Supercooling Water

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MCEN 5228: Flow Visualization

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Introduction

The image above is taken from a video of a marble being dropped into supercooled water. The video was taken for the first group project in the flow visualization course. The intent of this project was to demonstrate the spontaneous phase change from liquid to solid that occurs in supercooled liquid; water in this case. Supercooled water is water that has been cooled below its freezing point. This occurs when there is no nucleation zone for ice crystals to build upon. Nucleation zones are often any impurities in the water such as minerals or dirt on an unclean container in which the water is in. Without a nucleation zone the buildup of ice crystals is difficult and the water may drop below freezing temperature.

Once supercooled, impurities added may cause the water to instantly freeze. It is this phenomenon that our group desired to capture. Small quantities of water were supercooled in shot glasses. Once supercooled, a marble was dropped into the water. The marble itself acted as a nucleation point from which ice could form. Because the ice formation happens very quickly a high speed camera was used to capture the process.

Experimental Setup

The setup for this project was two step. The first step was to supercool the water and the second step was to film the water spontaneously freezing. Small volumes of water were chosen to be supercooled in order to decrease the time it took for the water to reach sub freezing temperatures. Shot glasses were used because they were clear and easily cleaned. Distilled water was also used because it contains very few impurities that could potentially act as a nucleation point. Before adding the water to the shot glass the glasses were scrubbed with soap and water then rinsed with distilled water. Once the distilled water was added the glasses were covered with parafilm to ensure no contaminants got into the water. The glasses were then placed into a salt water ice bath so that the level of the ice bath was above the water level in the shot glass.

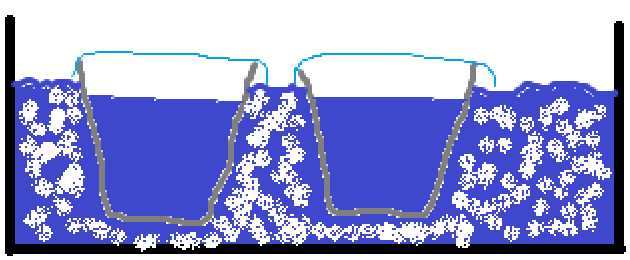

Figure 1: Shot Glasses in Ice Bath

Salt water was used in order to lower the freezing point of water thus creating a water bath below 0°C. It was imperative to determine when the water was supercooled so that attempts at imaging the water freezing were not wasted. This is because if the shot glass was left in the ice bath for long enough the water would eventually freeze solid regardless of how clean the glass or pure the water. Alternatively if the water was not left in the bath long enough it may not have even dropped below the freezing temperature. The temperature of the water could not be directly measured to determine whether or not the water had supercooled. This is because any form of temperature measurement in the water would act as a nucleation point if the water were in fact supercooled. Instead a dirty shot glass with tap water in it was placed alongside the other shot glasses in the ice bath. The water in this glass was unable to supercool. Once the water in the dirty glass was partially frozen it could be inferred that if the water in the clean glasses showed no similar signs of freezing that they in fact must be supercooled.

When the water in a given shot glass was determined to be supercooled, the glass was carefully removed from the bath as well as its parafilm cover. A marble was then dropped into the glass causing the supercooled liquid to instantly freeze. Although the marble was dropped from an arbitrary height, its impact velocity and drop height can be determined from the high speed video. Using the frame by frame function in VLC video player it was determined that the ball took 6 frames to travel the distance of its own diameter soon before it struck the water. Given a frame rate of 1000 fps and a ball diameter of 12.34 mm the balls velocity is determined to be approximately 2 meters per second before it strikes the water. The drop height is then determined from the equations below.

$$t = \frac{v_f}{a}$$

$$d = .5 * a * t^2$$

Where:

t = time

v_f = final velocity of the ball

a = gravitational acceleration

d = distance traveled

It was determined that the ball dropped from a height of .2 meters in .2 seconds.

Figure 2 below is a diagram of the experimental setup.

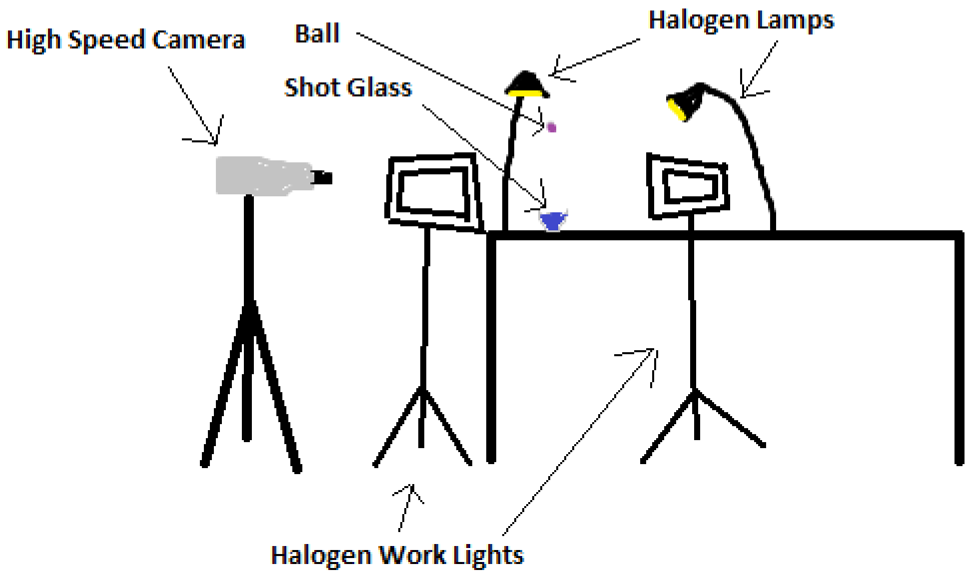

Figure 2: Video Setup

Visualization Techniques

A high speed camera was used to film this process. The camera used was an Olympus I-Speed. The camera had a 50 mm c-mount lens and with an aperture ranging from 1.4 to 16 f-stop. It shot at a maximum 1000 frames per second and has an 800 x 600 sensor resolution. For the shot the camera was placed approximately two feet from the shot glass and the highest frame rate, 1000 fps, was used. Because of the high frame rate lots of light was required. To help increase exposure the largest aperture was used, f/1.4 and the lighting for the video came from four halogen bulbs. The positioning of the bulbs was experimented with until the video no longer looked over exposed. Minor editing was done to the video itself. Only parts of the video were sped up.

Supercooling Physics

A supercooled fluid is a fluid that has been cooled to a temperature lower than its freezing point while remaining in its liquid phase. For a fluid to freeze nucleation must occur from which point dendritic ice crystals will grow.[1] A nucleation point in water occurs heterogeneously at an impurity within the water.[3] Such impurities could be anything from a ruff surface on the fluids container, dust or minerals within the water. When there is an abundance of impurities in the fluid nucleation will begin at the freezing/melting temperature of the fluid. Once nucleation begins the fluid is undergoing a phase change in which case it stays at a constant temperature and loses its latent heat. The latent heat of fusion (freezing or melting) for water is 334 kJ/kg and the total energy lost during freezing is shown below.[2]

$$Q_{fusion} = m * L$$

Where:

m = mass

L = latent heat of fusion

If there are few enough impurities in the fluid and the ambient temperature is below freezing then the fluid temperature may drop below its own freezing point before nucleation begins creating an unstable supercooled liquid. Once nucleation begins dendritic ice crystals will quickly and spontaneously form to regain equilibrium between the solid and liquid states. This process will continue until the liquid ice mixture is at the fluids freezing point and equilibrium has been established. For example if nucleation begins in water that has been supercooled to -5^{o} C, ice will spontaneously form until the ice water mixture is at 0^{o} C. As ice is formed in the water heat is released which warms the liquid and creates ice. The amount of heat that is released is depended on the heat capacity of the liquid state of water. The heat released during this process is shown below.[2]

$$Q_{released} = \int_{293}^{298} m * C_p dT$$

Where:

C_p = Specific heat of water

Given the latent heat of fusion for water and the heat released into the liquid to form ice the fraction of liquid transformed into ice can be determined.

$$Fraction\ Frozen = \frac{Q_{released}}{Q_{fusion}}$$

Conclusion

Overall the experiment was very successful. Our team was able to supercool water and film the water spontaneously freeze when a nucleation point was created with a dropped marble. For this particular test no colored dye was used. In other experiments dye was used which helped give definition to the ice crystals. More clarity could have also been achieved by wiping moisture off the shot glass. Finally calculations could have been directed more specifically to the actual experiment if the temperature of the ice bath had been recorded.

References

[1] Braga, S. L., and Milon, J. J., 2003, "Supercooling Water In Cylindrical Capsules." Fifteenth Symposium On thermophysical Properties. http://symp15.nist.gov/pdf/p697.pdf

[2] Gaskell, D. R.,2008 , "Introduction to the Thermodynamics of Materials," Tayor & Francis Group: New York, NY

[3] Haymet, A.D.J.,Heneghan,A.F.,Wilson,P.W., 2002, "Ice Nucleation in Nature," 46 (88-98), Cryobiology

Image Assessment Form

Flow Visualization

Spring 2010

Name(s)

Assignment: Date:

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

Art	Your assessment	Comments
Intent was realized	!	
Effective	!	
Impact	CHECK	
Interesting	CHECK	
Beautiful	OK	
Dramatic	OK	
Feel/texture	CHECK	
No distracting elements	OK	
Framing/cropping enhances image	OK	

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

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

Report		Your assessment	Comments
Describes intent	Artistic	OK	
	Scientific	!	
Describes fluid phenomena			
Estimates appropriate scales	Reynolds number etc.	NA	
Calculation of time resolution etc.	How far did flow move during exposure?	1MM	
References:	Web level	CHECK	
	Refereed journal level	CHECK	
Clearly written		!	
Information is organized		!	
Good spelling and grammar		CHECK	
Professional language (publishable)		CHECK	
Provides information needed for reproducing flow	Fluid data, flow rates	CHECK	
	geometry	CHECK	
	timing	CHECK	
Provides information needed for reproducing vis technique	Method	CHECK	
	dilution	NA	
	injection speed	NA	
	settings	CHECK	
lighting type	(strobe/tungsten, watts, number)	CHECK	
	light position, distance	Ok	
Provides information for reproducing image	Camera type and model	Check	
	Camera-subject distance	Check	
	Field of view	Check	
	Focal length	Check	
	aperture	check	
	shutter speed	Check	
	film type and speed or ISO setting	Check	
	# pixels (width X ht)	Check	
	Photoshop techniques	Check	
	Print details		
	"before" Photoshop image		