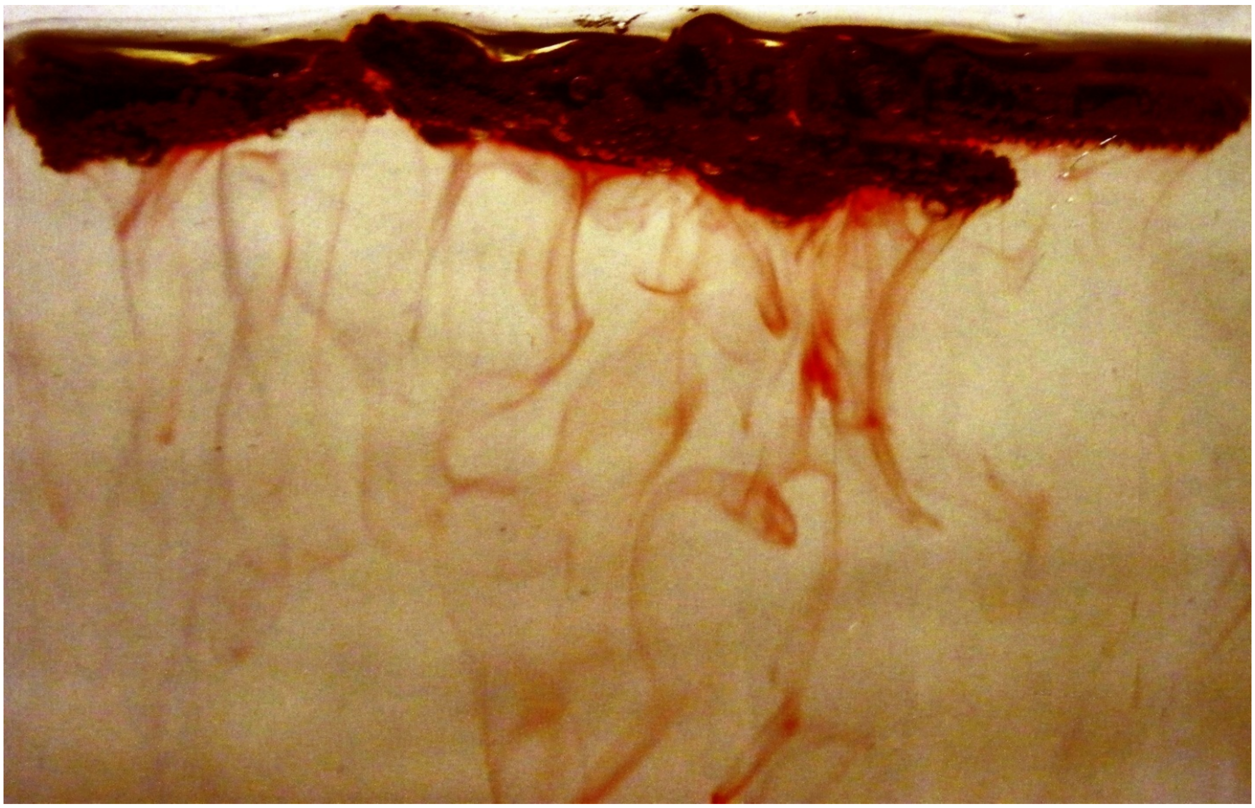
Tea Time

Flow Physics Involved in Brewing Tea

Assignment 1: Get Wet



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Intent

Mankind has been enjoying hot cups of tea for thousands of years, and tea is the most commonly consumed beverage in the world [Manikandan et al. 2009]. Yet, very few tea drinkers understand the physics and fluid mechanics involved in brewing a cup of tea. For the first assignment in Flow Visualization, the guiding physics and fluid flow associated with tea brewing were investigated. In doing so, visualization methods and photographic techniques were used to explore how a cup of tea can appeal to more senses than just taste. The intent was to capture the full scientific process as well as the beauty that goes into each cup of tea. In doing so, photographic editing was minimized to preserve the natural aspect of the image. Another goal of the image was to utilize a creative and original technique that hadn't been used in any previous images from this class.

Description of Apparatus

A piece of white paper was placed approximately 5cm behind a glass with dimensions 7.5cm diameter and height of 15.5cm (Figure 1). The glass was filled with boiling tap water, which cooled to approximately 85 °C at the time photography began. After waiting 5 minutes for any residual flow within the glass to decay, roughly 1 tsp of hibiscus tea (consisting of cut and dried hibiscus flower petals) was placed on the water surface within the glass. The tea was carefully placed in a tight cluster near the side of the glass closest to the camera (farthest from the paper backdrop). Over the following 3-4 minutes, several photographs were taken of the water surface. The line of sight of the camera is denoted by the red dashed line in Figure 1, perpendicular to the paper background. The final selected photograph was taken approximately 2 minutes after the tea was added to the water. The camera lens was located approximately 3cm away from the glass when the photograph was taken.

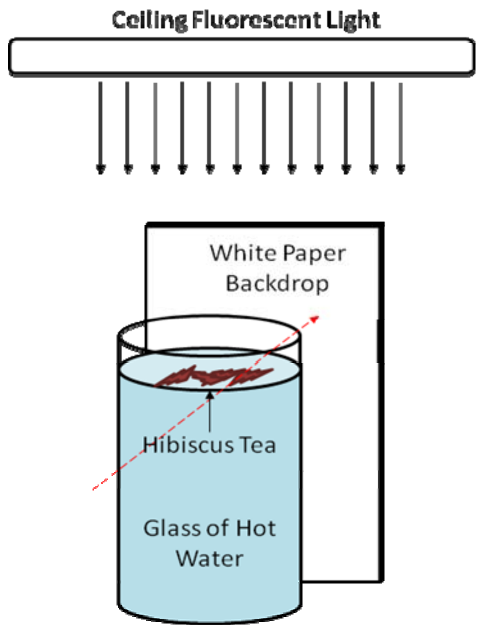

Figure 1: Apparatus diagram

Fluid Flow Visualization Techniques

The fluid flow was visualized through water-soluble solutes within the hibiscus tea as they leached out into the hot water. This produced a result similar to that of a water-soluble dye being placed on the water surface. The details of this process will be discussed in a later section. The hibiscus tea was obtained from Dragonwater Tea Co. LLC, which is described as "cut and sifted hibiscus flowers." The dried flower petals are dark red and purple, and produce a dark red-colored tea when brewed in hot water. To provide high contrast to the red-colored solutes used to visualize the flow, a white backdrop was used in conjunction with white fluorescent lights on the ceiling above the glass. The camera flash was not utilized during photography.

Photographic Techniques

All photographs were taken using an Olympus FE-370 8.0 megapixel digital camera. This camera has a focal length range of 6.3-31.5mm and an aperture range of 1:3.5-5.6. All photographs utilized the camera's "indoor" setting in conjunction with the "super macro" setting with the flash disabled. The camera was held in hand for all photographs. Table 1 lists detailed information about the final photograph.

Table 1: Details of photograph

Photograph Date and Time	Jan 21, 2009 8:12AM
Field of View	6 x 4 cm
Distance from Lens to Glass	3cm
Lens Focal Length	7.7mm
Original Image Size	3264 x 2448 pixels
Final Image Size	2872 x 1899 pixels
Shutter Speed	1/25 sec
Aperture	f/4
ISO Setting	100

Image processing was minimized, and was performed using the Paint.NET image editing software. Only four basic adjustments were made between the original and final images. First, the contrast was increased slightly using the "curves" feature in Paint.NET. This was used to increase the distinction between the white background and the red solute markers used to visualize the flow. Second, the red color was enhanced using the same "curves" function in Paint.NET. The blue and green colors were not changed. This was done to increase the vividness of the red solute within the water, which made the flow more visible and distinguishable. Thirdly, distracting elements of the image were removed using the "Clone Stamp" tool in Paint.NET. Removed elements consisted of small bubbles and scratches on the exterior of the glass. Lastly, the image was cropped so that the tea and the flow of the solutes filled the image. The original image can be found in the Appendix.

The Hydrodynamics Associated with Tea Brewing

The Leaching Process

The hibiscus flowers, like tea leaves, contain various water-soluble particles. When placed in contact with water, the hibiscus flowers become hydrated and swell. The absorbed water acts as a solvent, pulling various solutes from the flowers into the water. The green arrows in Figure 2 show the various regions in the photograph where this occurrence is observed. As the solutes are

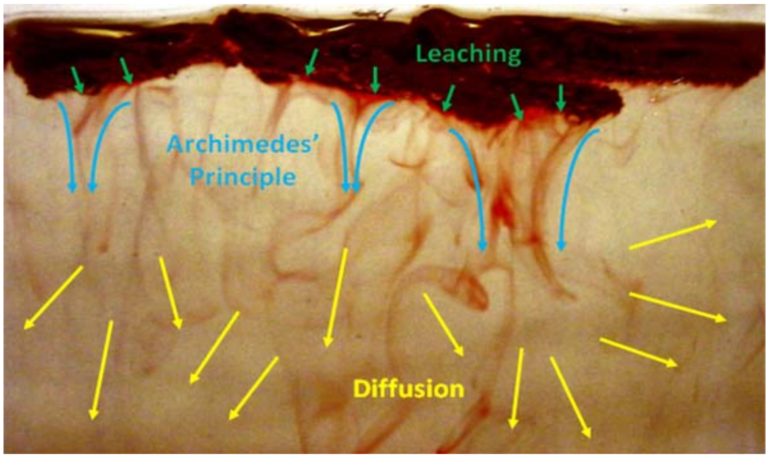

Figure 2: Identification of Observed Flow Phenomena

leached out of the flowers, the water that closely surrounds the flowers becomes saturated with a high concentration of solutes compared to the rest of the water in the glass [Lian et al. 2002, Rochefort].

Archimedes' Principle

Previous studies have determined the average density of inert tea solids to be 1600 kg/m^3 [Lian et al. 2002], which is higher than the density of water at 85 °C (968 kg/m^3) [Munson]. Archimedes' Principle states that these tea solutes have an upward buoyancy force equal to the weight of water they displace. Thus, each solute particle has an upward body force of 968*g*V, where g is the gravitational constant and V is the volume of the particle. The solutes also feel a downward body force due to gravity, which equals -1600*g*V for each individual particle. The gravitational force is greater in magnitude than the buoyancy force, which explains why the water saturated with leeched solutes sinks into the bulk water in the glass, shown by the blue arrows in Figure 2. However, because the volume of each particle is so small, the net downward force is very small, leading to a very small downward acceleration of each particle by Newton's Second Law of Physics.

Flow Characterization

The rate of sinking of the highly concentrated solutes was measured using a stopwatch immediately after the photograph was taken. Based on the field of view of the final image, the distance from the bottom of the hibiscus flowers to the bottom of the image is approximately 3cm. As the fluid flowed over this distance, the elapsed time was measured three times and averaged to be 1.7 seconds. The resultant average velocity of the sinking fluid is 1.76 cm/sec, which is comparable to velocities observed in similar experiments [Lian et al. 2002]. This velocity, along with the density (968 kg/m^3) and the dynamic viscosity (3.347×10^{-4} $N*s/m^2$) of water at 85 °C were used to determine the Reynolds number of the observed flow, yielding Re = 1527 [Munson]. This value of Re corresponds to laminar flow ($Re < 2100$). The flow observed in the photograph is lacking of any turbulent effects and appears to be laminar, evidenced by the calculated Reynolds number.

Diffusion

As the streams of water containing a high concentration of solute particles flow downward, they mix with the bulk water. Over time, the solutes will diffuse throughout the glass until there is an equilibrium concentration of solutes in the water, shown by the yellow arrows in Figure 2. Because the photograph was taken approximately 2 minutes after the hibiscus flowers were added, some diffusion had already taken place, which is why the bulk water in Figure 2 is slightly red in color. The diffusion process is very well defined on the left side of the photograph where one can observe the distinct flow of the highly concentrated solute down to a uniform concentration. This diffusion process is governed by Fick's Laws [Steward]. Too little information is known about the system to perform numerical calculations with Fick's Laws, but they are discussed in detail in the Appendix.

Image Discussion

My final image is a great and complete representation of the hydrodynamics and processes that govern the brewing of tea. The image reveals the chain of processes that transform tea leaves (or flower petals) into a cup of tea. Also, the image is fairly visually appealing. The vibrant red color stands out and the flow patterns are very pronounced and distinct yet also subtle and delicate, which is probably my favorite feature of the image. I wish I could have used less photographic processing, but the original image was too faint and the color required software enhancement to better depict the fluid physics. However, some of the processing could have been avoided had I used a new glass without any scratches. I underestimated how distracting these marks on the outside of the glass would be, and also how pronounced they would be. I would definitely improve this aspect of my apparatus in the future. Also, I would improve my photograph by using a tripod so stabilize the camera, and in all my future photographs for this class I will utilize a tripod to produce clearer images. Overall, I think my intent was realized and I am pleased with my final image.

References

Lian G, Astill C. "Computer Simulation of the Hydrodynamics of Teabag Infusion." Trans IChemE: **80C** (Sept 2002): 155-162

Manikandan N, Seenivasan S, Ganapathy MNK, Muraleedharan NN, Selvasundaram R. "Leaching of Residues of Certain Pesticides from Black Tea to Brew." Food Chemistry: **113** (2009): 522-525

Munson, Bruce, Donald Young and Theodore Okiishi. Fundamentals of Fluid Mechanics. Asia: John Wiley & Sons, 2006

Rochefort, Skip, Ellen Momsen and Tom Thompson. "Engineering Analysis of Tea Brewing – A Leaching Process." 2004. Oregon State University. Accessed 1/30/2009. <http://engr.oregonstate.edu/momentum/k12/oct04/>

Steward, Paul. "Fick's Laws of Diffusion." 2004. Accessed 2/1/2009 <http://www.initium.demon.co.uk/fick.htm>

Appendix

Calculation of Reynolds Number

The equation for Reynolds number is defined as

$$Re = \frac{\rho U L}{\mu}$$

where ρ is the fluid density, U is the average velocity, μ is the dynamic viscosity, and L is a characteristic length. Using the values discussed in the text, the Reynolds number can be determined as follows.

$$Re = \frac{\left(968\frac{kg}{m^3}\right) \times \left(0.0176\frac{m}{s}\right) \times (0.03m)}{\left(3.347 \times 10^{-4}\frac{Ns}{m^2}\right)} = 1527$$

Discussion of Fick's Laws of Diffusion

Fick's First Law states that the diffusive flux of a substance across a membrane of unit area is proportional to the concentration gradient of the substance in the fluid across the membrane, or in mathematical terms

$$J = \quad D\nabla\phi$$

where J is the diffusive flux, D is the diffusion coefficient (diffusivity), ∇ is the differential vector operator, and ϕ is concentration of the substance. Fick's Second Law describes how the concentration field of the substance changes with time due to diffusion, and is stated as

$$\frac{\partial\phi}{\partial t} = \nabla\cdot(D\nabla\phi)$$

For the apparatus described in this report, the concentration field of tea solutes in the water was not known and was also very spatially-variant, nor was the diffusion coefficient known. Thus, no quantitative analysis could be performed with Fick's Laws. However, it is important to understand the characteristics of these equations and how they govern the system.

Original Photograph