Champagne Bottle Opening in Slow Motion

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For Team Second 2016

Introduction

This video was created for the second team assignment for Flow Visualization. Special Thanks are given to the members of Team 3, Mark Noel, Jeremiah Chen and Jason Savath for their contributions in brainstorming, setup and filming for this assignment. Thanks are also given to Professor Tadd Truscott of Utah State University for the use of his high speed camera and assistance filming and lastly to Professor Hertzberg for her assistance, and use of her laboratory.

My main objective for this assignment was to completely immerse the viewer in the slow motion world shown in the video. Of the videos taken, two similar videos were used. The first is a wider shot of the champagne opening and spray taken at 8000 frames per second and is front lit. The second is a tighter shot from the same angle with a similar background. This clip, however, was backlit and captured at 25000 frames per second. The two clips show nearly the same phenomenon, but the difference is lighting and capture speed emphasize different details. This will be discussed in detail in this paper. In editing, a large emphasis was placed on the audio. Inspired by "The Slomo Guys" an artificial audio track was created based on imagining what the sound would be like at the slow speeds.

Flow Apparatus

The flow apparatus was, as it appears in the video, simply a bottle of champagne. Additionally, there was a black cloth placed on a corkboard behind the bottle to create high contrast between the light white foam and the background. A small tank was placed below the frame. It served the purpose of capturing most of the ejected champagne. Additionally it was used as an alignment tool to place the bottle, ensuring that the framing was as desired, and that the jet would be in the plane of focus. A towel was hung from the ceiling to catch the ejected cork.

Visualization Technique

This flow was captured with super slow-motion video. The two clips in the video were lit differently, and showed different aspects of the flow. Both clips utilized six lights. Four halogen work-lights, mounted in pairs on two stands, were used in conjunction with two LED panels. The quantity of lights used was to ensure that there was enough light on the subject to achieve the desired exposure at the necessary fast shutter speeds. The first clip was lit from the front with one halogen light stand on the left of the camera, one on the right of the camera. The LED panels were below the bottle, illuminating the bottle itself from below. This showed in detail the bottle and foam ejected from it.

The second clip was lit from behind. One of the halogen light stands was behind the bottle and to the left of the frame; the other was behind the flow and to the right. They were aimed around 120^{o} from the line of the flow, in hopes if hitting the peak of forward scattering that occurs from smaller particles at about that angle. While this adequately lit the foam, it did a much better job showing the condensed water vapor and smaller particles.

Photographic Setup

The camera used was a vision research Phantom 2512. This camera can capture up to 25000 frames per second at resolutions of 1280x800. Both clips used were captured with the 2512, along with a Nikon 50mm prime lens. The first clip was captured at 8000 frames per second, the second was captured at 25000 frames per second. Both were at the Phantoms native ISO of 6400.

The clips were exported from the camera in CINE format. Using the available CINE viewer software from Vision Research the files were converted into .avi files using mjpeg compression. The resulting files were 1280x800 pixels and 29.97 frames per second. These files were then imported into Cyberlink PowerDirector 11 for editing.

Video Editing

The first changes made to the video were speeding up sections of the video. The two clips had a combined length of over 8 minutes. This would surely lose viewer interest. Two sections of the video were emphasized in slow motion, the release of the cork, and emergence and popping of a gas bubble some time later. Both cork releases were kept at full speed, while the bubble popping for both cases were played at an equivalent speed of 8000 frames per second. A third area of interest, mid ejection of foam, was selected for the second clip and was played at the speed of 25000 fps. This was included to remind the viewer of the timescales shown in the video. This particular clip, which the viewer is aware is moving forward quickly and also affected by gravity, appears near frozen. All other clips speeds were adjusted to fit the clips within a desired one and a half minute. A transition between the clips was added, which include the first clip played in near real-time in reverse before crossfading to the second clip. This was done to show creatively to the viewer that the same thing was about to be shown again. In a way, time was rewound to show the effect again.

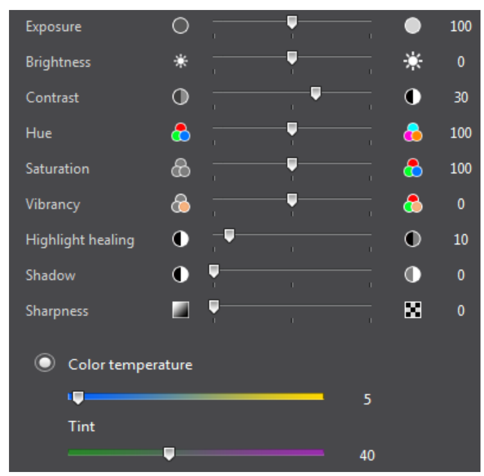

Figure 1

Color correction of video

The original footage seemed dark and warm. Colour correction tools were used to correct this. In post, the color correction tools were used to lighten the video, and shift the colour towards the blue side of the white balance(Figure 1).

A great emphasis was placed on the audio track. Inspired by “The Slomo Guys” I wanted to immerse the viewer within the slow world shown in the clips. As audio was not recorded when the video was, an artificial soundtrack needed to be created. This required imagining what the different parts of the video would sound like, and what it would sound like when it was slowed down greatly. About 15 different sounds were used to create the audio track.

Discussion of Resolution

This video shows a wide variety of phenomena. Especially with the use of super slow motion, these phenomena, from the cork departure on are shown with excellent temporal resolution. In terms of temporal resolution, the first shot was taken at 8000 fps and had a shutter speed of 45μs. The second shot was taken at 25000 fps and had a shutter speed of 35.2μs. Spatially, the first shot framed an area of 35.8x63.7cm, and at the published resolution of 720x1280 this means each pixel is .05x.05cm. The second shot framed an area of 17.8x31.6cm, and each pixel covered an area of .025x.025cm.

In terms of motion blur, the threshold of moving one pixel over the exposure time gives a velocity of about 11m/s for the first shot. Since the cork exit velocity is around 16m/s in this shot, (and the cork and champagne stream are both significantly larger than 1 pixel) this means that for the larger elements there is very minimal motion blur. Frame to frame, moving one pixel results in a velocity of 4 m/s. The only area of concern regarding the adequacy of this spatial and temporal resolution is in the initial burst of gas as the cork departs the bottle, whose velocities significantly exceed that of the cork.

The second shot being tighter increases the potential to blur, but a higher frame rate helps to compensate for this. Again for motion blur, moving one pixel over the exposure time results in a velocity of 7m/s. While this does not affect the larger droplets and the cork, which have dimensions in tens to hundreds of pixels, it is significant to the smallest particles released as the cork departs. These particles are pixel to sub pixel size, so they are not adequately spatially resolved. They also have an initial velocity of around 140m/s, meaning that they are dramatically temporally under resolved, moving over 20 pixels per frame.

Discussion of Flow Phenomena

These shots show a variety of phenomena which occur when opening a bottle of champagne. When shaken carbon dioxide dissolved within the champagne bubbles and causes pressure to build within the bottle. As the cork is pushed, it reaches a threshold where the pressure forces become greater than frictional forces, and the cork begins to accelerate. Once the cork is clear of the neck of the bottle, the gas and champagne are free to leave the bottle. They erupt from the bottle in a jet which impinges on the cork and propels the cork forward. For around a tenth of a second this jet continues, dominated by momentum of the pressure gradient. This dies down as the pressure equalizes with the atmosphere. A second jet of foam appears soon after. This is likely due to a second wave of carbon dioxide bubbles forming during the rapid pressure drop after the bottle is opened.

Champagne's bubbles come from the second fermentation process, where yeast and sugar are added to the then flat wine. The resulting carbon dioxide builds up in the sealed bottles, and under high pressure becomes dissolved within the champagne. The carbon dioxide reacts with the water, in the easily reversible reaction forming carbonic acid and making the champagne slightly more acidic.

$$CO_{2\,(aq)} + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H_2CO_3^- + H^+$$

When the bottle is shaken, the motion adds energy, which acts as a catalyst for the for the carbon dioxide to bubble, becoming gaseous, causing carbonic acid to become aqueous carbon dioxide, which with more shaking becomes gaseous. This buildup of gas causes a large increase in pressure.

From watching the video, there appears to be two phenomena related to this, both of which occur on different timescales. The first is the initial release of the gas. With exit velocities of over 140m/s, this rapid change in pressure around the bottle results in the pressure wave which is the "pop" sound of the champagne opening. Gas continues to escape at high velocities, entraining foamy champagne as it exits the bottle. A chart of the exit velocity created by tracking features of the foam in the jets is show in figure 2. The jet impinged on the cork, transferring energy. The corks in the first and second shots have velocities of 16.2 and 21.6 m/s respectively.

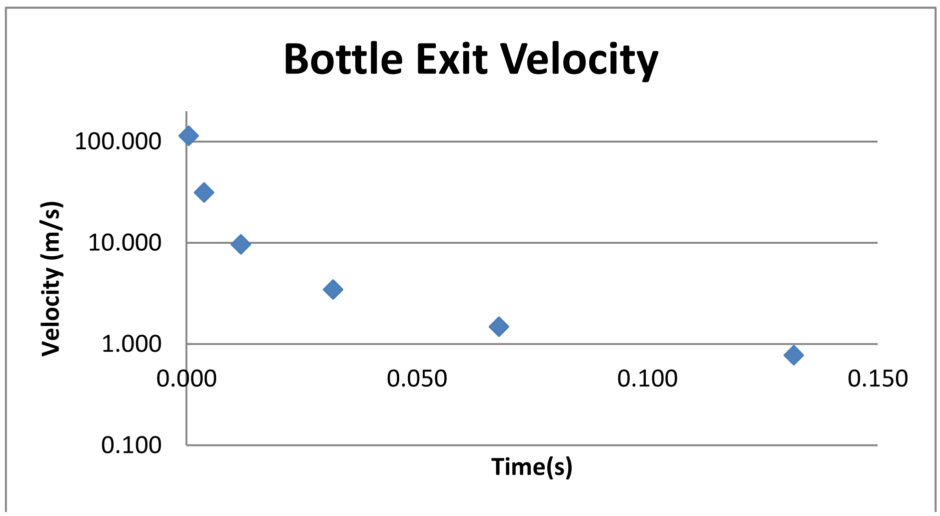

Figure 2

Log linear plot of jet velocity versus time. Note the exponential decay of velocity.

This pressure drop causes more carbon dioxide to bubble out of the champagne. Henry's law shows the amount of aqueous dissolved gas in a liquid is proportional to the partial pressure of the surrounding atmosphere.

$$K_H^{pc} = p/c_a$$

Where K is a constant determined by the temperature, gas and liquid, p is the partial pressure of the gas in the atmosphere surrounding the liquid, and c_a is the concentration of the aqueous gas in the liquid. Using this relationship, as the partial pressure of carbon dioxide goes from 5 atm to 1 atm (assuming pressure has equalized to atmosphere, but the gas immediately on the surface has not yet had a chance to escape the bottle and diffuse to the concentrations of the surrounding atmosphere) the potential amount of dissolved carbon dioxide is dramatically reduced, causing the carbon dioxide to effervesce and form a large volume of foam. This appears to be the cause of the second wave of foam shown in the video.

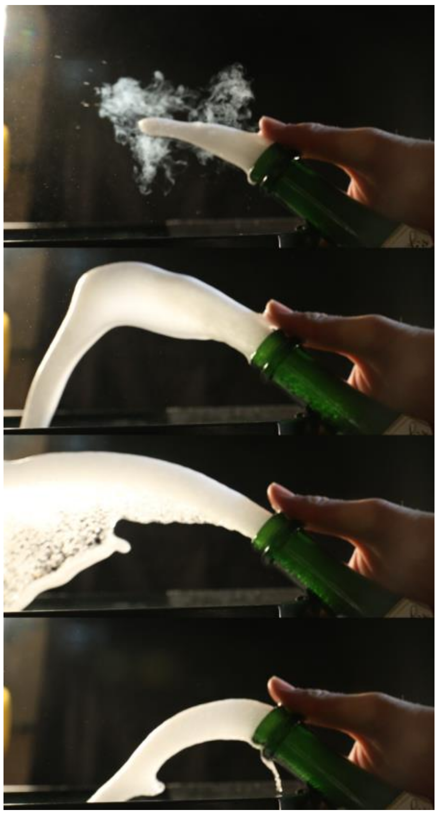

Figure 3

Sequence of still images. Top image about .4 seconds after cork departure, bottom image 1.4

This appears to be confirmed with a set of still images taken along with the video (figure 3). The stills, taken at about 8 frames per second, show the events of the video, the cork popping, the first jet and the emergence of the second jet through the mist. The images also show that for about three quarters of a second after the video ends, champagne foam emerges from the bottle at a relatively high volumetric flow rate, as indicated by the foam filling the entire opening of the neck of the bottle as it emerges.

As far as the mist which emerges before it, this appears to be water in the air condensing after the pressure drop. The air contained in the bottle is assumed to have a relative humidity of 100% because of the long exposure to a free liquid surface causing the water in the air to reach a state of equilibrium unlimited by the amount of water available. With the drop of pressure, the vapor condensed, and was seen exiting the bottle.

Conclusions

Peer review of the review was generally positive, saying the artificial soundtrack added artistically to the video overall. Some commenters said that a note cold be added that the audio is artificial, so as not to confuse it for collected data. A note will be added to the description of the video. I am ultimately pleased with the video overall, both in terms of the fluid mechanics it shows, as well as the artistic feel it portrays.

The video is absolutely fascinating, showing a common phenomenon in a new and unique perspective. Much more analysis of this video can be done, as there is so much information present. The video can be used to show the timescales of effervescing fluids reacting as pressure is changed, how fluid is entrained in gas jets, how a mixed gas and liquid jet impinging on a projectile imparts energy, and many more effects shown in the video.

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