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Capturing Natural Convection Vortices: The photographing of incense smoke between separated hot and cold surfaces

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Introduction

Almost every morning, most Americas have a cup of coffee (something hot) and a glass of juice (something cold) before they start their day. It is known by most that hot air rises and cold air sinks due to the density variation of air with respect to temperature. The inspiration behind this photo came from wondering what happens when something that produces hot air is placed next to something that produces cold air. More specifically, the curiosity lied within what was happening at the center distance between the two temperately diverse objects. Knowing that hot air rises and cold air sinks, the goal of this project is to see if the temperature difference between two surfaces (hot and cold) is significant enough to produce a single vortex at the center distance of the two surfaces. It was hypothesized that the potential flow caused by the rising and sinking air would produce a solid body (rotational vortex). Think about what would happen if you placed your juice and coffee right next to one another, but not touching. What would happen in the center of the space between?

Physics Background

A temperature driven vortex is a difficult thing to try and experimentally produce and capture on camera. That is why knowing the fundamental physics behind natural convection and vortices is so crucial to try and recreate this shot. In the fields of heat transfer and fluid mechanics there are two types of convection, natural and forced. Forced convection is convection that occurs due to an external device doing work to force a given fluid across a separate independent boundary.[1] The other type of convection occurs naturally because of a temperature difference between the separate, independent boundary and the fluid that the boundary exists within.[1] For this project there was no mechanism forcing the flow, just the temperature difference between the high/low temperature surface and the ambient air. This means that only the physics behind natural convection should be considered in determining the nature of the vortex formation.

Along with convection, there are two types of vortices that can occur. One type of vortex is an irrotational vortex, which is a vortex where the driving force of the flow is located at the center of the vortex.[2] This type of vortex is theoretically modeled to have an rotational velocity of infinity at the center, then having the rotational velocity decrease as the distance from the center increases.[2] An irrotational vortex can be represented by Eqn. 1.

$$u_\theta = \frac{\Gamma}{2\pi r} \tag{1}$$

Where u_θ is the tangential velocity with respect to the angle of rotation, Γ is the circulation around the theoretical boundary of the vortex, and r is the radius from the center of the vortex.[2] The properties and effects of an irrotational vortex are important to consider in evaluating the type of vortex phenomena taking place between the hot and cold surfaces in this project. The other type of vortex found in nature is a rotational, or solid-body vortex. Eqn. 2 defines the rotational velocity so that the rotational vortex can be easily compared to the irrotational.

$$u_\theta = \frac{1}{2}\omega r = \omega_o r \tag{2}$$

Where ω is the angular velocity with respect to the center of the vortex.[2] A rotational vortex rotates as one solid-body with the angular velocity the same everywhere in that solid-body.[2] It should also be realized that there is no shear in the solid body of the vortex.[2] Irrotational and rotational vortices are also considered free and forced vortices respectively. Having a preliminary understanding of the physics behind natural convection and the different vortices can give a better idea of what to expect when recreating this shot, and why this phenomena was chosen in the first place.

Procedure

Referring back to the introduction, it is known that in order to accomplish the flow of the shot a hot and cold surface is needed. For cost efficiency and safety, a rectangular glass planting jar was used to put a salt-water ice bath in for the cold surface and a ceramic fireplace brick was heated in the oven for the hot surface. Knowing that the lighting of this shot would be extremely difficult to get right, a black trash can was cut in half with a slot cut out of the top to allow light to directionally be let through. Incense smoke was used as the tracing fluid (fluid which can illustrate the nature and properties of the flow). Fig. 1 gives a visual representation of the project setup. After looking at Fig. 1, it is noticed that only three components of the whole project were shown. Fig. 2 gives a more complete understanding of where everything was located upon completion of the shot. After experimenting with the distance between the cold and hot surfaces and the placement of the incense sticks, it was determined that a distance of three inches between the two surfaces with the incense sticks placed next to the hot surface was the best location. Approximately four to six incense sticks were used to give a heavier tracing effect of the flow. It should be noted by looking at Fig. 2 that this shot was taken outside in cold weather on top of a cold surface.

Camera Setup

Camera – Canon EOS DIGITAL REBEL XSi
Distance from focus to lens – Approximately 1.5 feet, holding camera
Focal Length – 49mm
Exposure Time – 1/2sec.
Aperture – f/5.6
Sensitivity – ISO-1600
Image dimensions – 1281 x 2696
Field of View – Approximately 9”
Flash – No Flash

Discussion

In order to know how natural convection affects the flow of the incense, the flow characteristics for both surfaces needs to be determined so that the type of flow (laminar or turbulent) is known. For forced convection the Reynolds number is calculated for determining the type of flow. For natural convection, the Rayleigh and Grashof number are calculated to determine the type of flow and if it is transitioning towards turbulent or not.[1,2] For natural convection along a horizontal surface, Eqn. 3 is examined. [3]

$$Ra = \frac{\rho_o g \alpha \Delta T L^3}{k\mu} \tag{3}$$

Eqn. 3 gives the Rayleigh number for determining flow type along a vertical smooth surface.[1,3] In this equation, $\rho_o$is the density of the incense smoke (roughly 1.415kg/m^3)[4], g is the gravitational acceleration (approx. 9.8m/s^2), α is the coefficient of thermal expansion (approx. 5.9 for clay brick and glass)[5], T is the temperature difference between the air and the brick (roughly 90 Kelvin for hot surface and 10 Kelvin for cold surface), L is the effective length of the surface (approx. 4.5" for hot surface and 3.5" for cold surface), k is the thermal diffusivity of the effective surface (approx. 1.4 W/mK for brick and 0.96 for glass)[7] and μ is the dynamic viscosity of the smoke (approx. 1.9E^-5 Ns/m^2)[6]. Knowing these values, the Rayleigh number for both the cold and hot surfaces can be determined. Those values are presented by Eqns. 4&5.

$$Ra_{cold} \approx 3.15 * 10^6 \tag{4}$$

$$Ra_{hot} \approx 4.1 * 10^6 \tag{5}$$

Eqns. 4&5 have values that are very similar in order of magnitude. This is a very important parameter to try and achieve for obtaining vortex formation at the center distance of the surfaces. It is proposed that the reason the vortex formed at the center distance is because the surfaces were producing similar Rayleigh numbers of natural convection. Looking to experimental data taken from natural convection experiments, the transitional Rayleigh number to turbulence is around 10^7.[8] This means that both the hot surface and cold surface are responsible for natural convection that is producing laminar flow. The laminar flow is in the upward direction for the hot surface and the downward direction for the cold surface. Fig. 3 gives a better representation of the driving forces behind the vortex formation.

Upon looking at Fig. 3, it can be seen that the vortex formed in the image is a product of the laminar natural convection boundary layers, caused by the hot and cold surfaces, forcing the air in the counter clock wise direction. More testing and analysis would be needed in order to determine what type of vortex formation this is. By observation, it is hypothesized that the vortex formed is partially due to both the rotational and irrotational vortex phenomena (possibly a Rankine vortex).

Image Processing

The shot taken after conducting this project was, personally speaking, in great focus. The shot directly focuses on the center of the vortex formation which is what was originally desired. The contrast was enhanced through photo editing in Adobe Photoshop CS4. The image was cropped down from its original size of 4272 x 2848 pixels so that the audience was drawn only to the vortex formation.

References

[1] Mills, Anthony F. Basic heat and mass transfer. 2nd ed. Upper Saddle River, NJ: Prentice Hall, 1999.

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[3] S.C. Saha1, C. Akhter1, M.A. Hossain2, Nonlinear Analysis: Modelling and Control, 2004, Vol. 9, No. 2, 151–170

[4] Calculator: Smoke Density." DieselNet: Diesel Emissions Online. 07 Feb. 2011 http://www.dieselnet.com/calculator/smoke1.html

[5] http://www.engineeringtoolbox.com/linear-expansion-coefficients-d_95.html

[6] Air Properties Definitions." NASA - Title... 07 Feb. 2011 http://www.grc.nasa.gov/WWW/K-12/airplane/airprop.html . [5] Engineering Toolbox

[7] http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

[8] M. Ciampi, S. Faggiani, W. Grassi and G. Tuoni, Mixed convection heat transfer in horizontal, concentric annuli for transitional flow conditions, 1987, Vol. 30, No.5, 833-841

Figures

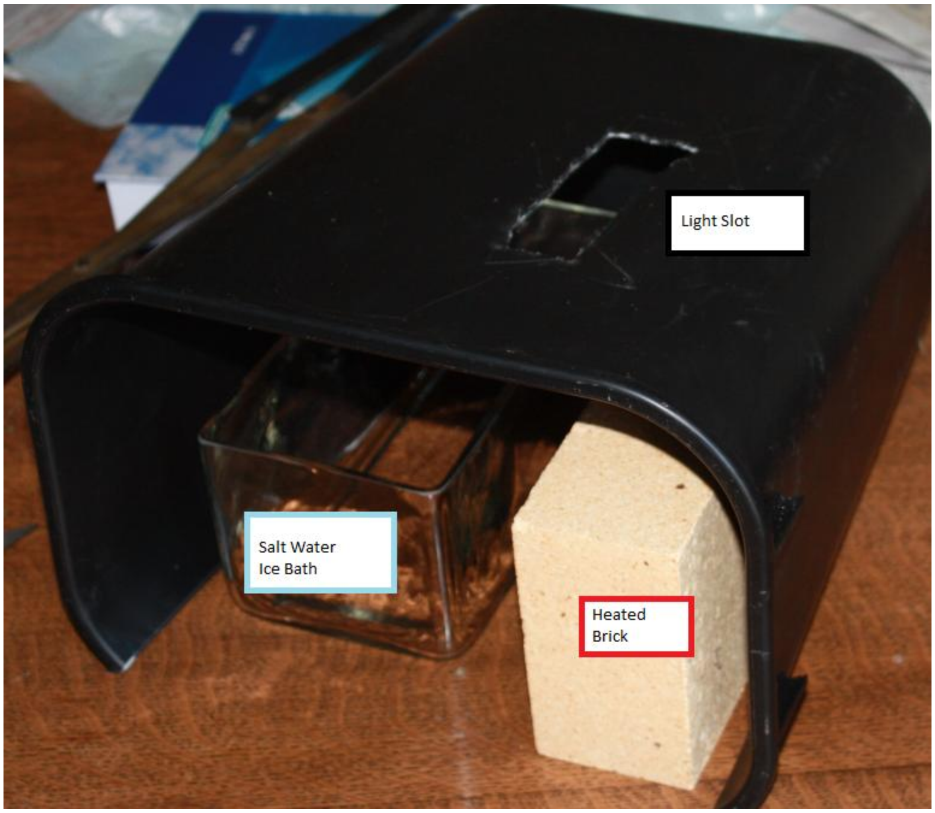

Figure 1: Experimental setup for natural convection vortices project. Figure only represents the main components of the project. It does not show where the project was conducted.

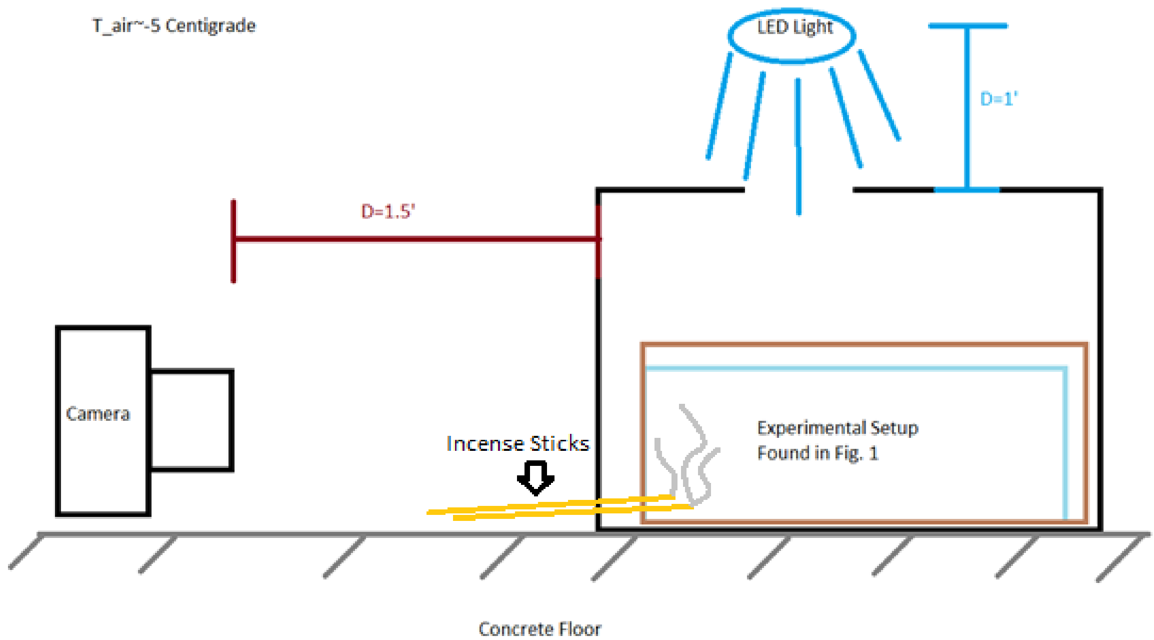

Figure 2: Dimensional representation of project set up including distance from camera and height of lighting.

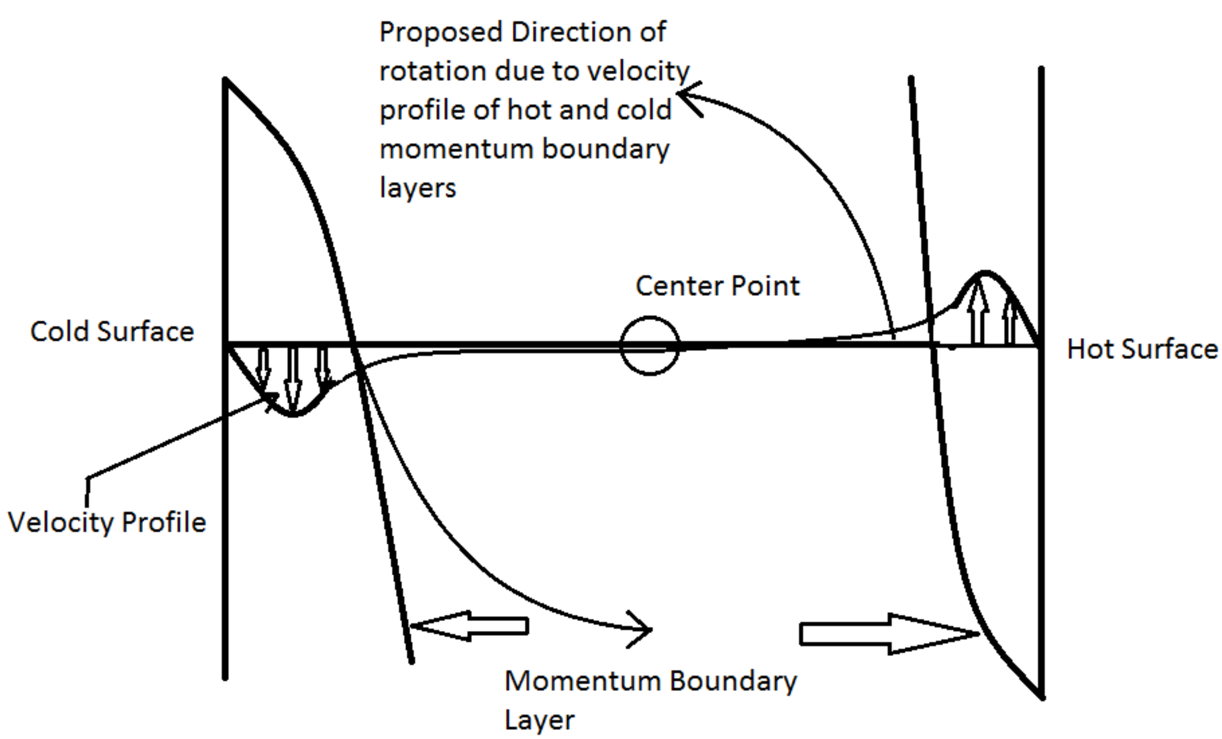

Figure 3: Proposed potential flow model of hot and cold surfaces affecting the ambient air and causing vortex formation.