The Leidenfrost Phenomenon

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Ref. PE/6274/S

August 22, 2011

Abstract

The Leidenfrost Phenomena arises when a heated object becomes insulated by a vapour layer. Vapour generation may also sustain oscillation. The Leidenfrost Phenomenon is easily studied using simple apparatus and water, and beautiful oscillations may be observed.

Cite as:
H. Thimbleby, "The Leidenfrost Phenomenon," *Physics Education*, **24**(5):300–303, 1989.

A GROUP of people run around and get themselves excited and prepared for their ordeal—walking on fire. How do they manage to walk across the hot, glowing embers of the fire in bare feet without being seriously injured?

A Dutch scientist Boerhaave described the basic phenomenon in 1732. He gave a beautiful description of a drop of alcohol floating on a hot iron plate without catching fire. But it was Johann Gottlob Leidenfrost who first made an extensive study of the subject twenty four years later. His name has since been associated with the phenomenon: the behaviour of liquids insulated by vapour layer.

Coming more up-to-date, Faraday managed to freeze mercury inside a red-hot crucible by using the same effect. Nowadays, the Leidenfrost Phenomenon is of interest in such applications as internal combustion engines and nuclear reactors. There is an everyday application of the Leidenfrost Phenomenon: you wet your fingers before snuffing a candle flame.

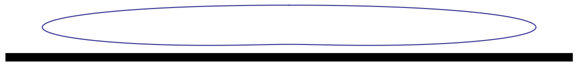

Figure 1: *Large water drop above hot plate, vertical cross-section*

Experimenting in the kitchen

The Leidenfrost Phenomenon is great fun in the kitchen, if you can get hold of a frying pan and a few drops of water! Check that your pan does not have a handle that will be damaged by heat, then clean and polish its cooking surface thoroughly. It will also be convenient if the pan has a flat, plane base, without any evident buckling. Place the empty frying pan on a ring and heat it; the ring will initially need to be set high. To check that you get the pan to about the right temperature without overheating it and perhaps causing damage, it may be advisable to put a drop of water in it: when the water has boiled away, the pan will shortly be ready.

Now splash a small drop of water on to the hot, dry pan. The pan should be hot enough for it to rapidly boil the drop away, but you will soon find (perhaps after a few attempts as the pan continues to increase in temperature) that drops will float around the pan, apparently oblivious to the intense heat. Oblivious, just like the firewalkers, in fact.

If the pan is sufficiently hot, water that is thrown in will form into droplets of varying sizes. The water will not wet the surface of the pan: the small droplets will dance around, jumping perhaps 10cm upwards, while larger drops will move rapidly about the surface. Smaller drops are spherical, or almost spherical, because of the overriding effect of surface tension.

Disc shaped drops approximately 20cm in diameter and 5mm thick are quite easy to achieve (Figure 1), especially on a gas ring which can transfer heat more efficiently even if the base of the frying pan is buckled. You will probably find that bubbles break through larger droplets, often accompanied by hissing and violent spitting. This gives a clue to the remarkable behaviour of the drops, and suggests why they float and do not boil away. The drops are supported on water vapour, and water vapour has excellent insulating properties.

If you have the equipment, you can try the converse experiment. Instead of getting a liquid to float over a hot metal plate, it is possible to get hot metal to float over a liquid. A ball of molten metal about 1mm diameter heated to about 1000 Celsius will 'swim' about on the surface of water until it has cooled sufficiently for the vapour layer to be inadequate support. It will then cool rapidly and sink with a hiss. It seems that almost any materials will work unless there is a chemical reaction or other unwanted deterioration as a result of the heating. Strangely, drops of paraffin wax and oils with low vapour pressures still seem to show the phenomenon. It is a well-known fact that it is possible (but inadvisable) to pour liquid air over one's hand with impunity. Solid carbon dioxide, which is readily available, will float around happily on a warm metal plate.

It is easy to perform the conventional water-on-hotplate experiment, using a slightly dished metal plate over a Bunsen. The plate is dished to help constrain the drops for observation. An alternative method of constraining the drops is to dangle a fixed wire into the drop so that the drop is held by surface effects, but this method disturbs the small drops, and hardly controls larger drops. However by injecting them with a hypodermic syringe it is possible to maintain a drop at a constant volume. Such techniques are necessary if stable measurements are to be taken.

I have achieved drop sizes approaching 30cm diameter on a gas cooker at home. Large drops of such size that vapour bubbles disturb their outline may, at intervals, disintegrate and eject small droplets. Often these droplets will be blown well clear of the parent drop by the rapid escape of vapour as a bubble bursts. It is even possible for such large drops to form into a ring which may remain stable for several minutes.

When considering the shape of the hot plate, it is interesting to note that Leidenfrost himself used a kitchen spoon, but modern researchers prefer as plane a surface as possible. Mathematical analysis is then somewhat easier, if not the control of the drop! But do not neglect other shapes, for instance the geometry of an immersion heater, or other shapes of hot objects in liquids.

Examining the evaporation

If hard or impure water is used for the experiment, then the evaporation of the drop will leave a residue. Incidentally, Leidenfrost noticed this and attributed the remaining residue to the Aristotlean philosophy Fire+Water = Earth. With care one can use a hypodermic syringe (clamped in a stand) to add more water as the drop evaporates to ensure its size is kept constant. This will give the opportunity for a substantial residue to develop, which, in the case of hard water, will take the form of a calcerous shell. The shell is well worth examining with a microscope, particularly if it can be sliced—but fill it with wax first so that it does not crumble. The thickness of the shell at various points is an indication of the rate of evaporation at those points. See Figure 2.

Examining oscillations and their cause

If small pieces of dust are introduced into the drop, they will be carried around by the internal convection currents, and by their violent motion it is plain that the drop is very nearly isothermal. If the density of the dirt is changed then other phenomena may be observed. Thus if fine iron filings are placed in a drop they fall to the inside of the lower surface largely unaffected by the convection

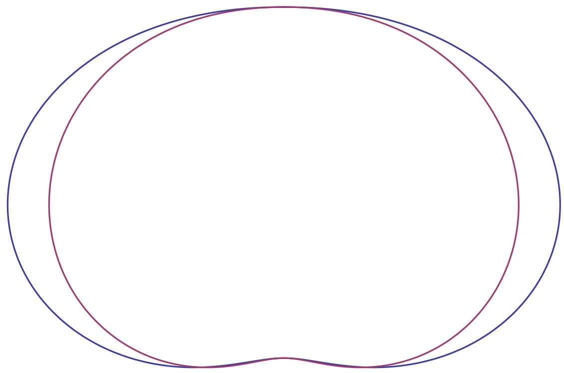

Figure 2: *Calcerous shell, vertical cross-section*

currents. With drops of certain size, about one or two centimetres in diameter, these iron filings will form into Kladne Figures, outlining undulations on the lower surface.

As the amplitude of the under surface oscillations increases, parts of the drop come closer to the hot plate. If the heat supply is adjusted carefully (or the conductivity of the plate is low), it will be cooled at peaks of oscillation. The drop may fall on to the plate and explode into violent boiling. Conversely, irregularities in the hot plate (e.g., scratches or bumps) may form nucleation points for bubbles which break up droplets. These observations raise the point that it may be possible to enhance the efficiency or safety of cooling systems—where the formation of insulating layers of vapour is a danger—by suitable surface contour to initiate such oscillation. It is interesting to experiment with surface coatings: try a non-stick frying pan, or one coated with cooking oil. Smooth, chemically inactive, surfaces will probably make little difference.

Water droplets with diameter in the range one to two centimetre are shaped like discs or upturned plates. They may spontaneously start oscillating radially around their edge. They look roughly like a round-toothed gear. These perimeter waves are transverse and only rarely does the pattern rotate. These oscillations can be quite beautiful. See Figure 3.

There is another mode of oscillation: the perimeter of the drop may move vertically, this happens sometimes with drops about 5mm in diameter. It is impractical to view this mode in a frying pan, but the drop assumes a pear shape, alternating with the neck at the top and bottom.

As vapour generated on the lower surface escapes radially from under the drop, drag causes the horizontal diameter of the drop to increase. With this increase in diameter the drop rises, given the same pressure of vapour. However, the now larger escape area causes the vapour velocity to decrease, as does the greater distance and insulation from the plate reduce the rate of vapour generation. The drop falls back towards the plate, falling to a minimum height less than before. Thus it rises with greater vigour, and oscillation may ensue.

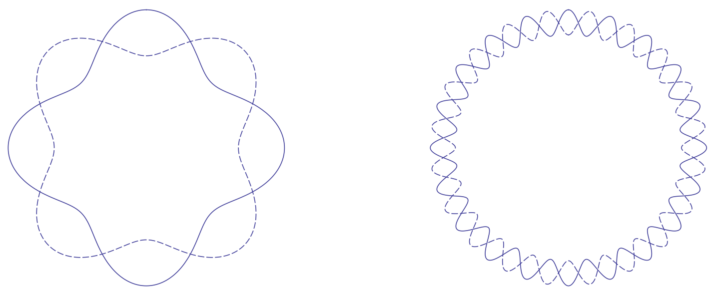

Figure 3: *Modes of radial oscillation, viewed from above*

The effect may manifest itself in two ways. Either the whole drop vibrates in a vertical direction resulting in the pear-shaped oscillations, or for larger drops, the preceding discussion applies to parts of the drop locally. Because of volume conservation, as one part spreads out, another part of the drop must draw in. For small enough drops, constrained by surface tension to be approximately circular and hence with an almost constant perimeter, a standing wave soon establishes itself.

Oscillation at a larger scale is possible too. Since the drop is supported by vapour pressure, and this pressure will drop as the temperature of the plate drops, the drop will tend to move *towards* cooler parts of the plate. In itself, this is a stable phenomenon, since the drop will tend to cool those attractive parts of the plate still further. In the limit, any contact with the drop will reduce the local surface temperature of the plate considerably, and the drop will end its life in a spate of rapid boiling. However, temperature gradients in the plate may lead to a suitable disc-like drop to tilt, causing a greater escape of vapour from one side. This may propel the drop across and *away from* the cooler area. The drop would be unlikely to return to repeat the performance except on a suitably shaped plate—your kitchen frying pan should have a rim!

You can easily demonstrate the outward vapour flow from under the drop by sprinkling fine powder on to the plate (talcum powder will do). The powder will be blown away from sufficiently large drops. Drops may be affected by powder already on the plate beneath them. More evidence for the escaping vapour can be seen in the behaviour of a group of small droplets. When drops collide they generally coalesce, but if their approach velocity is reduced then the drops are deflected by the outflow of vapour.

Measurement and control

Poggendorf first showed that the drop is electrically insulated from the plate and that, consequentially, it cannot be in contact with the plate. In the case of very small droplets that bounce, they do make momentary contact with the plate.

Similarly, a large droplet in a visible state of boiling, with bubbles breaking through, is connected, if erratically.

Measuring the height of the drop is tricky. Optical measurements are unsatisfactory. If you have the equipment, it is possible to dissolve barium acetate in the drop and use X-rays: this method eliminates unwanted reflections from the plate and the large effect at visible wavelengths of refractions caused by the water vapour and thermal gradients in the surrounding air. Note that an X-ray silhouette will measure the minimum drop-plate distance unless great care is taken with the contrast. Another possibility is to measure the capacitance of the drop/plate, but this will rely on assumptions about the permittivity of the water vapour and the geometry of the drop under the particular conditions being examined.

Of course, there are other parameters that are easier to measure, such as the size of the drop, its lifetime, or the drop and plate temperatures. Note that the plate temperature is unlikely to be uniform, particularly under large drops with direct flame heating. You should certainly use several thermocouples to examine the temperature variation across the plate.

I have experimented with different plate materials, to control the thermal conductivity. One experiment I tried that failed was to arrange the drop to be above the polished joint between two metals with very different conductivities. I had been obsessed with thermal effects and had forgotten that this particular metal interface would corrode under the conditions. As well as the plate material, you can also vary the drop liquid, its purity or the substances dissolved in it. It is useful to observe the oscillations with a stroboscope, and you can also determine their frequency. You may find photography more successful if you dye the drop a nice colour.

There are many variables that cannot be controlled satisfactorily and the phenomenon may be critically sensitive to certain variables that cannot be controlled precisely enough. It is therefore good procedure to take several measurements when the equipment has reached equilibrium—unless you are studying non-equilibrium effects! Note, too, that many of the experimental parameters are causally related, such as the drop lifetime and the plate temperature. There are many opportunities for graph plotting and interpretation of variations.

Further reading

For further reading I strongly recommend Leidenfrost's article, thankfully translated from the original Latin. A more recent article is the very readable Amateur Scientist article in the *Scientific American*. Firewalking is a popular (and hot?) topic, but see *The Skeptical Inquirer* volume X(1). A trip to a big science library, such as a university library or the Science Museum Library in London can be worthwhile. I found a number of nineteenth century chemistry books most rewarding; they will also give pointers into other literature which you should be able to follow up.

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Bibliographic details

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