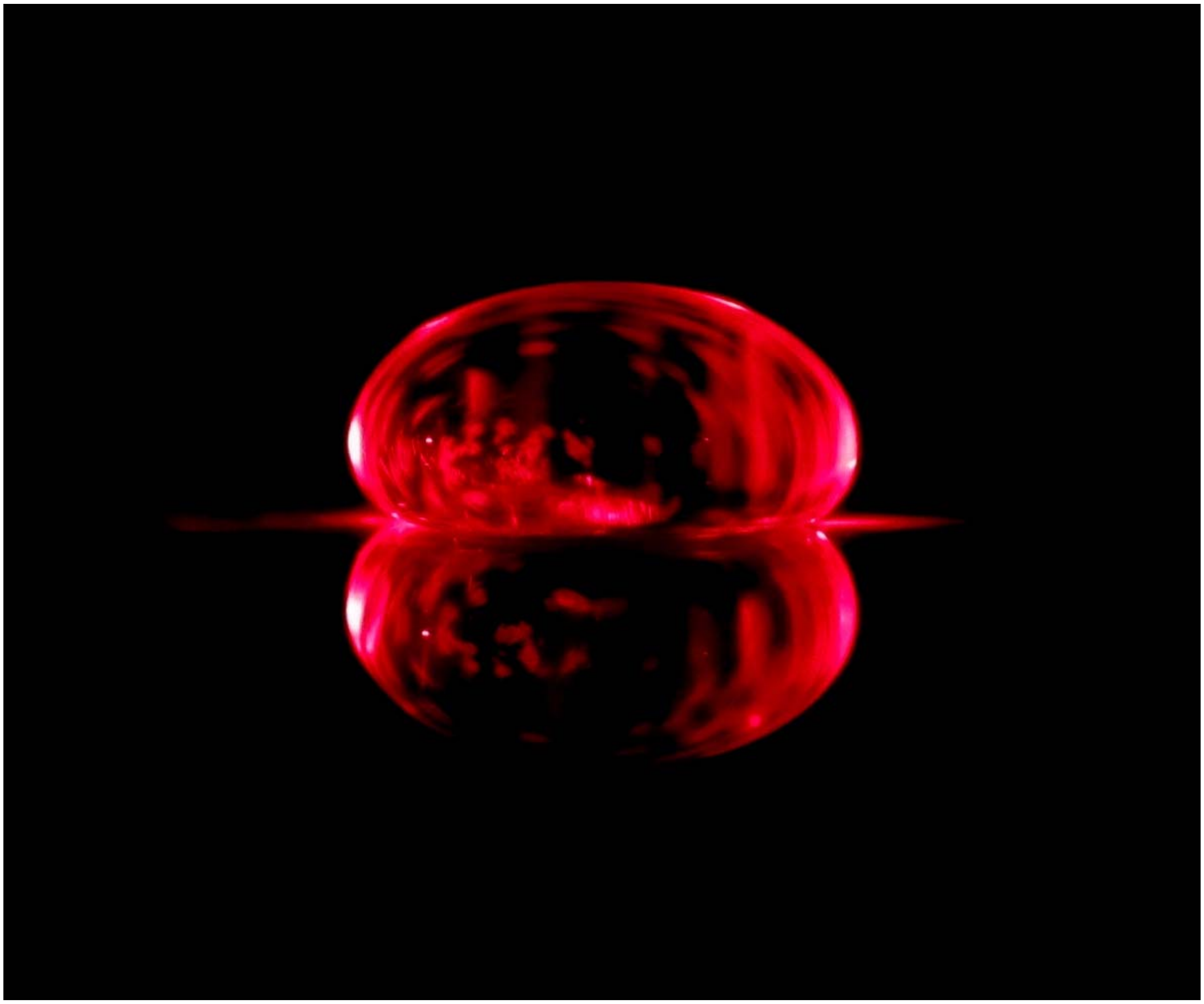
Circulation Pattern within a Drop Experiencing Leidenfrost Effect

Ilya Lisenker

MCEN 5228: Flow Visualization

2/8/2010



Introduction

Many cooks who have learned the skill from their elders are familiar with Leidenfrost effect. It is the measure that many grandmothers use to determine whether the pan temperature is suitable for frying. A droplet of water deposited onto a sufficiently hot surface will not sizzle but will instead form a near perfect ball that will persist for an inordinate period of time – much longer than if the pan was cooler. As such, the effect must have been known for ages; however it was not until the 18^{th} century that it was described in any sort of a scientific manner by J.G. Leidenfrost. The effect is of great significance in heat exchange, combustion and heat treatment processes as it can greatly reduce heat exchange rates.

Physics Background

Basic physics of Leidenfrost effect is fairly well understood. A droplet of liquid is deposited onto a surface that is maintained at a temperature significantly above its boiling point. The specific temperature threshold depends on the properties of the liquid such as boiling point, viscosity as well as ambient pressure, nature of the heated surface etc. If the temperature is sufficiently high, the surface of the liquid coming in contact with the hot surface experiences instantaneous nucleate boiling but the bubbles coalesce prior to reaching departure diameter forming a vapor film [2], . If the pressure required to escape from under the droplet is great enough to exceed the hydrostatic pressure of the liquid, the droplet is suspended over the surface like a hovercraft. Surface tension attempts to maintain a spherical shape but this is effective only for particularly small droplets. Larger droplets form a progressively flatter shape as Bond number increases until the surface tension is no longer sufficient to maintain integrity and vapor film bubbles through the droplet.

Procedure

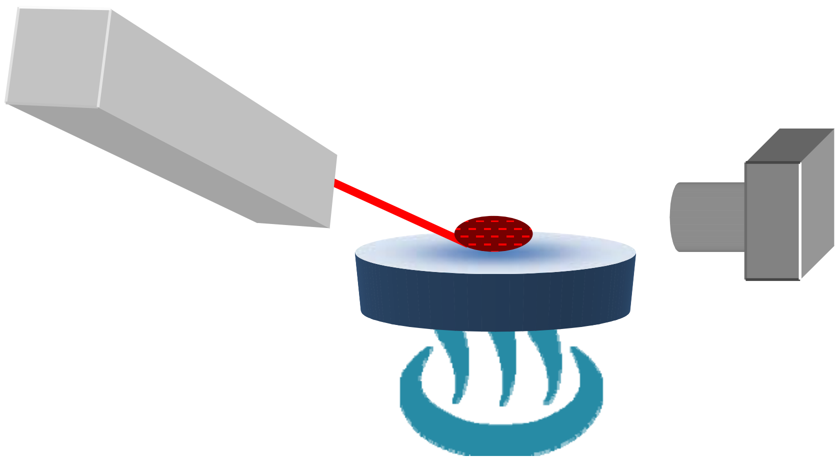
A thick aluminum plate was chosen as a hot surface due to its superior heat conductivity and machinability. A well known property of droplets experiencing Leidenfrost effect is their propensity to "scoot" around due to the exceedingly low friction of the vapor layer. To counteract this tendency, the upper surface the plate was machined in a shape of an approximately 1 deg. concave cone. The surface was polished to attain a near mirror finish. This lowers the Leidenfrost point [1] as well as creates a dramatic reflection in the image.

A gas stove burner was used as a heat source and was turned off once the plate reached appropriate temperature to eliminate it as a source of light.

Water was chosen as the fluid because it is most environmentally benign. It was deposited onto the plate approximately 0.5 ml at a time using a plastic straw as a pipette. Flow was seeded with aluminum powder generated by polishing the plate. Powder size is estimated at 3 micron.

A 1mW He-Ne laser was chosen as a light source. The well collimated beam reduces stray lighting and eliminates any need for background preparation. Laser aim is critical within approximately 1mm to eliminate stray reflections. Anyone attempting to replicate the experiment may benefit from a solid state laser as some of the pump source emission also exits from the aperture of this gas laser.

The circulation starts spontaneously once the droplet evaporates down to approximately 15mm diameter and seizes once it diminishes to approximately 8mm diameter. The circulation is generally two dimensional with the plane of the circulation slowly rotating around the z-axis. The photos were taken when the plane of the circulation aligned with the laser beam. The best view of the circulation is with the lens axis almost horizontal but some downward tilt was present for the best photographs because this vantage provided the most dramatic reflection from the plate. Relatively long exposure time was chosen to showcase the circulation pattern. Additionally, maximum aperture available for the level of zoom was selected to allow the camera to gather enough light. Unfortunately, these parameters combined with natural droplet instability result in an image that is not in perfect focus. Higher sensitivity can mitigate this effect somewhat at the expense of sensor noise in the image.



Camera Set up

Camera – Canon PowerShot SX-120IS digital
Distance from object to lens – approximately 5cm, handheld
Focal length – 12mm (72mm in 35mm equivalent)
Exposure time – 1/50 sec.
Aperture – f/3.5
Sensitivity – ISO 400
Cropped image dimension – 1158 x 906 pixels
Field of view – 2.5cm approx.

Discussion

As mentioned previously, relatively long exposure time was chosen to allow for motion blur of the seeded flow. The longest streaks that are easily distinguished in the image are approximately 1/10th the diameter of the droplet and thus measure 1.0mm in length. At 1/50th of a second exposure time, circulation velocity is D/t = 50mm/sec. This corresponds to

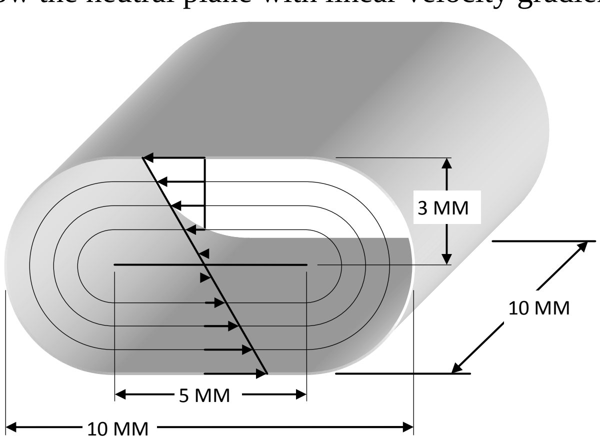
$$Re = \frac{\left(0.050\,{}^{m}/_{sec} * 968\,{}^{kg}/_{m^3} * 0.008m\right)}{0.3mPa * sec} = 0.5$$

Note: density and viscosity are for water at boiling point for 5500 ft. elevation.[2], [3],[4]

The actual velocity is likely somewhat greater since the streaks observed are likely not the longest and velocity estimated by naked eye is up to twice as high. Nonetheless, the Reynolds number is clearly in the laminar range and no turbulence was visually observed at any point.

More than one driver for the origin of the circulation has been proposed with no apparent consensus. Much of the literature treats the droplets as having uniform temperature, perhaps because most droplets of interest are much smaller in size. The three mechanisms that are featured in literature are surface tension differences, convective flows and shear drag generated by the escaping water vapor.

Surface tension of water near its boiling point has a temperature dependent slope of approximately $2x10^{-3}$N/m-K [5]. No mention of temperature gradient inside a droplet has been found in the literature though absolute temperatures are reported to be at or near the boiling point. If the extremes are representative of the gradient (ignoring all error) the gradients are on the order of 10K generating a total maximum force for a 10mm wide droplet of $2x10^{-5}$N. Actual gradients likely depend on ambient currents and other variables. If the droplet is modeled as an infinite "cylinder" whose cross section is visualized in the image, the following list of assumptions may lead to an estimate of circulation velocity: neutral plane approximately 3mm below the top (2mm above the bottom) of the droplet, 5mm width of neutral plane based on the image, no shear either left or right of the neutral plane, fully developed laminar flow above and below the neutral plane with linear velocity gradient and maximum velocity at the surface.



$$F(T) = \Delta\gamma * l = 2x10^{-3}\ N/(m * K) * 0.010m = 2x10^{-5}\ N/K$$

$$\tau(T) = \frac{F(T)}{A} = \frac{2 * 10^{-5}\ N/m}{5 * 10^{-3} m} = 4 * 10^{-3}\ N/([m]^2 * K)$$

$$\frac{du}{dy}(ave) = \frac{\tau}{\mu} = \frac{4 * 10^{-3}\ N/m^2}{3 * 10^{-4} Pa * sec} = 13\ (sec * K)^{-1}$$

$u = 3 * 10^{-6} m * 13\ sec^{-1} = 40^{\mu m}/(sec * K)$ for the upper surface

If this mechanism is in fact driving the circulation, it provides a rough estimate of the temperature gradient across the droplet on the order of 1K.

Vapor shear drag is impossible to calculate from the present set up. Evaporation rates can be estimated from droplet lifetimes and film thickness can be calculated using the methods proposed by Gottfried et al. [8] thus vapor velocity can be estimated as well. However, any imbalance that would lead to a circulation depends strictly on the imperfections in the geometry of the set up.

Finally, convective flows have been noted by Snezhko et al. [9]. However, the same limitation exists since the theoretical convection flow is axisymmetric.

Image processing

Due to inherent droplet instability and issues noted above, the image was not in perfect focus and there was some motion blur of the boundary. To mitigate this effect somewhat, the image was sharpened in Adobe Photoshop. Contrast and brightness were also adjusted. No other modifications were made.

References

[1] John D. Bernardin, Clinton J. Stebbins, Issam Mudawar, Effects of Surface Roughness on Water Droplet Impact History and Heat Transfer Regimes, *Int. J. Heat Mass Transfer.* Vol. 40, No. 1, p.73-88, 1997

[2] Niroh Nagai, Shegefumi Nishio, Leidenfrost Temperature on an Extremely Smooth Surface, *Experimental Thermal and Fluid Science* 1996; 12:373-379

[3] http://users.ameritech.net/knives/grits.htm

[4] http://www.engineeringtoolbox.com/water-dynamic-kinematic-viscosity-d_596.html

[5] http://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html

[6] http://www.csgnetwork.com/h2oboilcalc.html

[7] http://www.engineeringtoolbox.com/water-surface-tension-d_597.html

[8] B. S. Gottfried, C. J. Lee and K. J. Bell, The Leidenfrost Phenomenon: Film Boiling Of Liquid Droplets On A Flat Plate *Int. J. Heat Mass Transfer. Vol. 9, pp. 1167-I 187, 1966*

[9] Alexey Snezhko, Eshel Ben Jacob and Igor S. Aranson, *New Journal of Physics* **10** (2008) 043034 (12pp)