Leidenfrost Effect

Περιγραφή Πειράματος/Κατασκευής

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Abstract
In the Leidenfrost effect (named for Johann Gottlob Leidenfrost, who described the phenomenon in 1756), a liquid in proximity to a surface much hotter than the liquid's boiling point will produce a layer of vapor that insulates the liquid and physically separates it from the surface. Essentially, even though the surface is much hotter than the boiling point of the liquid, it vaporizes slower than if the surface was near the boiling point. The vapor between the liquid and the surface prevents the two from coming into direct contact, thus practically eliminating friction. For this demonstration, I have constructed an aluminum square shaped maze, consisting of 49 small square parts, some of them separated by vertical partitions, to create a maze. Some of the small squares have certain vertical indentations, to control and accelerate the fluid flow, whereas the other squares are flat, so as to control the speed. Furthermore, a few squares have inclinations, to demonstrate that water can even flow uphill. All the small squares and the partitions are moveable, so various combinations can be easily created. In order to heat the maze, I have used butane burners, and a cooking heater to achieve high temperatures and a modified thermometer to monitor the temperatures. In the diagrams, I present some of the underlying physics (e.g. friction, force vectors, liquid inertia). I present some of the possible future practical applications of this phenomenon and possible means of how it could be further controlled. I have also included videos and photographs of the experiment.

KEY WORDS: *Leidenfrost effect, boiling, Leidenfrost maze, heat flux*

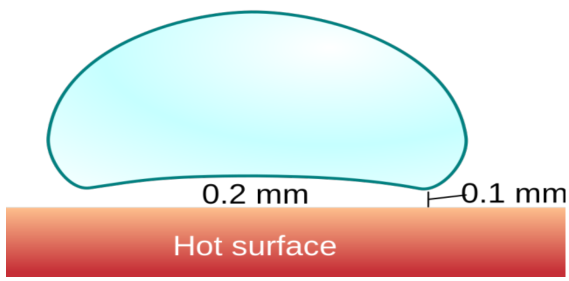
INTRODUCTION

Some physical phenomena seem to defy even the basic laws of physics. One such phenomenon is the Leidenfrost effect: This is what you see when a liquid comes in contact with an object that is a lot hotter than the liquid's boiling point. Someone would expect that the fluid would turn into gas, but instead it floats like mercury balls over the superheated surface. Vaporization of the liquid occurs only between the droplet and the hot surface. This strange effect was named after Johan Gottlob Leidenfrost, a German physician and scientist, in 1756.

For every liquid, the Leidenfrost point is different, because its boiling point is different. For water, this point is at about 220 degrees Celsius. At this temperature, the bottom part of the liquid droplet vaporizes so quickly that it does not let the liquid come in contact with the hot surface, thus insulating it, and so it takes much longer for the liquid to evaporate than it would if it came in direct contact with the hot surface.

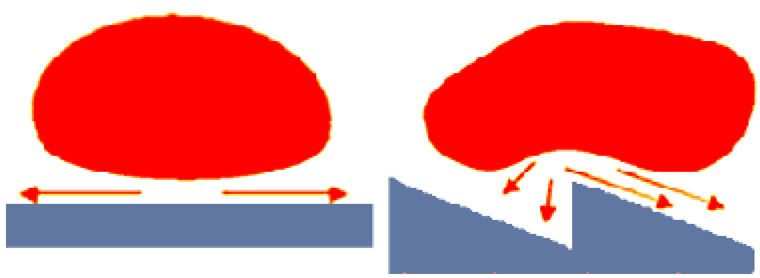
Because of the gas layer, the friction between the liquid and the surface is very limited. As the underlying gas escapes from under the droplet, it exerts repulsive forces on the droplet and it moves it in every direction. The bigger the size of the droplet, the more it is repelled by the gas cushion. It has been measured in laboratory experiments that the droplet may travel up to a meter. One of the factors that affect the directionality of the droplet is the characteristics of the hot surface. Any grooves or scratches on it cause disturbances in the escaping molecules of gas and change the directionality of the movement of the droplet. In a slightly concave surface it may even form star like shapes. (Kjeer, P., Kotchetkov Z., 2015).

Figure 1: Drop held up by layer of vapor



Having observed that, experiments were carried out to control the erratic movement of the droplet, by placing it on surfaces with finely processed grooves. If the grooves had specific inclinations, they would produce the appropriate vapor disruptions and make the droplet move in a controlled way, even uphill, as if defying gravity.

Figure 2: Leidenfrost ratchet. Droplets accelerate to the right on the saw tooth pattern, since vapor flow, as shown by the arrows, pulls them along. Forces cancel when no pattern is present.



Boiling is the rapid vaporization of a liquid, which occurs when a liquid is heated to its boiling point, the temperature at which the vapor pressure of the liquid is equal to the pressure exerted on the liquid by the surrounding atmosphere. Bubbles in the liquid can form only when the pressure of the vapor within the bubbles is great enough to resist the pressure of the surrounding liquid. If the pressure is not great enough, the surrounding pressure will collapse any bubbles that tend to form. At temperatures below the boiling point, the vapor pressure in bubbles is not great enough, so bubbles do not form until the boiling point is reached. At this point (100º for water at atmospheric pressure) molecules are energetic enough to exert a vapor pressure as great as the pressure of the surrounding water. If the pressure is increased, the molecules in the vapor must move faster to exert enough pressure to keep the bubble from collapsing. Boiling does not occur until the vapor pressure within the bubbles overcomes the pressure of the water.

There are three main types of boiling; **nucleate boiling** where small bubbles of vapor form at discrete points, **critical heat flux boiling** where the boiling surface is heated above a certain critical temperature and a film of vapor forms on the surface, and **transition boiling** is an intermediate, unstable form of boiling with elements of both types.

Nucleate boiling

Nucleate boiling is characterized by the growth of bubbles on a heated surface, which rise from discrete points on a surface, whose temperature is only slightly above the liquid's. In general, the number of nucleation sites are increased by an increasing surface temperature.

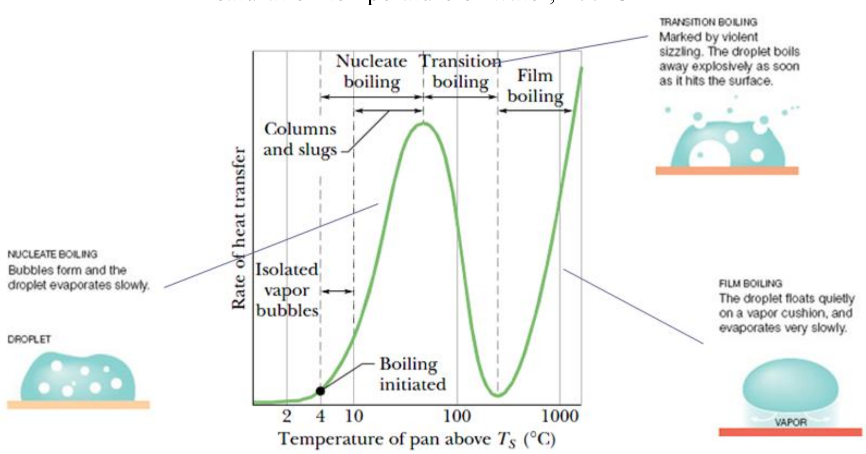
Critical heat flux

As the boiling surface is heated above a critical temperature, a film of vapor forms on the surface. Since this vapor film is much less capable of carrying heat away from the surface, the temperature rises very rapidly beyond this point into the transition boiling regime. The point at which this occurs is dependent on the characteristics of boiling fluid and the heating surface in question.

Transition boiling

Transition boiling may be defined as the unstable boiling, which occurs at surface temperatures between the maximum attainable in nucleate and the minimum attainable in film boiling. The formation of bubbles in a heated liquid is a complex physical process which often involves cavitation and acoustic effects, such as the broad-spectrum hiss one hears in a kettle not yet heated to the point where bubbles boil to the surface.

Figure 3: Behavior of water on a hot plate. Graph shows heat transfer (flux) v. temperature (in °C) above TS, the saturation temperature of water, 100°C



Film boiling or Leidenfrost effect

If a surface heating the liquid is significantly hotter than the liquid then film boiling will occur, where a thin layer of vapor, which has low thermal conductivity, insulates the surface. This condition of a vapor film insulating the surface from the liquid characterizes *film boiling*. Therefore, one can touch a hot stove very briefly with a wet finger and not get burned, (but not with a dry finger). This is because energy that ordinarily would go into burning the finger goes instead into changing the phase of the moisture on the finger. The energy converts the moisture to a vapor, which then provides an insulating layer between the finger and the hot stove. This has also been demonstrated on popular TV shows where a person dips his wet hand into very hot molten lead for a moment, without getting burned, or when some people walk barefoot across red hot coals without harm.

The Leidenfrost point signifies the onset of stable film boiling. It represents the point on the boiling curve where the heat flux is at the minimum and the surface is completely covered by a vapor blanket. This is why the droplet at the Leidenfrost point takes so much more time to evaporate, when compared to lower temperatures. Heat transfer from the surface to the liquid occurs by conduction and radiation through the vapor. In 1756, Leidenfrost observed that water droplets supported by the vapor film evaporate slowly as they move about on the hot surface. As the surface temperature is increased, radiation through the vapor film becomes more significant and the heat flux increases with increasing excess temperature.

LITERATURE REVIEW

In 2006, Linke, H., et al. (2006), did an experiment to demonstrate how the random motion of water molecules in hot steam could be channeled into a directed force. Their team scored a smooth metal surface with a series of skewed triangular grooves, to give it a saw-like profile. The water droplets appeared to push themselves off the long- slope side of the grooves and rocket across the heated surface instead of just dancing on the spot. They tried many liquids over a wide range of boiling temperatures. These included nitrogen (-195.79°C), acetone (56.5°C), methanol (65°C), ethanol (78°C), water (100°C) and hexadecane (287°C).

Later, in 2011, Lagubeau et. al. (2011), extended this work to sublimation of solids and measurement of the propulsion force on the droplets. They used the sublimation of dry ice for their experiments and the bending of glass fibers in the path of the droplets to measure the force. Forces as high as tens of micro-Newtons per droplet were measured, and the droplet velocities were generally about 10 cm/sec.

In 2013, at the University of Bath, Cheng and Guy manufactured a metallic construction like a maze, on which they demonstrated that they could completely control the direction of water droplets at the Leidenfrost point (220^0 C). The surface of their maze had specifically oriented grooves, and they were able to guide the droplets by only using the surface characteristics of their construction. Impressive as it was, the fact that this occurred only at the Leidenfrost temperature limited its practical applications.

One year later, Dupeux, G., et al. (2014), addressed this challenge by making Leidenfrost water droplets form at cooler temperatures. They modified the grooves of their hot surface by coating them with a hydrophobic layer of chemicals. With this surface modification, they were able to produce Leidenfrost droplets to form even under 100^0 C, which moved the same way as the ones that formed at 220^0 C.

The phenomenon has been studied for many other variables that affect it, such as: electric force and field (Celestini, F., Kirstetter, G., 2012), mechanical vibration, light, surface topography (nanoscale vs microscale features) (Agapov, R., et al., 2014), pressure (Celestini, F., Frisch, T., Pomeau, Y., 2013), and magnetic fields (Piroird, K., Clanet, C., Quéré, D., 2012).

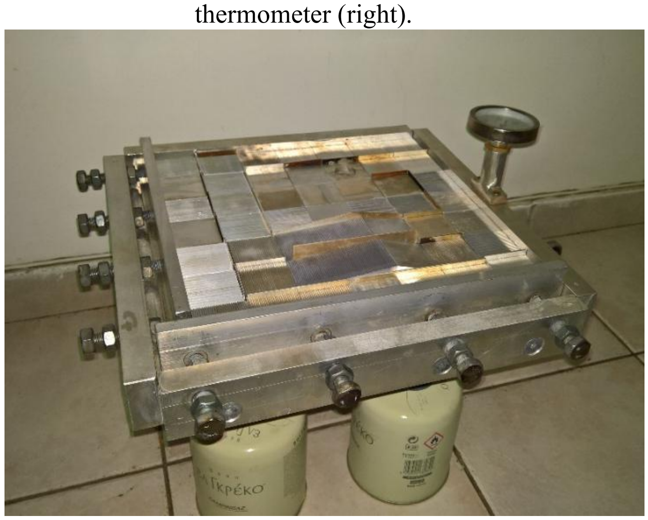
PURPOSE OF THIS STUDY

The purpose of this experimental setup is to demonstrate the Leidenfrost effect. I discuss the physics that explain the phenomenon, the variables that affect it, and its potential future applications.

MATERIALS AND METHOD

For this experiment, I constructed a square aluminum surface which consists of 49 smaller, square aluminum parts, which I can assemble in various configurations and try out various maze designs.

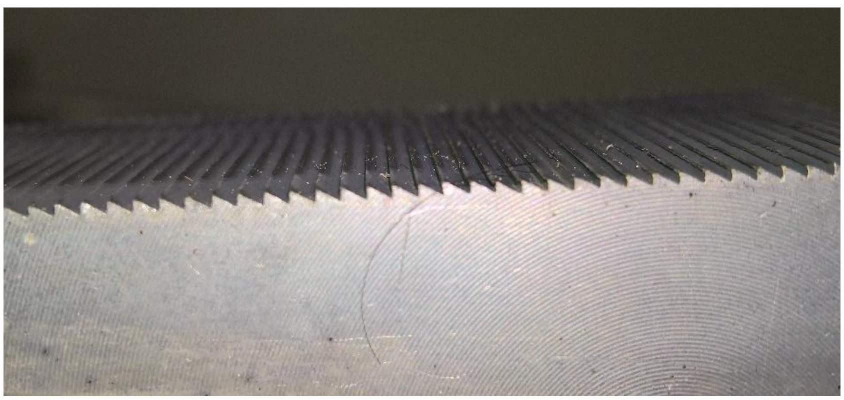
Figure 4: Experimental apparatus (Leidenfrost maze) consisting of four burners (below), the maze (middle), and thermometer (right).



Some of them have specific indentations, to control and accelerate the fluid flow. The indented blocks were prepared by milling the surface of flat, rectangular aluminum blocks with rotating blades that were scanned across the block surface. The slopping part of the saw-tooth was inclined at 60^{O} corners to the vertical, leading to vertically dropping steps and slopes 30^{O} to the horizontal. The size of the individual square blocks was 4cm wide and 1 cm tall. The final configuration of the indentations was: width 1mm, depth 0.5mm and dent inclination of 60º. This shape was decided after studying an article, (Grounds, A., Still, R., Takashina, K., 2012) where they tried out three different surface configurations, and concluded that this shape produces the best results. Two adjacent squares have uphill inclinations (8º), to demonstrate that water can flow uphill. They are separated from each other by thin, moveable aluminum dividers. The maze sits on top of a plate which is heated by four butane burners. Individual blocks were heated by a hot electric plate. The temperature was measured by an industrial thermometer which was soldered on the frame of the aluminum plate. Even though the temperature at the center of the construction may have been higher than that on the frame, for the purposes of this experiment this is not important, since the phenomenon appears anywhere between 220-250º C.

Droplets of tap and distilled water and other liquids were dropped from a pipette held a few centimeters above the aluminum surfaces. For filming purposes, I also used water soluble fluorescent dye.
The blocks were held horizontal as much as possible at all times.

Figure 5: Saw-tooth groove pattern on an inclined block.



I have taken close-up photographs of the experiment. I have also made a video of the working experiment, with a video and a photographic camera.

RESULTS

Sound observations:

At around 210º C the droplets boiled violently, with a lot of sizzling sound, due to nucleate boiling towards the middle of the droplet, which creates vibrations and large movements. This happens because the ratchet teeth cut into the droplets from below, leading to a relatively large area of direct contact, and hence rapid heat transfer, nucleate boiling and, in turn, a lot of sound. As the temperature increases, the droplets are forced higher, causing a reduction in the contact area. At the highest temperatures, the droplets no longer touch the teeth due to there being sufficient film boiling to completely levitate them, and the system becomes silent, showing that the system is fully in the Leidenfrost regime.

Optical observations

The paths the droplets took were highly reproducible. This means that the droplets followed the desirable path of the maze most of the time, but not all the time. One explanation could be that since the teeth were milled using rotating blades at a machinery, there were local imperfections such as dents, scratches and asymmetries on them. The maze and the experiment had to be repeated many times, with various configurations, to have the desirable outcomes over long distances. But the direction of movement on individual blocks were always predictable and reproducible. What was unexpected was the finding that on the slope of 8o uphill the droplets accelerated significantly more, when compared to their acceleration on the flat blocks.

The dynamics of this motion is complicated. The motion is presumably dominated by the flow of gas resulting from the film boiling and its interaction with the solid surface. The gas flow is affected in such a way that the net force on the droplet has a component parallel to the block and a direction vertical to the spikes and towards the acute angle of the spikes. Other forces that determine the results of the one-way motion should be surface tension, vibrations within the droplet mass and the actual wetting contact with the surface. The acceleration noticed at the 8o inclined block must be explained by the greater net gas flow at this inclination, contributing to the droplet's ability to climb the incline. At the 12º inclination, however, I could not monitor adequate and predictable droplet climbing, even when I tried various temperature adjustments (200-300º C), in contrast to other authors.

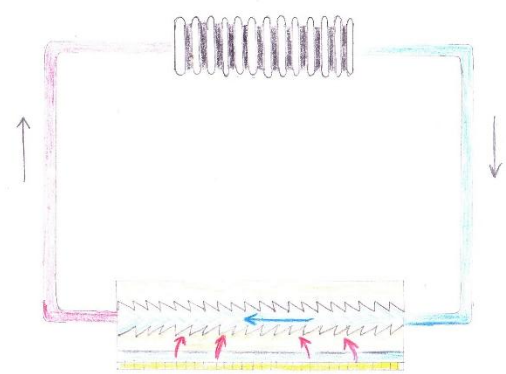
In summary, while the detailed mechanism of the controlled motion of Leidenfrost droplets is somewhat unclear, my experiment verifies that directional control of small quantities of liquids only by temperature is possible, and more research is needed.

APPLICATIONS

By controlling the way small amounts of liquids move, scientists would have a very useful technology. It could have applications in a wide variety of technological applications, for example cooling electronics at a micro scale, atomic reactor safety, ink-jet printing and much more.

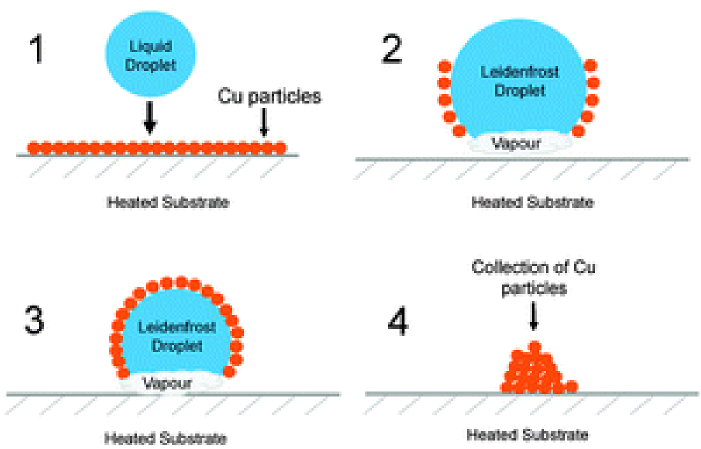
The electric currents passing through microprocessors are so large, the heat they generate can limit computing performance. Many chips have cooling circuits nowadays, but these require pumps to drive the coolant, which in turn generate even more heat. By utilizing the Leidenfrost effect, the heat from the chip would be the pump, and the pumping would only happen when the chip would be warm. So, it would be a thermostat at the same time! (Lehigh University, 2016)

Figure 6: Self-propelled water flows from the microprocessor (below) to the condenser (above) and vice versa, resulting to the constant temperature of the chip, without requiring a separate pump.



Furthermore, it could find future applications for minute matter levitation (Pease, R., 2006) and transportation of particles (like dust) (Hashmi, A., et al., 2012). There are applications for all that as the self- cleaning of metallic and semi-conductor surfaces where manual cleaning is not amenable (Tan, C., et al., 2015).

Figure 7: Water dropped on a heated surface above the Leidenfrost point acts as a simple cleaner, gathering small particles to a desired location, while requiring minimal maintenance.



This method of energy harvesting could even power life on Mars (Northumbria University, 2015). The Martian colonists could use energy from carbon dioxide, which is abundant there and undergoes cyclic phase changes as water does on Earth. Future stations there could exploit such a resource to harvest energy as dry- ice blocks evaporate, or to channel the chemical energy extracted from other carbon-based sources, such as methane gas. Even more, if the astronauts would want to have some fun there, they could skate board on dry ice (CO_2) on Martian slopes (NASA Jet Propulsion Laboratory, 2013) by taking advantage of this phenomenon.

One of humanity's biggest challenges this century will be finding new ways to harvest energy. The Leidenfrost effect could be one of the starting points in research in smart materials engineering. In the future, such devices could find applications in wide ranging fields, spanning from frictionless transport to outer space exploration.

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