FREEZING DROPLET

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A R T I C L E I N F O

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A B S T R A C T

If water droplets drip onto a very cold metal surface, they freeze quickly, but during the freezing process, the shape of the water droplets changes and they often become sharp, frozen droplets. This phenomenon is caused by the expansion of water during freezing and surface tension, which causes the droplet to grow taller each time it freezes in a conical shape as the volume in the upper layer of the drop increases. In this article, we will try to investigate the effect of surface tension and other parameters on this process by conducting a series of experiments.

Keywords : *Water droplet, freezing, cone shape, surface tension*

1. Introduction

One of the unusual properties of water is its freezing from the surface. According to the laws of thermodynamics, when water molecules freeze, their density becomes lower than that of liquid molecules, so they move upwards and accumulate at the surface of the liquid. In this phenomenon, when a drop of water hits a metal plate, it starts to freeze from the surface where it hits the metal. This is because at the moment the drop hits the metal surface, due to the very high temperature difference between the metal and the drop, the molecules are deprived of the opportunity to move and the drop freezes from the surface where it hits the metal. When the drop hits the metal surface, an ice shell forms and grows upwards and progresses along the contact surface. The molecules inside the liquid volume are pulled in all directions and the resultant force on them is zero, but the molecules on the liquid surface are pulled in only one direction by the liquid molecules and the attraction force in the other direction and beyond the liquid boundary that is in the vicinity of the air and is introduced by the air molecules is less, hence the progress of the freezing process around the droplet is faster than inside the droplet, so that the liquid and unfrozen part above the droplet takes the form of a round and spherical cap. Based on the exceptional properties of water, this fluid expands when freezing. However, since in this phenomenon the water does not expand in the radial direction and expands vertically, the expansion is concentrated on the tip of the droplet and finally the combination of the two factors of expansion and the restriction caused by surface tension causes the tip of the droplet to tilt upwards.

After the formation of the cone shape of the droplet tip, the gradient or concentration change of water vapor around the tip increases. Water vapor spreads around the tip, like an electric charge that is attracted to the tip of a lightning rod, and during the condensation process (preferably) freezes on the tip of the droplet. In this article, we try to examine the parameters and factors affecting this phenomenon with some experiments and to explain and prove the cause of its occurrence more clearly (Fig. 1).

As we know, the freezing of a drop is also a function of the pressure and temperature of the surrounding environment; changing the temperature and air pressure around the drop affects the formation of the phenomenon and leads to different results, therefore, in all experiments, the pressure and temperature of the surrounding air, as well as the humidity level, are constant .

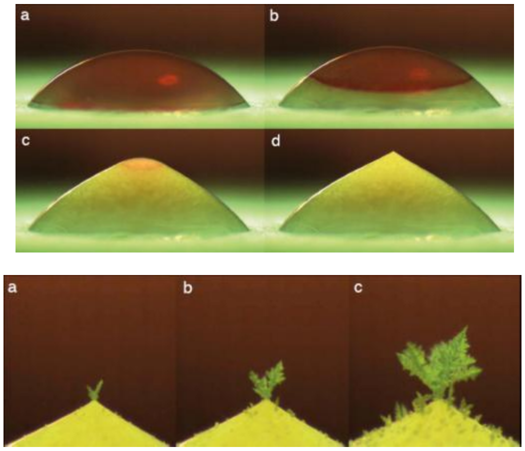

Fig. 1: The geometry of the water droplet

Another parameter whose change may affect the results of the experiments but is taken constant is the volume of the drop. 1 It is clear that the temperature of the water drop also has a significant effect on its formation, and the lower the temperature of the drop, the faster it freezes. The temperature of the drop in all experiments was 20 ° C and there was no change in it (Fig. 2).

Fig. 2: The hygrometer shows a constant number during the tests.

2. Theory

We need to know if the gravity influences on this Problem or not.

When water droplet is freezing, the radius of the spherical cap is decreasing and water is expanding upward (Fig. 3).

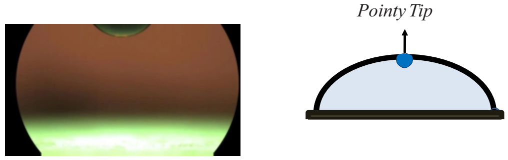

Fig. 3: The shape of water droplet

Droplet radius is too small and the Bond Number is given by:

$$Bond\ Number = \frac{\rho g R^2}{\gamma}$$

which in our experiment its range is: 0.25 – 0.4
As our assumptions :
1-Plate Temperature= T_0
2-The surface is Parabola shape
3-The Sum of θ and θ' is Constant and the surface propagates along θ.
4-The solidification front is planner .
5-The freezing process is directed along the water–vapor interface .
Philippe burnt assumed :

- The solidification front is planner .
- The freezing process is directed along the water–vapor interface (Fig. 4).

$$Tan\theta \frac{dR}{dZ} = -1$$

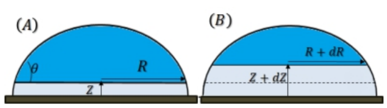

Fig. 4: Philippe burnt assumption

The geometry of the water droplet is explained as follows (Fig. 5):

$$Tan\theta = -\frac{\Delta h}{\Delta R} = -\frac{dZ}{dR} - \frac{dA}{dZ}\frac{dZ}{dR}R^2 - 2RA\frac{dR}{dZ}\frac{dZ}{dR}$$

$$Tan\theta\frac{dR}{dZ} = -\frac{\Delta h}{\Delta R}\frac{dR}{dZ} = -\left(1 + R^2\frac{dA}{Dz} + 2RA\frac{dR}{dZ}\right)$$

$$Tan\theta\frac{dR}{dZ} = -1 \underbrace{- R^2\frac{dA}{Dz} - 2RA\frac{dR}{dZ}}_{\text{The difference}}$$

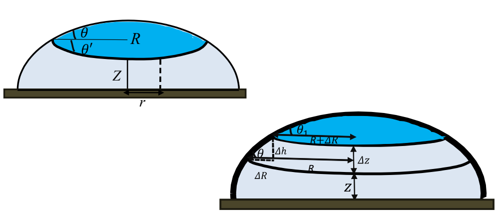

Fig. 5: The geometry of the water droplet

2.1. Mass Conservation

D.M Anderson and Philippe burnt assumed :The solidification front is planner (Fig. 6).

$$\rho_l\, dV_l = -\rho_s\, dV_s$$

$$\frac{\pi}{3}R^3\left(\frac{3Sin\theta - 3Cos^2\theta\, Sin\theta}{Sin^3\theta} - 3Cos\theta\left(\frac{2 - 3Cos\theta + Cos^3\theta}{Sin^4\theta}\right)\right) = -\frac{\rho_s}{\rho_l}\pi R^2 dZ$$

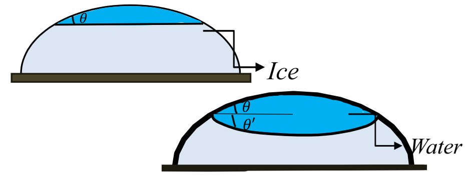

Fig. 6: Solidification shape

$$V_l = V_{sc} + V_{concave}$$

$$\rho_l\, dV_l = -\rho_s\, dV_s$$

$$\frac{\pi}{2}R^4\frac{dA}{dZ} + 2\pi A\frac{dR}{dZ} + \pi R^2\left(\frac{2 - 3Cos\theta + Cos^3\theta}{Sin^3\theta}\right)$$
$$+\frac{\pi}{3}R^3\left(\frac{3Sin\theta - 3Cos^2\theta\, Sin\theta}{Sin^3\theta} - 3Cos\theta\left(\frac{2 - 3Cos\theta + Cos^3\theta}{Sin^4\theta}\right)\right)$$
$$= -\frac{\rho_s}{\rho_l}\left(\pi R^2 + \pi\frac{R^4}{2}\frac{dA}{dZ}\right)dZ$$

and the contact angle:

$$\theta + \theta' = Constant$$

$$\frac{d\theta}{dz} + \frac{d\theta'}{dz} = 0$$

3 Differential Equation
$$\begin{cases} \theta + \theta' = Constant \\ \rho_l\, dV_l = -\rho_s\, dV_s \\ \frac{1}{Tan\theta} = -\frac{\Delta h}{\Delta R}. \end{cases} \longrightarrow \textit{Mathematica}$$

By using equations :

- $\theta + \theta' = Constant$
- $\rho_l\, dV_l = -\rho_s\, dV_s$
- $\frac{1}{Tan\theta} = -\frac{\Delta h}{\Delta R}.$

and initial condition:

- $R_0 = 0.001m$
- $\theta = 120° = \frac{2}{3}\pi$

we can plot the radius of the droplet during freezing (Fig.7).

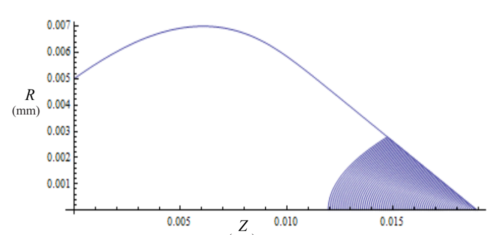

Fig. 7: The radius of water droplet Vs height

3. Experimental Setup

By taking photo in different steps the shape of the water droplet in different times during freezing is captured. Test equipment : Dropper, Metals frozen to minus 20°C, Detergent, thermometer, hygrometer, pressure gauge (Fig. 8).

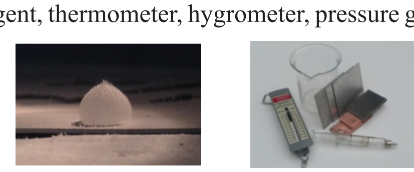

Fig. 8: Photo taken in our experiment

3.1. Experiment No. 1

In this experiment we are going to investigate the difference in the material of the plate and its purpose is to demonstrate the importance of the heat capacity of the object in the freezing of the drop. In the design of the experiment, we first cover all three types of metals (iron, copper, and aluminum) with plastic and cloth bags to protect the metals from moisture and reduce the percentage of error in the experiment. Then, we cool them to a temperature of minus 20 degrees and place a drop of water on them. It is observed that the drop on the aluminum phase, which has a higher heat capacity than iron and copper metals, freezes faster and its tip becomes conical (Fig. 9).

Fig. 9: The conical shape on the aluminum phase

3.2. Experiment No. 2

Another parameter that is effective in freezing the drop is the mass of the metal plate, and it is obvious that the greater the mass of the plate, the greater its capacity to absorb heat and the faster the heat transfer between the drop and the metal. In this experiment, we tried to observe the effect of changing the mass of the plate on the freezing process of the drop. The design of the experiment is similar to the previous experiment, with the difference that here, instead of three types of metal, one type of metal with different masses was used. As expected, the drop froze faster on the metal piece that had the greater mass.

So increasing the mass of the plate can improve the freezing process (Fig. 10).

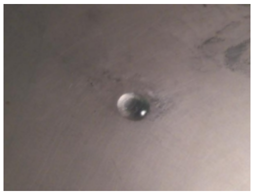

Fig. 10: The conical shape by increasing the mass of the plate

3.3. Experiment No. 3

To prove the importance of the surface tension of water in the occurrence of the phenomenon, based on the fact that impurities reduce the surface tension, an experiment was designed in which three different percentages of impurities were used and the results were analyzed and examined. Instead of pouring pure water, we used a mixture of water and detergent. Given that the molecule of this type of detergent has a polar (hydrophilic) end and a non-polar (hydrophobic) end; and on the other hand, the water molecule is also a polar molecule, as a result, the water molecule attracts the polar parts of the detergent and creates adhesion. By releasing this droplet, which is accompanied by impurities, on a metal plate whose temperature has been lowered to 20 degrees Celsius below zero, changes occurred in the freezing process of the droplet. In the first stage, a mixture of water and 8% impurities was used1 and the result was almost similar to pure water and the droplet froze and its tip became conical. In the second stage, 14% impurities were used and it was observed that the droplet froze but its tip did not become conical. In the third stage, 50% impurities were used and, as expected, a droplet formed on the metal and did not freeze.

So the evidence shows that surface tension plays a fundamental role in the formation of the phenomenon and its absence prevents the phenomenon from occurring, and the lower the percentage of water purity, the lower the probability of freezing the drop (Fig. 11).

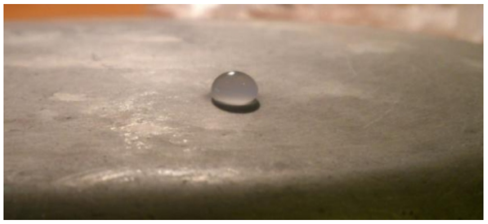

Fig. 11: The surface tension plays a fundamental role in the formation of the phenomenon

4.2. Experiment No. 4

The way the drop is placed can also affect whether it freezes or not, as well as the formation of a conical tip. The purpose of designing this experiment is to investigate how to place the drop on the screen and freeze it. In this experiment, all parameters are constant and only the drop is dropped from different distances on the screen. It is obvious that the further the drop is placed from the screen, the greater its gravitational potential energy, and when it hits the screen, it has more energy and breaks up. When the initial height of the drop is reduced, it was observed that the drop spreads out when it hits the surface on the screen, as a result it freezes, but its tip does not become conical. Therefore, it is better to place the drop from a lower height and near the surface on the screen, because if we drop the drop from a higher height, the desired result will not be obtained.

4. Conclusion

In the process of freezing a drop on a cold metal, if the temperature and mass of the drop and the metal, the way the drop is placed on the surface, and other parameters such as the drop temperature, viscosity, drop volume, ambient air pressure, ambient temperature and the water drop, and the specific heat capacity of the metal and water are appropriate and the phenomenon is formed; it is observed that the ice shell that forms from the contact surface of the drop with the metal advances upwards, and the water expands vertically and the tip of the drop becomes conical. As we observed in experiment number three, if we reduce the surface tension by increasing the impurity, the cohesion decreases and eventually the drop loses its drop shape and does not freeze naturally.

References

[1] http://phys.org/news/2012-10-droplets-sharp-ice-peaks.html

[2] Physics Halliday