiple slits, named standards resolution chart, is revealed. According to these standards, one photographic line is equivalent to two television lines. Thus, a photographic material line and its adjoining space are included when counting the number of lines. This is similar to the counting line pairs in electronic images.

A commercial reversible film used in a still photography camera has more than 125 lines per millimeter of resolution in each direction when adequately developed. Considering a 35 mm format roll film, i.e., a frame of 24 x 36 mm, represents the equivalent to 6000 electronic horizontal lines. An electronic image recorded in VHS (video home system) has less than 240 lines of horizontal resolution. Others more high-resolution, a video system used to broadcasting proposes is very expensive and shows only 1000 horizontal lines. On the other hand, photographic materials to specific application, as the material utilized to scientific research, can have more than 2000 resolution lines per millimeter in each direction, showing a very high resolution power, second Dancy (1987). Utilizing magnetic media, it is possible a sensible cost reduction but the image resolution is poor. The sensible chemical pellicle obtains image of highest quality but the price is an enormous obstacle.

The movement of the film at high speed produces the stretch of the film when this moves with very high velocity in order to obtain sufficiently large pictures. For instant, 5000 pictures per second for each photography of 12 mm frame, the film has to move at speed of 60 m/s implicating in very high dynamics forces.

Many low cost intermediate solutions, using several configurations and different devices, have been proposed to obtain high-speed images with high quality in substitution the expensive high-speed cameras. Obviously, all of this alternative solutions have limitations, for example, Sudheer & Panda (2000) used an ordinary SLR camera to study sprinkler drops and Mao *et al*. (1997) used a conventional digital fast-shutter-speed CCD still camera to study drops of 1.5 to 3.5 mm of diameter with 0.5 to 6.0 m/s of impacting velocity.

A special CCD photographic cameras is very indicated because they are capable of taking pictures at shutter speed as fast as 1 µs, or less. Fast shutter speed permits to take sharp pictures without a sophisticated illumination system. Unfortunately, CCD cameras of fast shutter are made only to engineering or scientific applications, representing a high acquisition cost.

3. Liquid drop spreading

Drop impact on a solid surface has been the subject of numerous theoretical and experimental studies. In theoretical studies, because the large drop deformation which is observed subsequent to drop impact, the problem cannot be analyzed without using the numerical computation. Highly questionable assumptions are made in problem formulation to make it tractable by analytical means. Computational analysis of drop impact was carried out successfully by Bussmann *et al*. (2000).

Of course, the liquid drop spreading on a solid surface is a complex phenomenon. Generally, the liquid drop spreading on a horizontal solid surface can be classified into high-speed impact spreading and low-speed impact spreading. The spontaneous spreading occurs when the impact speed is equal to zero. Both high and low impact speeds, strongly depends on the inertial, viscous, gravitational, capillary forces, and the wettability of the spreading system.

Second Gu & Li (2000), a classic fluid mechanic approach fails in modeling the motion of the solid-liquid-fluid contact and treating of the spreading phenomenon, like a pure surface physics problem, thus very complex and fail to produce a predictive model. The development of adequate mathematical models which contain a minimum of empiricism and result a correct prediction mechanism. The experimental high-resolution captured images of liquid drop spreading on a smooth plane surface at different impact speed can be a good support to validate these models.

Furthermore, in an experimental viewpoint, it is a problem of determining the drop dimension and shape just before the impact. Several techniques have been proposed to measure the drop size, according to Sudheer & Panda (2000), the methods to measure drop size are cumbersome, expensive and time consuming.

Emitter-detector techniques are largely utilized in a drop measurements. In this technique, a light beam, generally a laser or an infrared emission, is generated to produces electrical signal in some optical detector. When the drop falling, it is cross the light beam producing an electric pulses in a electric-optical device. These pulses operate a timer or a delay circuit which will start the data record system, according to Buch *et al*. (1998). Emitter-detector techniques found an extensive field of applications on two-phase flow measurement and in gas-liquid systems, second Jones Jr. (1983).

Fukai *et al*. (1995) used the weight technique. First, the weight of the droplet was measured. The average of ten individual measurements was recorded in each case. Next, the droplet radius was evaluated using the measured mass and droplet density. This technique found excellent agreement which the data obtained from the image analysis.

Range & Feuillebois (1998) calculated the drop diameter from gravity force and capillary force, acting on a liquid bridge between the drop and a needle. Those authors in order to verify the accuracy of their formulation compare the calculated diameter of 100 water drops with the drop diameter measured directly from pictures of free falling drops 1 meter below of the needle. Many others drop diameter measurement techniques have been explained in the work of Sudheer & Panda (2000).

The use of droplet image just before the impact in order to measurement the droplet diameter is possible and utilized by several researchers – Mao *et al*. (1997). The use of drop visualized image to obtain drop dimensions requires an image calibration. Several ways can be utilized to calibrate an image however, the more utilized it is an employment of commercial precision calibration graticule (a micro scale forming a network) such as in the work of Šikalo *et al*. (2002) and Zhang & Basaran (1997).

The use of spherical stainless balls of several known diameters can be utilized for calibration purposes and different researchers also utilize it, Mao *et al*. (1997).

Generally, the drop impact velocity is also measured using images in the last time period (around 0.1 to 1.0 ms) before these contacts the target surface, according to Wang & Chen, (2000).

4. Experimental device and methods

The description of the experimental device utilized in this work was divided in three parts. The first one describes the set-up utilized to generate an impact of a single drop onto the dry smooth surface. The second ones describes the image capture system, based on an electronic circuit, developed in this work, to execute the synchronism of an electronic flash in a target time. The images are captured in a SLR camera. The third part is dedicated in the analysis of the images.

4.1 Experimental device

A schematic of the set-up utilized in this experiment is shown in Fig. (1). From elevated oil reservoir a feed line leads through a valve to a needle, and the droplets are formed and fall onto the target surface. The ambient air should remain as calm as possible in order to produce no perturbations in the drop, however, the droplet was enclosed in a vertical 50 mm O. D. Plexiglas tube in order to protect it from wind. The droplet cross a laser barrier that activates an adjustable electronic delay circuit and thus, triggers an electronic high-speed flash. The camera takes a single image of the drop impact event at a specified delay time. Using different delay times is possible to obtain different instants of the impact. The drop velocity and the drop diameter just before the impact and the spreading diameter upon impact could be precisely determined using only the captured images. The liquid flow rate was adjusted so that individual droplets first formed at the tip of the needle, then detached and fell due to the force of gravity. The time delay varied so those images were taken at different times after the initial droplet impact. A sequence of pictures describing the impact process was created from individual images of many droplets taken in different time delays. Just varying the time delay between the droplet first touching the surface and triggering of the flash, different stages of droplet impact could be photographed. In order to repeatability, droplet impact process could be rebuild from different images, captured at progressively advancing stages of impact.

The present apparatus has been mounted in a dark room currently utilized to chemical processing of photographic. The experiments occurs is a controlled surrounding and a complete darkness.

Cutting oil dissolved in tap water was utilized, in the same condition of real use of this product. The physical properties of this emulsion (water-oil) have been determined. Since the drop size is a function of needle outside diameter, liquid density and surface tension. Pasandideh-Fard, (1996) measured the surface tension by measuring diameters of spherical droplets in free fall, after they have detached from the needle tip. Surface tension values were calculated by equating the weight of each droplet to the surface tension force attaching it to the needle tip, whose diameter was well known.

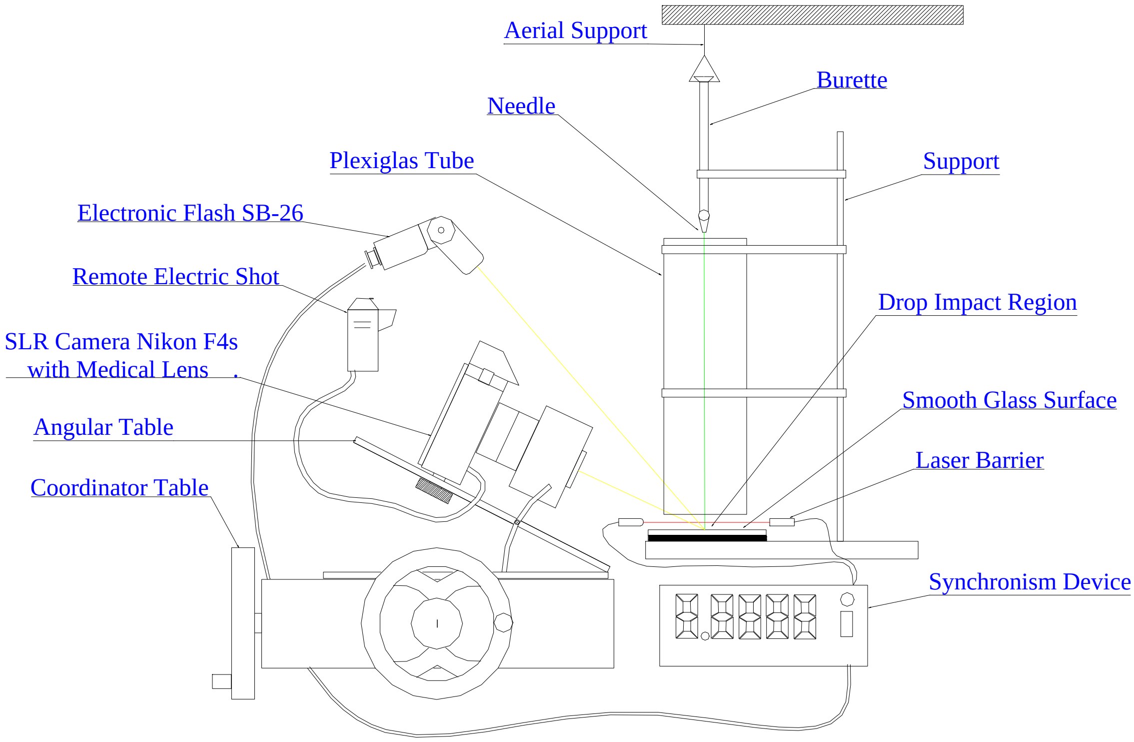


Figure 1. Experimental apparatus.

This measurement method is very similar to apply in ring tensiometer. A ring tensiometer (also named *Du-Nouy* tensiometer) was tested to measurement surface tension (σ) using twice-distilled water and etilene Glycol ($C_2H_6O_2$): measured surface tensions agreed closely with values reported in the literature, showed in Table 1.

Table 1. Experimental results for surface tension obtained *Du-Nouy* tensiometer, average of 5 measurements.

Fluid	Literature (N/m) Temp. 25ºC	Measured (N/m)	Error (%)
H_2O (twice-distillated)	7.280×10^{-2}	7.419×10^{-2}	1.9
$C_2H_6O_2$	47.991×10^{-3}	51.063×10^{-3}	6.4

The cutting oil viscosity was measured utilizing a sphere viscometer type *Hoeppler*, made in German by *VEB Kombinat MLW* model *B3*. The cutting oil is soluble in tap water. The present test, was utilized two oil/water concentrations (20:1 and 30:1). For industrials use the oil producer recommend at 20:1 concentration, but several low concentrations have been frequently utilized. The surface tension (σ), the density (ρ) and the dynamic viscosity (μ), measured by the sphere viscometer, in the room temperature of 28 ^{o}C is showed in the Table 2.

Table 2. Cutting oil proprieties for two oil-water concentrations.

water–Oil Concentration	Surface tension (σ) [N/m]	Density (ρ) [kg/m^3]	Viscosity (μ) [kg/m.s]
20:1	2.994×10^{-2}	1142	1.252×10^{-3}
30:1	3.254×10^{-2}	1136	2.631×10^{-3}

4.2 Images capture device

For illumination, a professional electronic flash Nikon SB-26, with a glass diffuser was utilized in order to produce a uniform, bright light source. The time illumination of this flash is up to 1/23000 s lead to produce a high SNR image. A high light intensity Xenon lamp permits less than 2 μs of flash duration, and it is indicated to macro photography, unfortunately it is a relatively expensive apparatus and only should be implemented in future works. SB-26 run in TTL (Through The Lens) mode, as a result sensible automated control of flash intensity made through of the camera lens, but in order to assure a controlled operation and a constant flash time, all images have been captured in manual operation with 1/64 of the flash power. The distance of the flash unit to the drop has been careful estimate using a *Minolta flashmetter* IV F.

All the images have been captured utilizing a Nikon F4-s camera. This is a SLR (Single Lens Reflex) camera with a remote electric shot system and shows very low vibration level, ideal to macro photo, laboratory application and others scientific application. Using a right-angle viewing provides an upright and unreversed image, ease the focus and framing operation.

Utilizing special macro lens (*Medical – Nikor* 120 mm f/4), different image magnifications (*M*) from 1/11x to 2x could be obtained. The magnification was manipulated so that the image could accommodate the maximum spread of the droplet. The operative aperture is fixed at f/32 in all the takes, regardless the magnifications. The deep of field, in the more adverse operation – reproduction ratio of 2x – is +0.41 to – 0.40 mm. The camera was positioned on a rigid support with two-dimensional translation and the critic focus of the camera was careful adjusted (using f/4) utilizing the translation function of this coordinate table. Use of the Medical – Nikor 120 mm lens dispenses the utilization of bellows, adapter rings and attachment lens.

The images have been captured utilizing *Kodak Tmax* film ISO 400 for B&W prints and *Kodak Ultra* 400 for color prints. The prints have been digitized in a flat bed scanner in 8 bits of color (256 gray tons). Kodak Tmax has an ultra-fine grain with a controlled contrast producing sharp images, ideal to scientific applications. Development processing has been made using *Kodak Tmax RS* developer in 6 minutes (22^{o}C). Use of Tmax film is recommended and utilized by several researchers, second Liu & Reitz, (1997).

The project of the control digital circuit counted with nothing less than 25 integrated circuits, without considering the discreet components (capacitor, resistor, transistors, etc.) and the construction of a prototype with handle dimensions were prejudiced. An equipment of great dimensions could not contribute to turn functional any photographic apparatus. In those conditions, an additional research was accomplished so that the device of digital synchronism reached minimum and practical dimensions. The present digital electronic synchronism circuit has been developed based in a PLD (Programmable Logical Device) type FPGA (Field Programmable Gate Array) using *Max 7000* family of *Altera Co*. This is a high complex digital programmable solid-state device.

With the use of (PLD), the project of the synchronism circuit used only one integrated circuit. Working with the development software MAX II - Plus, Version 10.0, supplied free by *Altera Co.*, let able to simulated the operation of the circuit and, after this, recording the FPGA. The recording module is connected in a computer through an interface and of an appropriate cable and the chip to be engraving is placed in the respective socket.

The FPGA model utilized was the EPM 7128s from line MAX 7000, with capacity for up to 2.500 gates. In the project implemented in this FPGA, the use rate was of 75% in other words; it was used about 1.875 gates.

The delay circuit has adjustment from 0.0000 s to 0.9999 s, that way; the count frequency should be 10 kHz. In the intention of facilitating the adjustment of this frequency, an oscillator of 8 MHz to crystal was added to the project. As it is known, oscillators based on piezoelectric crystals they are high stability and precision, in fact, such crystals is base of time of all electronics clocks and many other devices like computers, digital radio and cellular telephone. The frequency of 8 MHz is then divided 800 times and it is arrived like this in the frequency of 10 kHz, necessary to count the regressive time. The use of a divided frequency generates stable signal and with less noise with relationship to the signal produced directly in the oscillator source.

When the laser barrier is crossed, a trigger signal is send to synchronism device by optical sensors. The circuit could make an immediate shot when a time is set in 0.0000 s or, wait for a programmed delay time when a time is set up by a program displays. The error of the regressive count is less than 36.5 ns, obtained through numerical simulations.

The synchronism device has an especial characteristic for blocking another shot, before push rearm button, in this way, a second drop could not activate the system when it is not ready.

Figure (2) shows a picture of the electronic synchronism device utilized in this work. The apparatus have only $200 \times 120 \times 70$ mm of external overall dimensions and run with 9 VDC supplied by 6 AA alkaline batteries. The laser barrier can be distanced several meters of the device and it is connected through a DB9 connector. Depending on the flash model available in the market, the electronic device providence a polarity inversion. The time display shows since 0 to 0.9999 s of time delay.

4.3 Images analysis

The diameter of a drop was measured from the acquired image just before impact. The droplet was not perfectly spherical. Both horizontal and vertical diameters were measured. Assuming that that the droplet is rotationally symmetric with the respect to the vertical axis, the equivalent droplet diameter (*D*) can be writing:

$$D = (D_h^2 \; D_v)^{\;1/3} \tag{1}$$

where (D_h) is the horizontal diameter and (D_v) is the vertical diameter.

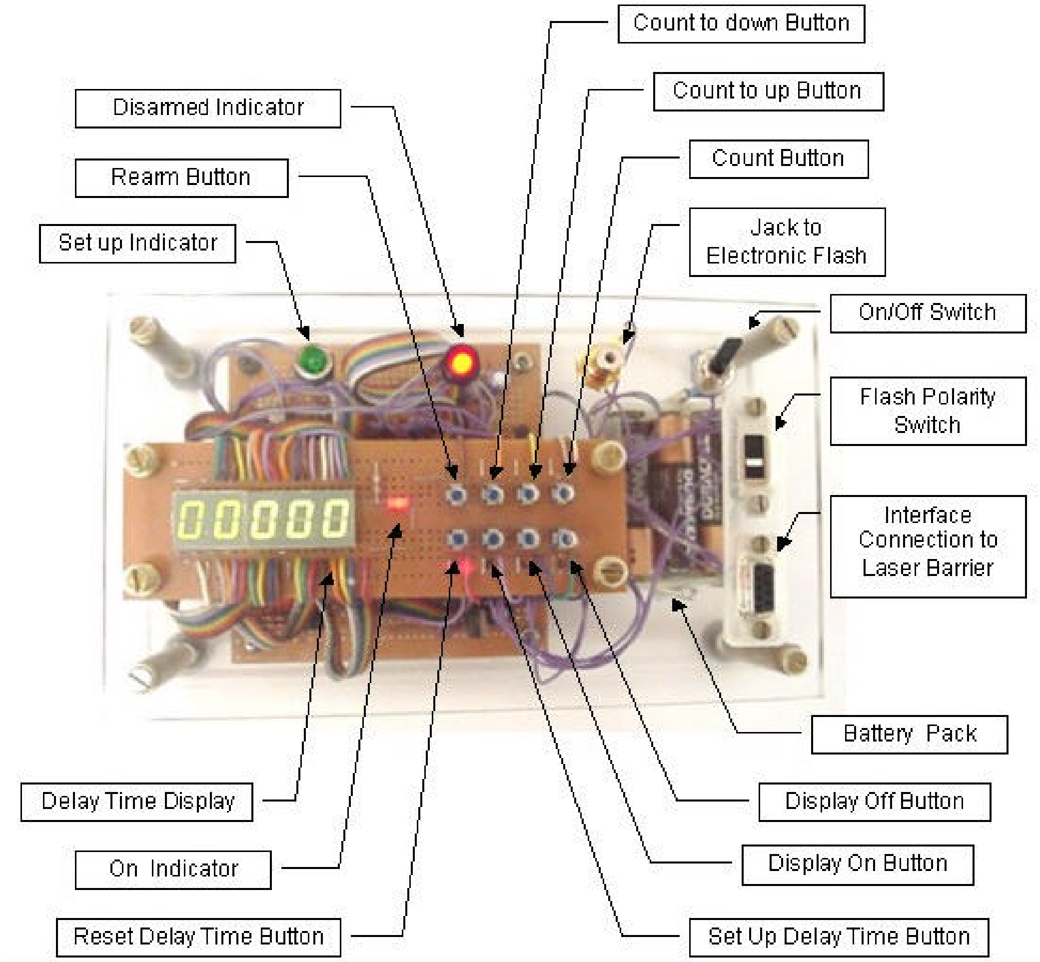


Figure 2. Front view of the developed digital electronic control device.

The droplet velocity just before the impact was calculated from a distance measured and a pre-set time delay between two subsequent shots. A variant way of measurement the terminal velocity of the drop using superimposed images was utilized. No appreciate differences can be noted in this two measurement ways. No noticeable temperature rise was detected during the test period.

Droplets did not break up during impact since their kinetic energy was too low to overcome surface tension. A measure of the relative magnitudes of kinetic and surface energies is the Weber number (W_e), defined by:

$$We = \rho \, D V^2 / \sigma \qquad (2)$$

where (V) is the drop velocity just before the impact.

The Reynolds Number (*Re*) is other important non-dimensional parameter:

$$\mathrm{Re} = \rho \, D V / \mu \qquad (3)$$

where (ρ) and (μ) are, respectively, the density and viscosity of the air.

5. Results

The impact velocity was derived with an accuracy of less than 0.05 m/s (95 % of confidence). The uncertainty of the droplet diameter determination has been considered of the ±0.3 mm. The maximum error of 3 pixels for estimation of the droplet contours was achieved. The time accuracy is mainly defined by the uncertainties of defining the moment of impact ($t = 0$). In the worst case, an accuracy of 1 pixel corresponds typically to a time error of 50 µs.

Drop diameter and drop velocity was determined using drop images. Fig. (3) shows a typical drop image just before the impact. Image was previously calibrated using steel spheres and a graduate scale is showed in the background only to illustrative purposes. The shadow of the drop can be visualized projecting in the background rule provoked by flash illumination. It shows a vertical to horizontal diameter ratio (D_v / D_h) equal to 0.90, measured in pixels directly in the image.

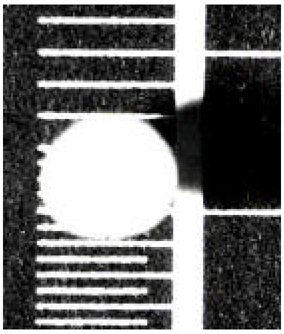
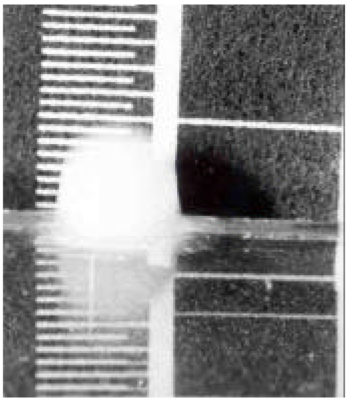
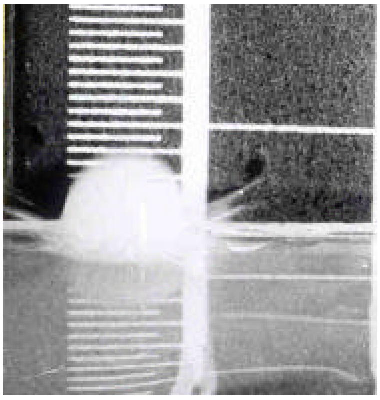


Figure 3. Drop image just before the impact.

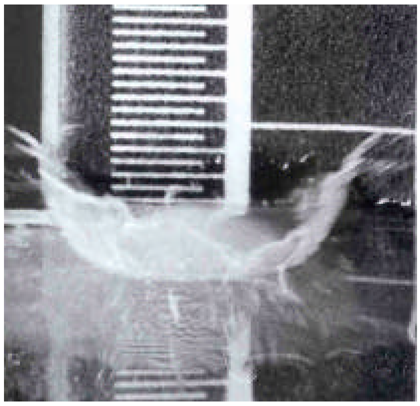
In the first experiments, a high concentration (20:1) oil drop, with 3.96×10^{-3} m of diameter and a terminal velocity of 3.50 m/s, implicating in a Reynolds number equal to 830 and a Weber number equal to 1840, shocking against a plane glass surface, is showed in Fig. (4). The images have been captured in a frame-to-frame delay time equal to 1 ms. A graduate scale is showed in the background only to illustrative purposes and the drop and rule reflex can be visualized in the glass plate.



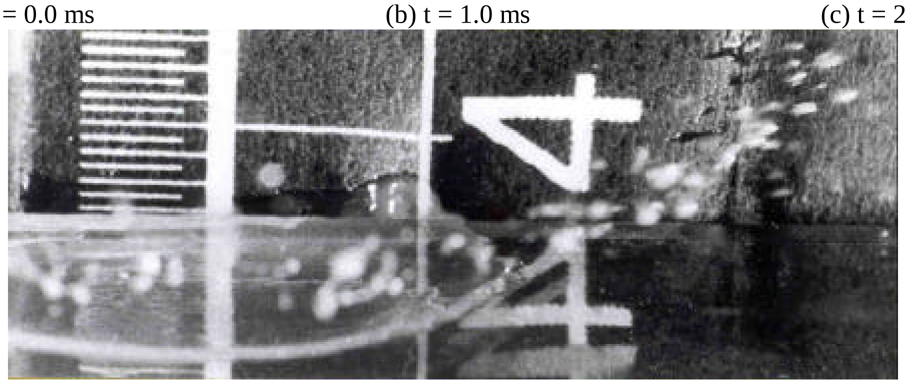
(a) t = 0.0 ms



(b) t = 1.0 ms



(c) t = 2.0 ms

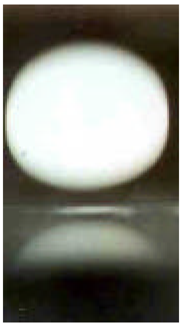


(d) t = 3.0 ms

Figure 4. Drop impact sequence – high concentration.

Just after the drop impact occurs, a loss of coalition, i.e. a drop fragmentation producing many micro secondary droplets also named satellite droplets. These secondary droplets are emitted in high speed in many directions. The satellite droplet velocity is relatively high and they are recorded, in this present work, no freeze, i.e. the droplet image is recorded in a track format. Known the droplet tracking length and the time period of the flash illumination is possible determinate the secondary micro droplet velocity.

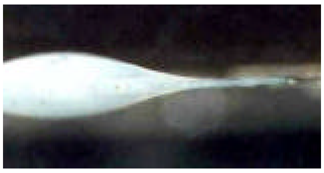
In the second experiment, using a low concentration (30:1), has been observed a non-drop fragmentation, how has observed in the first experiment using high concentration. The low concentration oil drop spraying in the glass surface is showed in the Fig. (5). The oil drop was 4.30×10^{-3} m of diameter and a terminal velocity of 3.50 m/s, implicating in a Reynolds number about 900 and a Weber number equal to 1850.



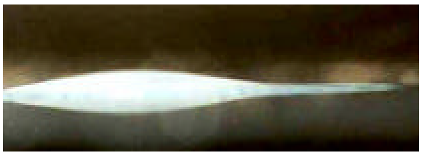
(a) t = 0.0 ms

(b) t = 0.5 ms

(c) t = 1.0 ms



(d) t = 1.5 ms



(e) t = 2.0 ms

(f) t = 2.5 ms

Figure (5) Drop impact sequence – low concentration.

6. Conclusions

Drop impact on a solid surface has been the subject of numerous theoretical and experimental studies. A photographic technique named "Single-Shot-Flash" has been utilized in this work to freeze the instantaneous motion of the droplet impacting before and after impact. A digital electronic circuit for trigger equipped with a delay device has been developed and performed. The precision of timing and spatial measurement determines the experimental reproducibility. In the present work, the experiment was highly reproducible, allowing the use of the present technique proposed.

When a droplet falls onto a dry plane smooth surface, in general, two outcomes of post-impact process are possible. At relative small impact velocities the droplets may deposit on the surface and form a liquid film or at high impact velocities, the droplet can splash and secondary droplets are formed. The two possible configurations have been observed in the captured images.

Soluble oils are essentiality tenseactives, consequently a high oil concentrations in the drop collision displayed in Fig. 4 shows a high level of splashing and others micro-droplets formation. The surface rugosity is other important parameter of analysis. Range & Feuillebois (1998) show the rugosity influence on the crown and satellite droplets formation.

In the two oil concentrations utilized, the respective Reynolds and Weber have been calculated. The soluble oil dissolved in water can be view how water with contaminants and more detailed studies need to be performed in this direction.

The electronic circuit developed shows adequate to drop splashing image capture and a precise delay time adjust is available. An ultra-high sound detector can substitute the laser barrier and the device can be utilized to image capture of the gas bubble formation in liquid medium. A first prototype of the ultra-high sound sensor was made and the first test has been performed showing adequate to bubble formation image capture.

The developing of an electronic circuit to implement the "Single-Shot-Flash" technique to ultra-high photographic studies of an oil drop in free fall shocking against a solid plate has been made in this work and the results show a versatile and practice device useful to obtain the capture of the oil drop splashing images.

7. Acknowledgement

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