Jet formation due to a water droplet impinging on a water pool

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The intention behind this image was to observe what is so well known as a Worthington jet. When a liquid droplet impinges on a liquid surface, in this case both droplet and surface were water, many results can be obtained. The inertia or kinetic energy contained in the water droplet and the surface tension of the liquid basically causes this to happen. In this case, the formation of a jet can be seen going upward after the water droplet hits the water surface. Also, it is noticeable how the jet is formed by a sequence of droplets, being one completely detached from the jet. Furthermore, the framing of image, the orientation of the shot and the blurred background shows the behavior of the jet in an artistic and peaceful way.

In order to recreate the jet, a kitchen sink was used as the domain in which a plate filled with water will be hit by a water droplet. To fix the droplet size together with the elevation from the plate, a Ziploc bag was used trimming down slightly one of the edges. The height measured from the plate to the bag was 15.125" (38.41 cm) while the depth of the water pool was 0.8125" (20.64 mm) (Fig. 1). Many have studied the behavior behind a droplet impinging on a liquid surface, finding that a droplet can bounce, coalesce, float or splash. The behavior of each case will depend on the properties of the droplet, the surface, the impact velocity, the geometry, and the medium through which the droplet crosses prior impacting the water pool [1]. The first experiments were done taking into account a relationship between the Reynolds number $(DU\rho/\mu)$ and the Froude number $(U/(Dg)^{1/2})$ in order to calculate the transition between a coalesce drop and a splashed drop, being D the droplet diameter, U is the droplet impact velocity, ρ the liquids density, μ the liquids viscosity and g the force of gravity [2]. It was stated by [2] that a Reynolds number larger than 3000 and a Froude number between 6 and 18, the impact of a water droplet with the pool will result in a splash. Nevertheless, it was later proved that the real contribution between a drop coalescing and splashing was the Weber number [3]. Additionally, a particular study measured, under different Weber numbers and different depths of the pool, the distinct formations made by the droplet-pool interaction. They found that with a pool depth of 25mm, a Weber number of 206, an impact velocity

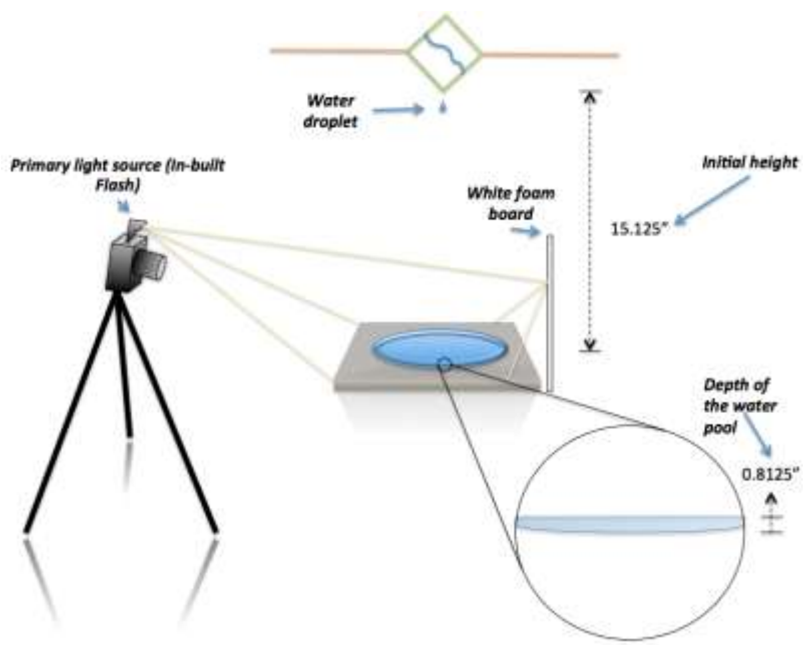

Figure 1. Experiments setup sketch

of 2.3 m/s, and a surface tension of 0.072 N/m, a jet originated breaking up at the end forming droplets [4].

$$We = \frac{\rho * U^2 * D}{\sigma} \tag{1}$$

Where:

ρ: liquids density (kg/m^3)
U: droplet impact velocity (m/s)
D: droplet diameter (m)
σ: liquids surface tension (N/m)

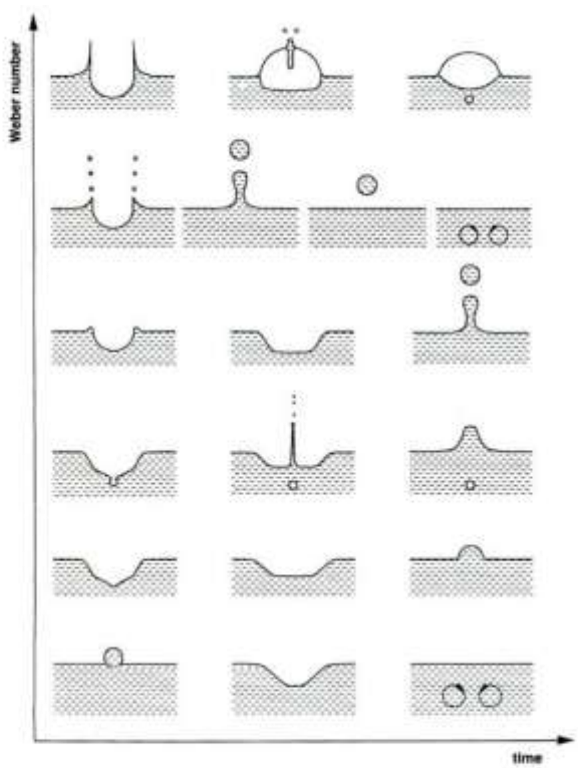

Figure 2. Sketch showing the different droplet-pool interactions due to the Weber number

Source: Rein, M. 2002. Drop surface interaction

Is noticeable from (1) that all the parameters involved are somehow straightforward to calculate and/or find. However, when it regards to the liquids surface tension, many studies have been done on this subject mainly knowing that the surface tension of water is a function of temperature. As temperature increases the surface tension of water decreases [5]. Based on the study made by [5], the drop volume and capillary rise methods can be used to estimate the water surface tension as a function of temperature. For this experiment, the water pool was at the same temperature as the room (20°C approx.), which according to [5], at that temperature the surface tension of water is 73.08 dynes/cm or 0.07308 N/m. Using the height and the gravitational force it was possible to determined the impact velocity of the droplet to be about 2.75 m/s. The liquids density was close to the room temperature density which is 998 kg/m^3. Finally, the droplet diameter was estimated to be 3.18 mm ($m = 10^{-3}$). Consequently, with all the parameters deciphered, the Weber number resulted to be about We=326, which according to fig. 2 and [4], corroborates the jet formation together with the jet breakup.

To capture the phenomenon many shots were taken from different angles to find the appropriate one. To accomplish a sharp capture of the jet going upward, the camera focus was set up accordingly to catch the jet at the desired location. However, lacking form equipment the timing of each drop was not exactly the same, which made the shot a pretty demanding task. In order to get that feeling of nothingness together with sharp pool and jet a large depth of field was used. Nevertheless, a slow shutter speed was chosen to diminish the harshness of the built-in flash together with a low ISO. As mentioned, the only light source came from the built-in flash. The uniform and smooth lighting was achieved by placing a white foam board at the back of the pool.

As mentioned, an ISO 100 was used to decrease the harshness of the flash, an f/8 stop to maintain in focus the majority of the fluid in the frame, and a low shutter speed of 2" to give the image that smooth, almost blurred effect. Due to the low shutter speed, a tripod was settled in order not to undermine the quality of the image. In addition, to achieve such settings the camera was on manual mode as well as the flash. The flash was changed to be 1/8 of its maximum capacity. A Nikon D5100 with a 55-200mm zoom lens was chosen to be the equipment for this task in particular. After the desired image was captured (4751 × 3002) at the maximum focal length (200) it was transformed from the raw format .NEF to .TIFF using Adobe Lightroom 3.4.1. Likewise, using the same software it was possible to change the temperature of the image, increase saturation, vibration, sharpness and a little bit of brightness. Figures 3 and 4 show the original and the post-edited image respectively.

Figure 3. Original image

Figure 4. Post-edited image

As was previously mentioned, the image reveals the nature behind a water droplet hitting a water surface. It's well noticeable to watch how actually the droplet of water coming with a certain speed creates an air layer around it and breaks the surface tension of the water making a crater, and it's the liquid wanting to fill that void what creates the jet. In my opinion, I like how the phenomenon is shown in an artistic setup, locating the jet to the right and accomplishing the composition rule of thirds. I personally don't dislike anything about the image. Regarding the physics behind the image, I think it well represents the relationship between the surface tension of the water and the inertia/momentum of the droplet, corroborating once again that the Weber number is an accurate measurable parameter. I would like to further develop this same experiment with other fluids to see the difference in behavior. Also, to achieve a more visually dynamic shot, I would like to experiment with food coloring or dye and watch the results.

References:

[1] M. Rein, "Phenomena of liquid droplet impact," *Fluid Dynamics Research*, vol. 12, no. 2, pp. 61–93, 1993.

[2] F. Rodriguez & R. Mesler, "Some drops don't splash," *J Colloid Interface Sci*, vol. 106, pp. 347–352, 1985.

[3] M. Rein, "The transition regime between coalescing and splashing drops," *J Fluid Mech*, vol. 306, pp. 145–165, 1996.

[4] S.L. Manzello & J.C. Yang, "An experimental study of a water droplet impinging on a liquid surface," *Springer-Verlag*, no. 32, pp. 580–589, 2002. [Online]. Available: http://fire.nist.gov/bfrlpubs/fire02/PDF/f02065.pdf. [Accessed Feb. 8, 2012].

[5] G.J. Gittens, "Variation of Surface Tension of Water with Temperature," *J. Colloid Interface Science*, vol. 30, no. 3, pp. 406–412, Jul. 1969. [Online]. Available: http://pdn.sciencedirect.com/science?_ob=MiamiImageURL&_cid=272564&_user=918210&_pii=0021979769904093&_check=y&_origin=article&_zone=toolbar&_coverDate=31-Jul-1969&view=c&originContentFamily=serial&wchp=dGLbVlV-zSkzV&md5=ab4a861d66808ec970ecdf0e463c22fb/1-s2.0-0021979769904093-main.pdf. [Accessed Feb. 8, 2012].

Image Assessment Form
Flow Visualization
Spring 2012

Name: Ernesto Grossmann

Assignment: Get Wet

Date: February 16,2012

Scale: +, ! = excellent √ = meets expectations; good. ~ = Ok, could be better. X = needs work. NA = not applicable

Art	Your assessment	Comments
Intent was realized	+	
Effective	+	
Impact	+	The peoples' reaction was positive.
Interesting	~	The phenomenon is well represented, but somehow there can be different ways to make it more interesting.
Beautiful	+	
Dramatic	+	
Feel/texture	+	
No distracting elements	+	
Framing/cropping enhances image	+	Framing to the right and applying the rule of thirds make the image attractive.

Flow	Your assessment	Comments
Clearly illustrates phenomena	+	
Flow is understandable	+	
Physics revealed	+	
Details visible	+	
Flow is reproducible	+	
Flow is controlled	~	
Creative flow or technique	~	
Publishable quality	√	

Photographic technique	Your assessment	Comments
Exposure: highlights detailed	√	
Exposure: shadows detailed	√	
Full contrast range	√	
Focus	+	
Depth of field	+	
Time resolved	+	
Spatially resolved	+	
Clean, no spots	+	

Report		Your assessment	Comments
Describes intent	Artistic	+	
	Scientific	√	
Describes fluid phenomena		+	
Estimates appropriate scales	Reynolds number etc.	+	In this case the Weber number was the dimensionless parameter that established the behavior.
Calculation of time resolution etc.	How far did flow move during exposure?		
References:	Web level	√	
	Refereed journal level	+	
Clearly written		+	
Information is organized		+	
Good spelling and grammar		+	
Professional language (publishable)		√	
Provides information needed for reproducing flow	Fluid data, flow rates	+	
	geometry	+	
	timing	√	
Provides information needed for reproducing vis technique	Method	+	
	dilution	NA	
	injection speed	+	Impact speed in this case.
	settings	+	
lighting type	(strobe/tungsten, watts, number)	In-built flash	The harshness of the flash was reduced by setting it manually at 1/8 of the capacity.
	light position, distance	√	
Provides information for reproducing image	Camera type and model	+	
	Camera-subject distance	~	
	Field of view	+	
	Focal length	~	
	aperture	+	
	shutter speed	+	
	film type and speed or ISO setting	+	
	# pixels (width X ht)	+	
	Photoshop techniques	+	
	Print details	√	
	"before" Photoshop image	+	