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Flow and Visualization

Report 1

The image that I have taken for the first assignment is of a buoyant plume of smoke. After nearly a hundred photographs taken under various lighting conditions, angles, backdrops, and setups, I chose this photograph for its simple elegance. I felt that esthetically it was my strongest photograph and it illustrates some interesting dynamics. The flow depicted is the motion of a buoyant plume as it impinges upon an angled surface. It is important to note that the photograph has been flipped 180 degrees and will be discussed throughout the paper as it actually took place.

To take this photo I used household objects that most anyone can get access to. To begin with, the photograph takes place inside of a black fabric overcoat; this is the texture seen in the background. Using tape I attached a thin cutting board to the outside of the jacket in order to provide a relatively flat surface. The cutting board was then used as the point of connection to suspend the whole setup from the ceiling, using coat hangers. The point of the jacket is that it created an enclosed volume, blocking airflow and light from five out of six sides. This allows the smoke to move under its own influence. The setup was also somewhat adjustable for the angle of the surface, for this photo the angle α is approximately 30 degrees. Figure 1 below shows the setup in further detail.

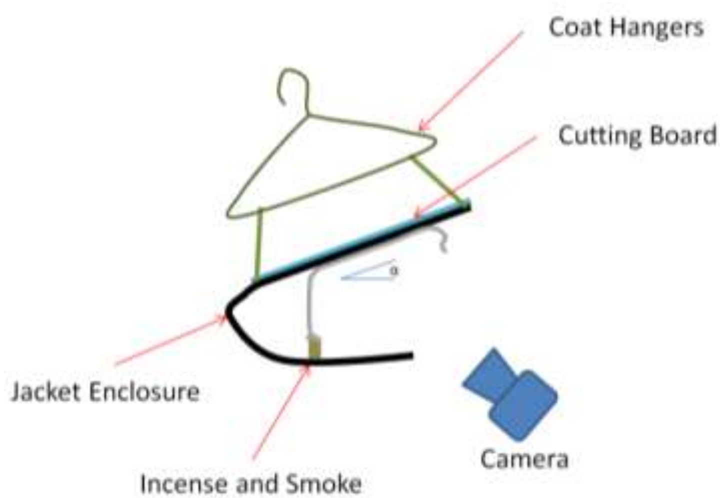


Figure 1: Basic setup sectional view.

The plume in the photo is a thick stream with a slight *C shape* (with the top and bottom of the C pointed away from the viewer). The lighter regions on the sides of the buoyant plume (Region 1) indicate that these are thicker sections of smoke. Rising off the burning piece of incense, the smoke has a higher temperature than the ambient air which surrounds it. At this point the hot smoke is less dense than the cooler air and so it feels a buoyant force up. When a plume like this flows through a static fluid atmosphere it tends to expand linearly (Turner 1969). As the smoke plume moves it entrains air to move along with it and as the two gases diffuse into each other we see the linear expansion of the smoke plume. In Figure 2 I have cropped the image to only include the section from the center of the flow rightward and edited the image so that the expansion of the fluid can be more carefully observed. It is clear that there is a slight linear growth to the radius of the plume (Region 1). Between Region 1 and 2 the smoke impinges upon the surface and a change in the dynamics begins. To explain this I will start with a simpler example. In the case of an interaction with a horizontal surface such as a ceiling, one would expect all the upward momentum to be lost. However the smoke does not stop moving. It still carries thermal energy and the kinetic energy associated with the bulk flow. Though much of the energy is dissipated during this interaction, some is kept and is translated to new bulk flow motions. This is what causes the *spreading* which occurs at the point of impingement. In the case of an interaction with a horizontal surface, the motion of the smoke particles will be radially symmetric and will form (give or take) a circle flowing out from the center of the plume. This symmetry can again be understood from the conservation of momentum. Initially the cylinder of smoke has only an upward (+z) momentum and zero horizontal (x and y) momentum. After the collision the smoke should still have a total horizontal momentum of zero as it flows in all horizontal directions. This is why you can see the symmetric spreading in the photo, there is approximately the same amount of smoke going in one horizontal direction as in the other, for a total of zero new horizontal momentum. The force that the surface provides against the smoke can be derived from the conservation of momentum, where you get equation 1 below. With a good measurement of the smokes density this reactive force could be found. However this would be assuming an incompressible fluid, which in the case of smoke is not a great assumption. I like to think of this spreading in the context of the change in spatial dimensions. There is a 3D volume which is changing to a (roughly) 2D surface and it is doing this through a spot the size of the cross sectional area of that volume. In order to avoid spreading the smoke would have to rapidly move away from the area. However we know that some energy is lost in the interaction and as drag forces become more significant, the smoke slows down and piles up and is pushed out horizontally by the continuous flow of incoming smoke. This is what accounts for the non-linear spreading which happens just before and just after the point of impact. The smoke is still hot so it still feels a buoyant force up the slope. Just as with 3D plumes, 2D plumes tend to take in air molecules and expand linearly once they have moved far enough from their source (Turner 1969). In figure 2 the non-linear behavior close to the source is clearly displayed. As the smoke moves further along the spreading becomes more and more linear as is expected.

$$Equation\ 1: \qquad F = \rho A \boldsymbol{v}^2 \mathrm{Cos}(\alpha)$$

Where ρ is the density, A is the cross sectional area, v is the velocity and α is the angle.

I have roughly measured the velocities of the smoke in the three regions of the photo. These help to give a better idea of the overall motion. The trend is exactly what one would expect. The buoyant plume was moving the fastest in the beginning where it is hottest and is experiencing the least drag. After impinging, a large portion of the velocity is lost. As the smoke continues spread it loses more velocity to drag and feels a loss of buoyancy as it cools. Assuming a dynamic viscosity and density close to that of air, $1.983\times10^{-5}$ (kg/(m*s)) and 1.1839 (kg/m^3) respectively, I have estimated the Reynolds number in the first two regions of the flow. With a characteristic length of 2 cm and velocity of 50cm/s, in region 1 Re = 596 and with a length of 10 cm and a velocity of 25 cm/s, in region 2 Re = 1492. With Reynolds numbers this low we expect, and find, strictly laminar flow.

$$Reynolds\ Number\colon\ Re = \frac{\rho v L}{\mu} \quad where\ \rho\ is\ the\ density, \mu\ is\ the\ dynamic\ viscosity,$$
$$v\ is\ the\ velocity\ and\ L\ is\ the\ characteristic\ length$$

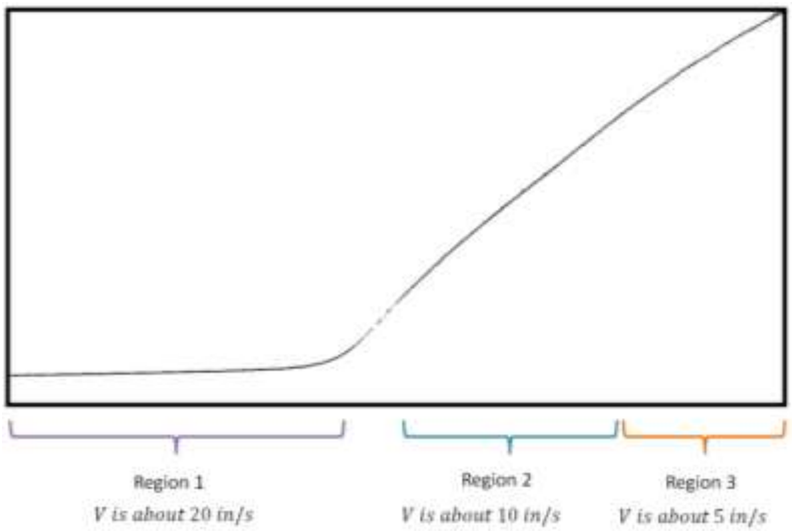


Figure 2: Velocity changes.

The smoke provided both the motion of the fluid and the means to visualize it. The type of incense used was called Laxmi Dhoop. It is an Indian incense that comes in the form a dense putty. This is a great medium to form plumes of various cross sectional shapes because it can be worked into whatever form is needed. The setup seen in Figure 1 was placed inside a small bathroom with white walls and plenty of diffuse sunlight. The shot was taken in the late morning when the room tends to be well lit.

The field of view in the photo is approximately 7 inches across (in the foreground) and about 10 inches high (in the plane of the flow in Region 1). The camera used was a Canon EOS Rebel T2i with a Canon EF Macro 100mm f/2.8 Lens. This lens has a 67mm focal length. In order to keep a large amount of the planar flow in focus I used an ISO of 6400 so that I could use a smaller aperture, f/11, and not need to take a long exposure. The shutter speed was still slower than I wanted, at 1/6.2s. The only downside to the camera settings was that the photo became grainier with the high ISO. With better lighting this could certainly be improved upon. The original photo is 3456 x 5184 pixels. I used the programs Gimp and UFRaw to edit the photo. I started by rotating it 180 degrees because I liked the shape of the flow better in this orientation. Then by adjusting the curves and the contrast/brightness I was able to darken the back drop while keeping a clear image of the lighter smoke. I also adjusted the saturation levels (mostly in the reds) to help bring out the slight diffraction taking place at left edge (in the edited photo) of the expanding plume.

I am pleased with the way my image came out. As I mentioned earlier it is grainier than I would have hoped but for viewing small image sizes it is not a problem. The flow in the photo is not the typical way one usually sees smoke move. The perfectly smooth laminar flow combined with the spreading which occurs almost hides the fact that it is smoke. My reasoning for picking this photo because it was something I had not really seen and I thought it would be interesting to analyze. As an expansion to this in the future it might be possible to analyze the relative densities optically if one also has the various thicknesses in the flow. Should I do something similar to this in the future there are some things I would change. I would build a better set up, probably out of a box and some spray painted sheet metal. I would also experiment more with the thermodynamics in the system. For instance by cooling the surface which it hits, the smoke would cool quickly and begin to fall from the surface more rapidly. This would give another layer of control and new understanding could be obtained. I think, too, that a lot of the interesting dynamics that take place at the point of smoke impingement would be better visualized using video.

Sources:

Turner, J. S. “Buoyant Plumes and Thermals,” Annual Review of Fluid Mechanics, Vol. 1 (1969): 29-44.