Natural convection of an Ice Cube Melting in Water

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Nomenclature

β	=	volumetric thermal expansion coefficient	$[K^{-1}]$
ν	=	kinematic viscosity	$[m^2s^{-1}]$
D	=	diameter or characteristic dimension	$[m]$
g	=	acceleration due to Earth gravity	$[ms^{-2}]$
Gr	=	Grashof number	[ ]
T_s	=	surface temperature	$[K]$
T_∞	=	bulk temperature	$[K]$

I. Introduction

THIS experiment was designed to capture an image of the natural convection caused by an ice cube melting in water. The image was recorded as part of the Flow Visualization class at the University of Colorado at Boulder. The initial assignment for this class, "Get Wet," was designed to produce images from students that demonstrated a phenomenon of fluid dynamics and demonstrated aesthetic beauty. This image used a melting ice cube that was dyed blue with food coloring in order to visualize the physical phenomena of natural convection, laminar to turbulent flow transition, and Rayleigh-Taylor instabilities.

II. Flow Apparatus

To create this image, a blue ice cube was submerged in water at room temperature and allowed to melt. Upon submersion into the water, the ice cube initially measured approximately 3.8x3.8x2.5cm. 0.47L of liquid water was

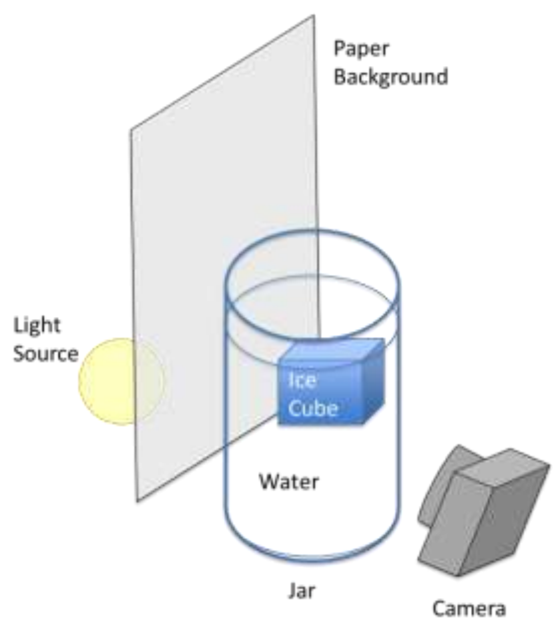

Figure 1: Visualization setup diagram

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contained in a 0.6L household glass jar and its temperature was measured at 17°C. The image of the ice cube was recorded within less than 10 seconds of the initial submersion, so the analysis that follows will assume that the temperature of the water was the same as its initial conditions.

III. Visualization Technique

The goal of this image was to provide a visualization of natural convection. A melting ice cube was selected to produce this phenomenon, because the ice cube offered the ability to easily segregate the food dye used to visualize the flow. This offered advantages compared to a natural convection case driven by a heated surface, where dye segregation would be more difficult. One weakness of the implementation of this dye was that as the melt water flowed away from the ice cube, its color diminished. Accordingly, the amount of dye used should be increased from 3 drops per ice cube to at least 10.

The setup of the ice cube, water, and light source are described in Figure 1. Through experimentation, it was found that a backlit image was preferable to lighting from the side of the camera, because a backlight eliminated stray reflections from the light source. There were still some reflections recorded on the surface of the jar, but these were easily removed in post processing and will be discussed in the "Photographic Technique" section.

IV. Flow Analysis

The phenomenon captured by the image for this report was the natural convection of melting ice in liquid water. Natural convection is driven by the temperature gradients in fluids that cause differences in fluid densities [3]. This difference causes colder heavier fluids to fall while warmer lighter fluids rise in the presence of a gravitational field. In this case, the melt water from the ice cube, indicated by its blue dye, is the heavier fluid that falls and pushes the warm, clear water to take its place. The non-dimensional Grashof number is a useful description for describing natural convective flows, because it relates the ratio of buoyant to viscous forces acting on a fluid. For a blunt body, it is calculated as follows:

$$Gr = \frac{g\beta\,(T_s - T_\infty)\,D^3}{\nu^2} = \frac{9.81[ms^{-1}]2.14 \cdot 10^{-4}[K^{-1}]\,(273-290)[K]0.038^3[m^3]}{\left(1.09 \cdot 10^{-6}[m^2s^{-1}]\right)^2} = -1.6 \cdot 10^6$$

In this case, the Grashof number shows that the negative or downward buoyant force on the melt water is much greater than the viscous forces that are acting in resistance to the shear stress of the sinking water. The Grashof number also relates to the turbulent-laminar flow transition. Grashof numbers between 10^4 and 10^9 correlate to a laminar boundary layer in natural convection on a vertical plate [1]. This fits the flow described by the image, because its absolute Grashof number of $1.6 \cdot 10^6$ fits within this range and shows a laminar sheet as it cascades down the face of the ice cube.

The image in this report also revealed the presence of Rayleigh-Taylor instability within the flow on the horizontal face of the ice cube. This is a "fingering instability of an interface between two fluids of different densities [2]." In this case, the lighter warm water beneath the ice cube cannot maintain the shape of the cool dense water above it, so the denser water begins to deform and fall downward from the horizontal surface of the ice cube. Because the image is rotated half a revolution in its final state, it appears as though it is rising rather than falling.

V. Photographic Technique

The image was captured using a Panasonic DS20 point-and-shoot digital camera. The image was recorded with a focal length of 4.5mm, an aperture of f/3.9, an exposure time of 1/60s, and an ISO sensitivity of 250. Because of the constraints of the camera used, the settings could not be adjusted manually, and the imaging setup had to be adjusted with an external light source in order to achieve the shutter speed and low ISO sensitivity used to capture an image without motion blur or sensor noise. The biggest advantage of this small camera was that it could achieve a very short focal length that allowed for a distance of 13cm between the subject and the lens. This short distance was ideal for photographing such a small object in detail.

The image was processed using Adobe Photoshop software. The image was first cropped from an original size of 1920x2560 pixels to 864x1361. This severe cropping could be avoided in future images, because the camera used is capable of even shorter distances between the lens and object. Based on aesthetic preference, it was decided to rotate

Figure 2: Image alteration comparison

the image, so that the ice cube was at the bottom of the image. Next, each RGB color curve was adjusted individually to increase contrast as desired. Finally, a stray reflection was seen on the surface of the glass jar in the bottom left corner of the final image. This was removed by adjusting the brightness curves over small areas to decrease highlights. A comparison between the original and final images can be seen in Figure 2.

VI. Conclusion

The image in this report successfully demonstrated natural convection of melting ice in water, and also gave an example of Rayleigh-Taylor instability as the heavier fluid sank. This was accomplished by using a camera capable of taking large images of small objects, and by using a diffused light source to backlight the objects. Despite these accomplishments, the image could be improved by using more food dye in the ice cube, and by positioning the camera even closer to the subject matter to avoid excess cropping.

Acknowledgments

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