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Get Wet Assignment
MCEN 5151-001

This video was a result of our first individual class assignment, "Get Wet". The goal of this assignment was to find or create any interesting fluid flow phenomena and attempt to capture it in a still image or video clip. I work at an aerospace start-up where we regularly use liquid nitrogen (LN2) to test components at cryogenic temperatures. In order to accomplish this, a nitrogen Dewar must be used and in the process the outlet hose gets very cold, causing tendrils of water vapor to fall from it. I have always been fascinated with this phenomena and so decided to capture it for this project. I initially took a series of stills, which were slightly more elegant than the video, but I felt a video clip captured the actual phenomena much better and so decided to stick with that.

Because the phenomena captured in this video was naturally occurring, no experimental set-up was needed, beyond draping the hose in such a way that the condensate would collect and fall off in a smooth and observable fashion. The effect being observed here is referred to as a negatively buoyant plume and is discussed in a number of scholarly articles, including Trevor McDougall's "Negatively Buoyant Vertical Jets" published in Tellus(1981). In this article, the effect studied is "When a continuous jet of dense fluid is ejected vertically upwards into less dense surroundings it proceeds initially upwards, increasing in size and slowing down. The buoyancy force then becomes important, causing the plume to slow down even more and then, after reaching its maximum height, it falls down as an annular plume around the inner rising jet." (McDougall, 1980). In the case captured here, there is no initial upwards velocity and so we will only consider the second half of the effect, where the dense plume begins to fall from a zero velocity position. The model developed in this paper gives a set of equations, which we will explore below.

The conservation of mass and buoyancy gives:

$$\frac{d([r_2^2 - r_1^2]v^2)}{dz} = -2\alpha_\beta r_1(v_1 - v_2) + 2\alpha_v r_1 v_2 + 2\alpha r_2 v_2$$

Evaluation of the buoyancy effects:

$$\frac{d([r_2^2 - r_1^2]v^2)}{dz} = [r_2^2 - r_1^2]g_2' + r_1^2(g_2' - v_2\frac{dv_2}{dz}) - 2\alpha_\beta r_1 v_2(v_1 + v_2) - 2\alpha_v r_1 v_1 v_2$$

Because there is no initial upwards velocity in my case we can assume v1 = 0 and r1 = 1 in the above cases. The constant α_v refers to the transfer of velocity between the "inner" and "outer" plumes, so we can assume this to be 0 as well. The last constant needed to solve for velocity is α_β, which can be assumed to be equal to 0.85 as the plume is driven by buoyancy (McDougall, 1980).

You may also notice from the video that the outer edges of the plume begin to curl up as plume falls lower, before dissipating into a vapor cloud, allowing us to see laminar, transition, and turbulent flow all at once (wide range of Re numbers). I believe this to be a result of the Kelvin–Helmholtz Instability which is an instability in the shear layer of a fluid caused by two fluids of different densities moving against each other at different velocities (Drazin, 2015). In my case we have the dense vapor plumes moving buoyantly downwards against the otherwise still atmosphere of a lesser density. This action causes a shear force to be exerted on both fluids, but most importantly, on the denser slow moving fluid. This in turn causes sinusoidal waves of linear instability to form and grow ultimately resulting in the shear layer curling and forming the visible "waves" around the edges (Drazin, 2015). Now in order for this instability to occur, the dimensionless Richardson number must be less than or equal to ¼. Assuming that the effect is in fact occurring, we can then assume $Ri(z) = -\frac{g\frac{d\rho}{dz}}{\rho\left(\frac{dU}{dz}\right)^2} \leq \frac{1}{4}$, giving us further information about the flow at the point where the effect is visible.

No advanced visualization techniques were used to capture this image as the bright white plumes offered enough contrast against the background to eliminate the need for any additional effects. These plumes were generated by running the pressure building circuit on the LN2 Dewar until the internal pressure reached 600 psi. The outlet valve was then cracked about $1/8^{th}$ of a turn and a mixture of liquid and vapor nitrogen was allowed to flow through the hose and into the atmosphere. This flow of sub-cooled nitrogen chilled the outlet hose causing water vapor from the air to condense and freeze on the hose. As more and more layers of water vapor started to build up the outer layers began to warm up and vaporize causing plumes of dense water vapor to fall from the hose in the fashion described in the previous paragraph. Once the phenomena began to occur, I opened the garage door next to the Dewar, allowing natural sunlight to shine in, perpendicular to the direction I was shooting the video. This illuminated the plumes as they fell, allowing me to capture the phenomena in great detail, without oversaturating the shot with light.

As I mentioned previously, I decided to record this phenomena as opposed to photographing it because I felt it captured the flow much better. The interesting part of the flow is not so much the shape or appearance, but rather the smooth motion of it as it falls from the hose before breaking up into turbulent flow. I wanted to get as close to the flow as possible while still capturing the full extent what was going on and so ended up about a foot away from the flow. I captured the video using my Moto Z2 Force smart phone with a double 2.1 MP camera as it captures much better video than my camera. The video was recorded at 1080p and 30 fps with a F# of 2.0. No zoom was used as the phone does not support mechanical zoom. The camera itself has a sensor size of 1/2.9 in. and a pixel size of 1.25 uM. In order to better visualize the flow after capturing the video, I used iMovie to slow the recording down 8x and added a slight amber filter to reduce the glare off the LN2 Dewar, no other effects were added in post-processing though.

I believe that through this video I was able to capture a wonderful example of one of the many inconsistencies in fluid dynamics, occurring naturally, outside of a lab environment. Fluids have proven to be one of the least predictable things in nature with so many unique phenomena and instabilities, often occurring out of sight. I set out to capture one of these phenomena occurring in the real world and I believe I achieved just that. I would however, love to recreate this exact effect in a more controlled environment. With good lighting in both cross directions, a solid background, and the lack of a cross breeze, I believe the physics occurring here could be far more vivid and even more fun to observe.

References

Drazin, P.G. “DYNAMICAL METEOROLOGY | Kelvin–Helmholtz Instability.” *Encyclopedia of Atmospheric Sciences*, Edited by Gerald R. North et al., 2nd ed., Elsevier/Academic Press, 2015, pp. 343–346.

McDOUGALL, TREVOR J. "Negatively buoyant vertical jets." *Tellus* 33.3 (1981): 313-320.