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2014 Problem 8 : Freezing Droplet

The shape of the water droplet may become cone-like with a sharp top

Iman Mojtahed
Mofid 1 High School

Amir Reza Soheili
Science & Technology University

Reported in PYPT 2014, Ariaian Young Innovative Minds Institute, AYIMI
Tehran, Iran
P.O.Box: 17185-614
info@ayimi.org

Place a water droplet on a plate cooled down to around -20 °C. As it freezes, the shape of the droplet may become cone-like with a sharp top.Investigate this effect.

Abstract

When a water drop is placed on a very cold surface, it freezes and is changed to a pointy tip drop. This phenomenon is not limited to water drop, and with every liquid that meets some specifications we can observe this happening.

The main reasons for this phenomenon are vertical expansion of drop and overcoming of surface tension of drop on its weight. If these two conditions exist for each fluid, its drop will expand vertically. Thus the bottom section of drop will expand vertically and the remaining portion of drop (which is above the frozen part) will move upward without any change. This happening will continue until we reach to the top of drop. At this point, the entire lower surface has been frozen, so the last point will move upward, without any transformation, and produce a sharp point (a pointy tip) which is called singular shape.

In this article, I am going to prove this theory and analyze pointy ice-drops phenomenon using some experiments.

Observations

The first step to solve any problem is observation. So according to the question, we should prepare necessary conditions for freezing the drop and appearing singular point. The first condition of the problem is temperature. There are many ways to receive -20°C, like using liquid nitrogen or liquid hydrogen; but the simplest way is using freezer. To do that, we should fill a plate with salty water and place it in a freezer with temperature control. The reason to use salty water is its lower melting point in comparison with other accessible liquids. Because of its low melting point, it can keep temperature constant for a long time and reaching to thermal equivalence between the plate and the environment takes longer time. Also it is recommended to add color to water (which we use to take drops) for better observation.

The following pictures show the steps of our experiments. In picture 1, a drop is deposited on the icy surface using a syringe. Then 2 seconds (picture 2), 9 seconds (picture 3) and 13 seconds (picture 4) after depositing drop on the cold plate, we took photos. The environment and plate temperature were 23^{0c} and -22^{0c} respectively.

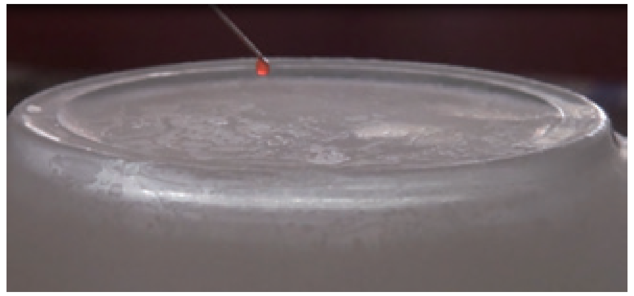


Fig. 1: depositing drop on the plate.

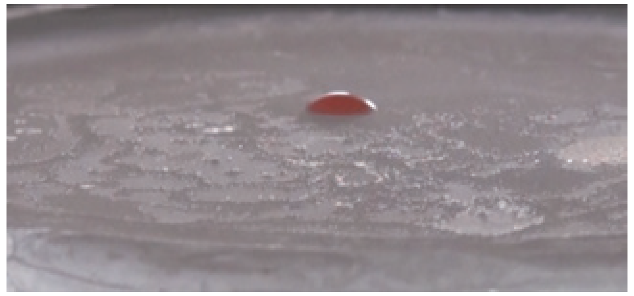


Fig. 2: 2 seconds after drop depositing.

As you can see in picture 2, there is no effect of singular point phenomenon after 2 seconds and water drop behavior is as normal liquids.

Fig. 3: 9 seconds after water drop depositing on the plate.

Fig. 4: 13 seconds after water drop depositing on the plate.

As it is clear in picture 4, the water drop shape changed from nearly perfect spherical cap to a drop with singular shape at the top of it.

Observations analysis

Pointy ice-drops phenomenon has been studied by some physics groups already, so we use their published images here to show water drop solidification process.

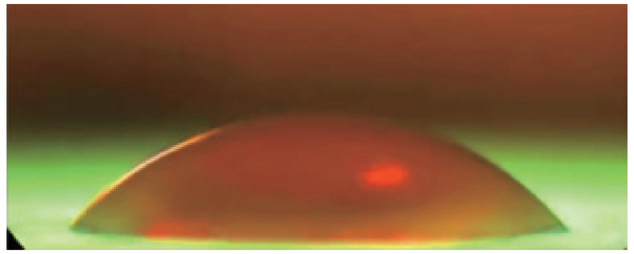


Fig.5

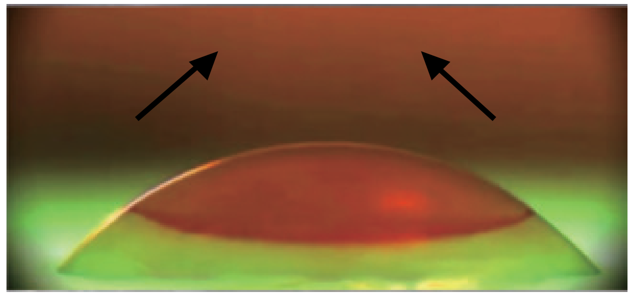


Fig.6

As you can see in pictures 5 and 6, the drop starts to freeze as soon as it is deposited on the cold surface. According to picture 6, this solidification appears from bottom to top levels of the drop.

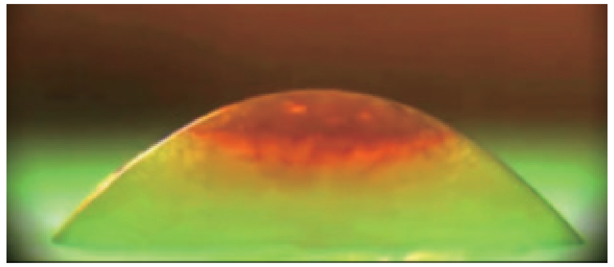


Fig.7

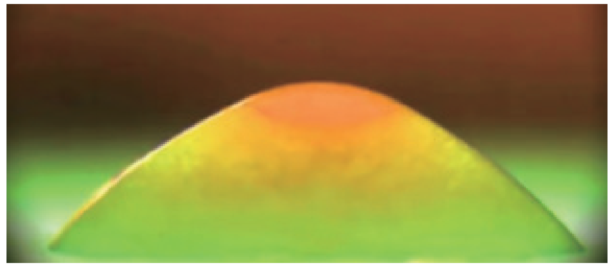


Fig.8

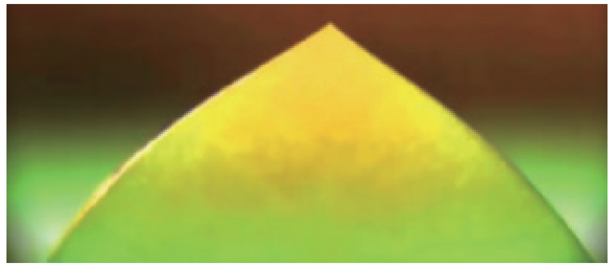


Fig.9

As it is obvious in the above pictures, solidification process propagates upward and in surface direction, and volume of liquid section of drop is decreasing continuously. In picture 8 almost all parts of the drop are frozen. In picture 9, that is the last moment of drop freezing, the singular point is appeared at top of the drop and solidification process is finished.

In the rest of this paper we will study this behavior of water drop. First we should discuss some initial facts:

1-Volume changes during solidification

A few liquids expand as they are freezing. Water is one of them. So it is clear that the volume of frozen water is larger than liquid form of it. This expansion can be vertical or radial. In vertical expansion radius of drop is constant and its height increases; while in radial one radius of drop increases.

For vertical expansion, there are some necessary conditions that will be described later in this article.

2- Bond number

Bond number is the ratio of weight to surface tension of fluid and can be calculated by the following relation:

$$Bo = \frac{\rho \cdot g \cdot R^2}{\gamma} \qquad (1)$$

Where R is the radius of a perfect sphere of the same volume and c are the liquid density and surface tension, respectively, and g is the gravitational field strength.

So if Bond number ranges in a specific boundary, which should be less than 1 definitely, surface tension forces dominate over gravity, and then vertical expansion will be happened.

Now we can represent the Pointy ice-drops theory.

Theory

As we mentioned earlier, a few liquids expand during solidification. If surface tension of the fluid is large enough to concentrate the weight ($\gamma > \rho g$), radial expansion of liquid is not possible, so vertical expansion will occurred.

According to very high and unusual surface tension of water, probably in this liquid, the necessary condition for vertical expansion exists and drop will expand vertically.

Now we will study the most important effective parameters on pointy tip generation.

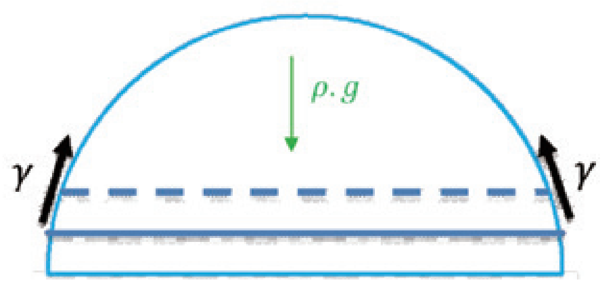


Fig.10

Effective parameters

1-Volume changes during solidification

As mentioned earlier, the pointy tip described in the question, will appeared in fluids which expand during solidification. Because volume of drop should increase, and so the drop will occupy more space and the increased volume will be appeared as a pointy tip (or any other shape).

2-Ratio of weight to surface tension (Bond number)

As we described in previous sections, and according to picture 11, for generating a pointy tip in vertical direction, expansion should be happened vertically, and the essential condition for this happening is that surface tension forces drop's weight. It means that the Bond number should be in a specific range.

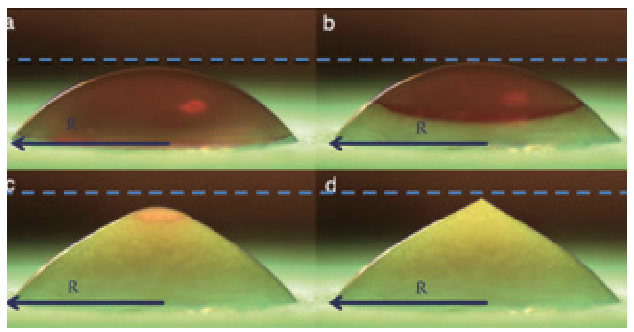


Fig.11

3-Perfect spherical cap shape of drop

To study this phenomenon, we should consider general condition. This condition is the shape of water drop, which is perfect spherical cap, when it is deposited on the plate.

To establish this condition, the drop should be placed onthe platefrom ashort distance (maximum 7-8 cm), so it will not diffuse on the plate and its shape will be remained spherical cap on it.

Experiments

Now, according to our understanding of the problem, we can design the required experiments. As we want to study the effect of density and surface tension on pointy tip of ice-drop, we experiment our examination with 4 materials with different densities and surface tensions in constant environmental conditions:

Temperature of drop: 25ºc

Temperature of plate: -25ºc

All drops are deposited on the plate from 3-4 cm distance

We did the experiment with four materials: water, salty water, cola and syrup. (Figs. 12-15)

a. Water drop

$\gamma = 0.073\ N/m \quad \rho = 1000\ Kg/m^3 \quad R = 2\ mm$

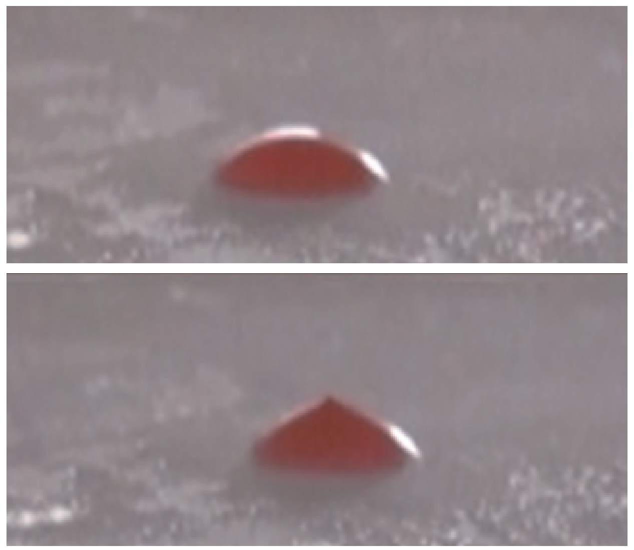


Fig.12

$$Bo = \frac{1000.10(2.10^{-3})^2}{0.07} = 0.28$$

b. Salty water drop

$\gamma = 0.073\ N/m \quad R = 2\ mm \quad \rho = 1100\ Kg/m^3$

Fig.13

$$Bo = \frac{1100.10(2.10^{-3})^2}{0.07} = 0.62$$

c. Cola drop

$\gamma = 0.12\ N/m \quad R = 2\ mm \quad \rho = 1070\ Kg/m^3$

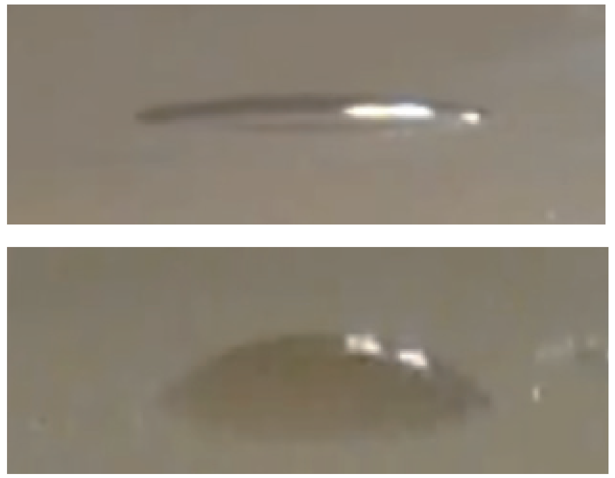


Fig.14

$$Bo = \frac{1070.10(2.10^{-3})^2}{0.07} = 0.39$$

d. Syrup drop

$\gamma = 0.04\ N/m \quad R = 2\ mm \quad \rho = 1500\ Kg/m^3$

Fig.15

$$Bo = \frac{1500.10(2.10^{-3})^2}{0.07} = 1.5$$

Experiments inspection

To study the results of experiments, we plotted two figures:

1- Radius – Time changes during solidification of four drops

2- Height – Time changes during solidification of four drops

As you can see in figure 16, the radius of water and cola has been remained constant as time improved; so radial expansion has not occurred in these two drops. While in salty water and syrup, radial increase is obvious, so expansion of these two drops has been radial.

Radius- time

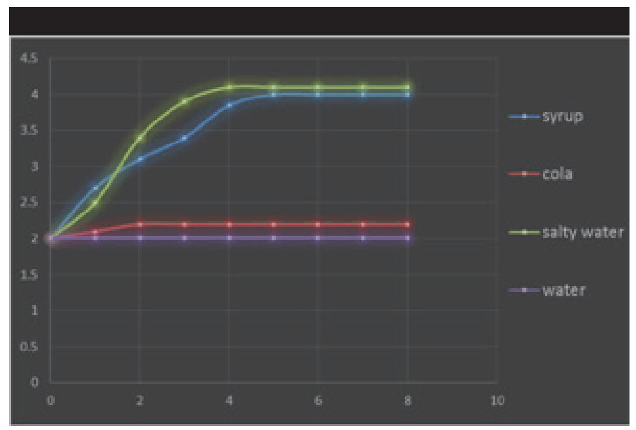
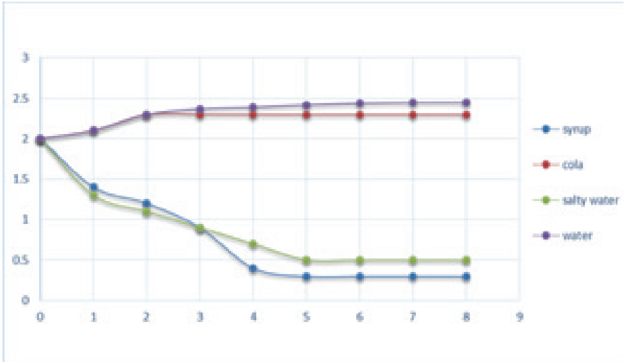


Fig.16

As it is clear from figure 17, height of water and cola drops increased and height of syrup and salty water decreased during solidification. Because of vertical expansion of water and cola drops, we can observe point tip phenomenon with these two drops.

Height- time



Height (mm) Fig.17

Time (s)

Experiments results

According to the fact that water and cola drops (with 0.28 and 0.39 Bond numbers respectively) had expanded vertically, and salty water and syrup drops (with 0.62 and 1.5 Bond numbers respectively) had radial expansion, and with attention to "Freezing Singularities in water drops" article, we can conclude that:

"If Bond number of a fluid is between 0.25 and 0.4 and the fluid expands during solidification process, we can observe a singular shape during it is freezing."

Conclusion

In this article, according to the question, we studied how water and some other liquids freezes into a singular shape (pointy tip). As described in the article, to happen this phenomenon, there are two necessaries:

1-During solidification, drop should expand. (Because the volume of the drop should increase, so the drop will occupy more space and increased volume will appear as a singular point.)

2-This expansion, should be vertical. For vertical expansion happening, surface tension of drop should overcome its weight. This condition can be explained using Bond number (weight to surface tension ration) that we mentioned in this article.

So, we can say the following expression about water drop:

"When a water drop disposes on a cold surface, it starts to freeze from bottom (cold surface-drop interface). According to special property of water – It expands during solidification – volume of drop increases. There are two ways to expand: radial expansion and vertical expansion. Because the Bond number of water drop is between 0.25 and 0.4 so it is capable of vertical expansion. Thus the button section of drop expands vertically and remaining parts of drop (which are still liquid and are placed on the solid section of drop), without any transformation, will move upward. This happening will continue until we reach to the top of water drop. At the top point, the entire lower surface has been frozen. So the last point (top point) will move upward without any transformation, and the sharp point will be produced."

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2014 Problem 12: Cold Balloon

As inflated, a rubber balloon's surface becomes cooler to the touch

Wang Han Wei
Tianjin Experimental High School, China
henry.w_Hwi@yahoo.com

Zhang Ruo Yang
Department of physics, Nankai University, China
zhangruoyang@gmail.com

Abstract

The surface temperature of a balloon would decrease during the deflating process, which originates from the characters of rubber. We construct a semi-quantitative model to investigate this phenomenon, and obtain the temperature of the balloon as a function of time theoretically with some parameters which need to be measured experimentally. And we verify the model though experiment. We also analyze factors that affect the cooling process, and find that thickness is particularly important. By measuring the thickness distribution of the balloon, we can predict the temperature distribution theoretically, as observed in the experiment.

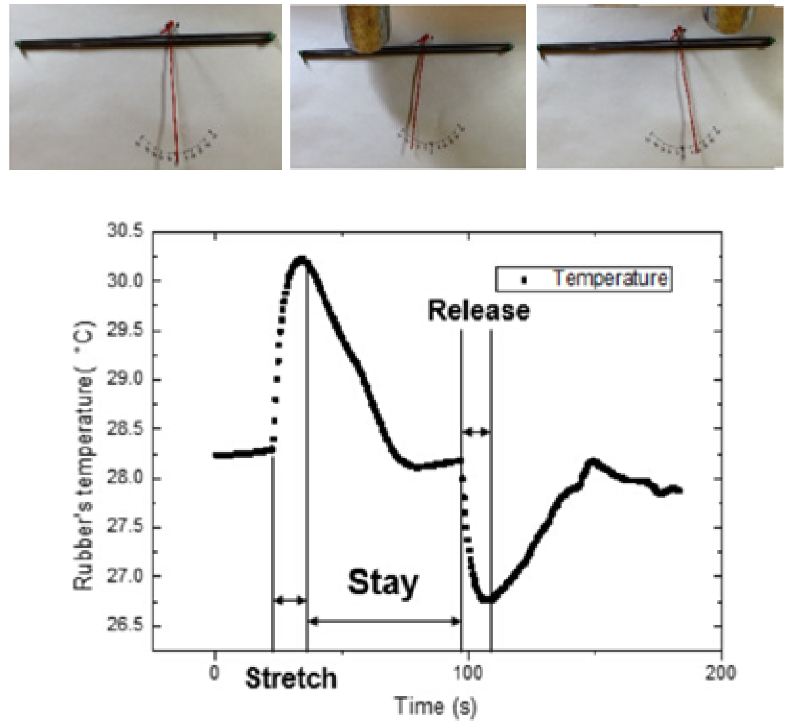

Fig.1: (a) Measuring the temperature of a piece of rubber, we can clearly observe that the temperature will change when work is done by or on the rubber. (b) Fasten a stretched rubber band on two sides, and put an indicator to show the motion of middle point. (c) Heat its left side by an electric air blower. (d) Heat its right side.

Keywords

Balloon, deflation, Cooling, Thermodynamics of Rubber