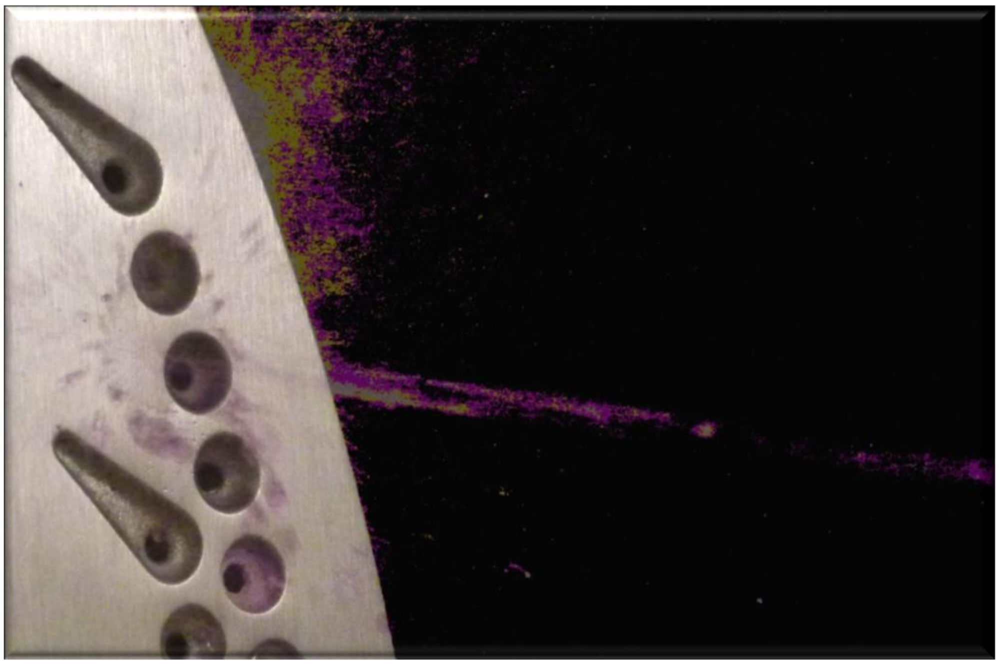
Second Team Project Report



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I. INTRODUCTION

This reports documents the visualization techniques and physics of an evaporating jet of water for the second of three team projects of the Flow Visualization course at the University of Colorado at Boulder. The goal of this document is to describe the image of dyed water impacting a hot clothes iron presented on the cover page (p. 1) and photographic techniques used to capture and process the image. The flow details of the jet of water as well as heat transfer involved in vaporization will be described in some detail.

II. EXPERIMENTAL PROCESS

The original goal for the second team project was to visualize fluctuating natural convection cells inside a glass container. An experiment was run in order to capture an image of buoyant air rising and falling due to a temperature difference between two parallel plates. The setup included a 13 in x 8 in x 3 in glass baking dish (in order to photograph the cells) placed between a baking stone heated from below with an oven range and a baking sheet taped to the dish that had been chilled. A stick of incense was placed inside the baking dish to create smoke to visualize any convecting cells of air. The figure below shows the experiment and a faint trace of smoke.

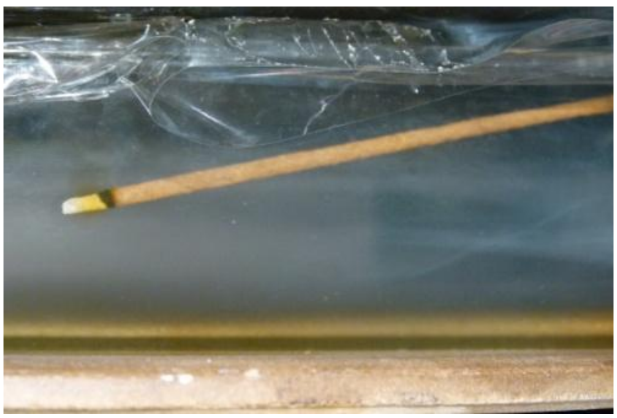

Figure 1. Experiment photo of incense smoke used to visualize convecting air cells between two parallel plates.

As the experiment was run the appearance of cells was present but the amount of smoke available did not result in good visualization. The original goal of natural convection visualization was abandoned in favor of the water jet/iron experiment described in the remainder of this report.

III. FLOW APPARATUS

Figure 2 depicts the experimental setup used to capture a water jet impacting a hot clothes iron. Setup begins by combining room temperature (around 20 °C) tap water with several drops food coloring for enhancing the liquid in the image; neon purple food coloring was used for this experiment. The water is then placed into a standard plastic spray bottle with adjustable nozzle. The spray bottle nozzle is then rotated to the jet stream setting and placed approximately two feet from the iron. The iron which is placed on top of an ironing board is adjusted to the highest (hottest) setting. A Black and Decker X322 Quick N Easy iron was used. It is recommended that towels be placed below the iron and ironing board especially if using dyed water. For lighting, four standard 60 W light bulbs that were present in the room were located four feet above and approximately four feet behind the iron. A fifth 60 W bulb was placed closer to the iron to brighten the subjects as described in Figure 2. A light blue blanket was used as the backdrop for the image. Once the lighting and camera were set, a team member shot a spray of water at the surface of the iron while another team member snapped photos. The jet from the spray bottle was aimed at the steam holes of the iron in order to generate steam directly from the jet; it is important to note that the steaming feature of the X322 iron was not used during the experiment. Images saved featured the jet, impact on the iron surface and the steam created.

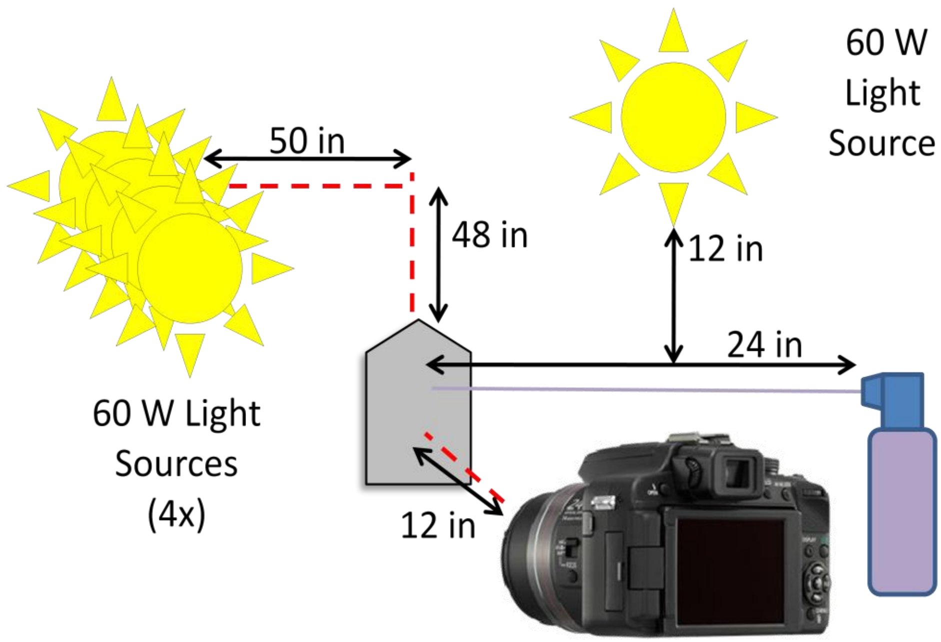

Figure 2. Flow apparatus including camera location, fluid container, subject (iron, jet and steam), light sources and length of fluid travel (FZ100 camera image courtesy of Panasonic[1]).

IV. DESCRIPTION OF FLOW

The flow depicted in the photo of concern occurs in three stages at steady state: 1) jet sprayed from a nozzle, 2) fluid impact on a surface with splattering and 3) evaporation into a vapor. Water evaporating on the surface of the iron depends highly on the temperature of the iron at the location of impact. In order to determine the heat transferred from the hot iron to the room temperature water and therefore the surface temperature of the iron the Reynolds number *Re* and heat transfer coefficient h_c are calculated. The properties of water at 20 °C (density ρ of 998.2 kg/m³, thermal conductivity *k* of 0.597 W/m-°C, viscosity μ of 993 x 10^{-6} N-s/m² and Prandtl number *Pr* of 7 {ratio of fluid momentum dissipation to thermal dissipation}) and correlations for Reynolds number and heat transfer coefficient are taken from Kreith and Bohn [2]. The addition of food coloring into the water is assumed to not alter the properties of water. The Reynolds number for jet flow through a round nozzle can be defined as

$$\boldsymbol{Re} = \frac{4\dot{m}}{\pi d \mu} \qquad \textbf{(1)}$$

where *mdot* is the mass flow rate of the fluid in kg/s and *d* is the diameter of the jet in m. The diameter of the spray bottle nozzle was measured to be 1 mm or 0.001 m (radius of 0.0005 m). The mass flow rate can be calculated dependant on the velocity *V* of the jet as well as the water density and jet cross-sectional area. The velocity (distance/time) of a jet sprayed from 24 in from the iron and impacting in one second (measured) can be calculated to be 0.6 m/s using dimensional analysis. Therefore, the mass flow rate and Reynolds number can be computed as follows:

$$\dot{m} = \rho V A_j = \left(998.2\ \frac{kg}{m^3}\right)\left(0.6\ \frac{m}{s}\right)(3.14 * \{0.0005\ m\}^2) = 4.8\ x\ 10^{-4}\ \frac{kg}{s} \quad (2)$$

$$Re = \frac{4\left(4.8\ x\ 10^{-4}\ \frac{kg}{s}\right)}{(3.14)\ (0.001\ m)(993\ x\ 10^{-6} Ns/n^2)} = 615 \quad (3)$$

Since the Reynolds number is less than 4000 the flow in the jet phase (stage 1) is considered laminar, meaning less heat will be transferred from the iron to the water than if the jet were turbulent. The convective heat transfer coefficient can be determined using the dimensionless Nusselt number *Nu* which is derived from the following correlation for a free surface jet impacting a surface for Prandtl numbers greater than 3:

$$Nu = 0.797 Re^{1/2} Pr^{1/3} = (0.797)\left(\sqrt[2]{615}\right)\left(\sqrt[3]{7}\right) = 38 \quad (4)$$

In addition to the Nusselt number, the heat transfer coefficient is dependent on the thermal conductivity of the water and the jet diameter

$$h_c = \frac{Nuk}{d} = \frac{(38)\left(0.597 \frac{W}{m°C}\right)}{0.001\ m} = 22,686\ \frac{W}{m^2 °C} \quad (5)$$

Finally, the surface temperature of the iron T_s can be calculated using the following equation for convective heat transfer:

$$T_s = \frac{q}{h_c A} + T_j \quad (6)$$

where q is the heat or power of the iron in W, A is the area of impact of the jet on the iron surface and T_j is the temperature of the water jet. Based on the subject photo the diameter of the impacting water jet (stage 2) was 2 cm which results in a radius of 0.01 m and an impact area of 3.14 x 10^{-4} m². The specifications for voltage and current of the Black and Decker X322 iron are 120 V and 10 A respectively for a power of 1200 W since power equals voltage multiplied by current. Using these values, the temperature of the iron at the location of impact is

$$T_s = \frac{1200\ W}{\left(22{,}686 \frac{W}{m^2 °C}\right)(3.14\ x\ 10^{-4}\ m^2)} + 20\ °C = 188\ °C = 370\ °F \quad (7)$$

Since the temperature of the iron is significantly higher than the boiling temperature of water (100 °C) the impacting jet vaporizes into steam immediately upon impact (stage 3).

V. VISUALIZATION TECHNIQUES

The materials and apparatus described in Section III were used to visualize the three stages of water from the spray nozzle to the impact on the iron to the steam forming. The choice of using purple food coloring mixed in with the water was to contrast the metallic color of the iron as well as the light blue background chosen. The fluid is created using tap water and materials readily available at any supermarket. The iron and spray bottle used are low cost items available at department stores. As will be noted in Section VI, posterization was used to visualize two of the three stages of water in the image. Posterization can be described as altering the pixels in an image in order to highlight changes in color tones by reducing the colors into fewer blended tones [3]. Posterization was chosen for visualization of this image for a number of reasons. As seen in the original image in Figure 3, the jet of water and especially the steam were not easily seen against the somewhat grainy background of the blanket backdrop. Posterization helped alleviate this problem by creating a solid black background while revealing the presence of the steam (at the cost of a somewhat grainy appearance). Using posterization also created an infrared-like feel to the image though the postulated colors appearing in the post-processed image don't necessarily represent temperature gradients as in an actual infrared image.

VI. PHOTOGRAPHIC TECHNIQUES

a). Camera Settings

A 14.1 megapixel Panasonic Lumix DMC-FZ100 digital camera was used for the image. The photograph of the fluid flow was taken with the camera lens 12 inches from the front of the iron as depicted in Figure 2. A focal length *f* of 24 mm was used in order to zoom in on the steam holes of the iron as well as keeping the water jet and steam formed within frame. The field of view was approximately 12 inches. For the exposure, a shutter speed of 1/250 s and an f-stop (relating to aperture size) of *f*/3.6 was used. The shutter speed and aperture diameters were required in order to balance the incoming light into the camera lens with a relatively quick exposure time in order to capture the instantaneous formation of the steam and impact. The ISO was set to 800 in order to bring detail to the jet and impact at this exposure speed. The 11 frames per second burst shooting feature of the camera was used to snap several images of the flow quickly.

b). Image Post Processing

Adobe Photoshop CS5 was used for post processing of the image. The original 4320 x 2432 pixel JPEG image was imported into Photoshop to begin post processing. The image was then cropped to 2952 x 1940 pixels in order to remove unnecessary details of the iron. The posterization feature was used to highlight and reduce the tones of the water and backdrop. The area to the right of the iron boundary was selected using the magic wand tool while all details of the iron and the splattering water were left unchanged. Finally, the yellow color contrast was reduced to the minimum value in order to match the purple hue of the water on the iron with the posterized section of the image. The original image and post processed image are shown side-by-side in the figure below.

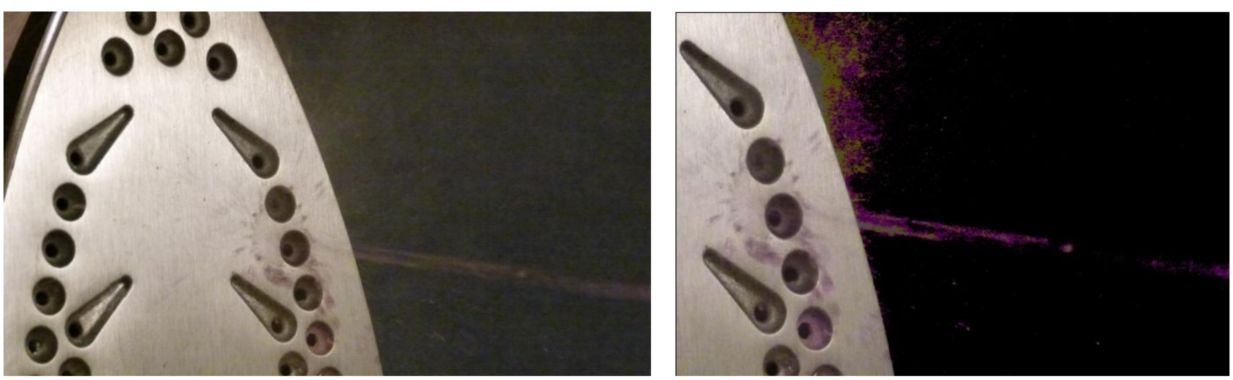

Figure 3. Original image (left) and image following post processing (right).

VII. IMAGE ANALYSIS AND CONCLUSIONS

The image captures the steady state process of fluid in the form of a jet, impact on a hot surface and phase change into a gas. Overall, the goals of describing the physics of a fluid jet were realized, although much more detail can be investigated on the subjects of fluid impact flows and flow during phase change. The visualization of this process can be improved in a number of ways. A better backdrop is required to create a clean image where all three phases of flow are visible simultaneously, especially the steam. More powerful lighting would be required to better highlight the clear fluid at a high shutter speed while keeping the ISO setting low and reduction of detail minimal. The process of simultaneously capturing the jet, impact and steam is challenging but the goals were met.

VIII. REFERENCES

[1]Panasonic. "DMC-FZ100K - Lumix Digital Cameras." Panasonic Digital Cameras. 2009. Accessed 9 February, 2011. <http://www2.panasonic.com/consumer-electronics/shop/Cameras-Camcorders/Digital-Cameras/Lumix- Digital-Cameras/model.DMC-FZ100K.S_11002_7000000000000005702#tabsection>.

[2]Kreith, Frank and Bohn, Mark S. Principles of Heat Transfer (Sixth Edition). Pacific Grove: Brooks/Cole, 2001.

[3]Wikipedia Article on Posterization. 8 February 2011. Accessed 8 April, 2011.

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