Levitation Time Measurement of Water Drops on the Surface of Liquid Nitrogen

Heetae Kim* and Young Hee Lee
Department of Physics, Department of Energy Science, Sungkyunkwan University, Suwon 440-746, Korea

Hoonyoung Cho
Department of Physics, Dongguk University, Seoul 100-715, Korea

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The levitation of water drops on the surface of liquid nitrogen is studied. The water drop evaporates the liquid nitrogen, which makes a nitrogen vapor film between the water drop and the surface of the liquid nitrogen. The temperature of the drop falls from the initial temperature of the drop to the melting temperature and then eventually reaches the Leidenfrost temperature at which an ice sphere falls into the liquid nitrogen. The floating time of the water drop on the surface of liquid nitrogen corresponds to how long the temperature of the water drop takes to go from the initial temperature to the Leidenfrost temperature. We measured the floating time of the water drop on the surface of the liquid nitrogen as a function of the size of the drop and the initial temperature of the drop. The floating time increases linearly with increasing drop size and increases linearly with increasing initial temperature of drop, which can be explained reasonably well by assuming uniform cooling of the drop by heat conduction.

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I. INTRODUCTION

Levitation phenomenon of drops has been of interest for centuries. The film boiling of small droplets of liquid on a flat hot surface in the atmosphere is commonly called the Leidenfrost phenomenon. The behavior of the droplet on a heated surface was observed by using high-speed photography [1], and the vaporization of spheroidal drops undergoing film boiling was investigated [2]. The total evaporation times for many kinds of liquids, such as water, carbon tetrachloride, ethanol, benzene, and n-octane, on a stainless-steel plate at surface temperatures ranging from 150 °C to 500 °C were determined [3], and the scaling laws for the lifetimes of Leidenfrost drops were deduced [4]. The evaporation of a liquid nitrogen droplet levitated during film boiling above a solid surface was studied [5], and two helium drops did not coalesce because of the vapor layer between the drops, that layer being caused by the evaporation of the drops [6]. Helium droplets were generated from the surface of liquid helium by using a piezo transducer [7–10], and the evaporation of a drop in vapor was investigated [11]. The forces and associated governing equations for isothermal and nonisothermal spheres floating on the surface of liquid nitrogen were studied [12,13]. Molecular-scaled growth kinetics for the ice-water interface at the supercooling state was shown by using a molecular dynamics simulation [14]. The levitation condition of the water drop was derived from a force balance by equating the weight of the sphere to the vapor force, which was considered to be the dominant radial term, and the surface tension force [15].

In this research, we measured the floating time of water drops on the surface of liquid nitrogen as a function of the drop size and the initial temperature of the drop. A simple model was introduced to understand the floating phenomenon of a water drop on the surface of liquid nitrogen. The temperature of the water drop decreases from the initial temperature to the melting temperature and then to the Leidenfrost temperature. The floating time is expressed as the time that corresponds to how long it takes to go from the initial temperature to the Leidenfrost temperature. The floating time was measured as a function of drop size and initial temperature of the drop. The floating time increased linearly with increasing size of the drop and increasing initial temperature of the drop.
A drop of water floats on the surface of liquid nitrogen, where the sensible heat of the floating sphere evaporates the encompassing liquid. The heat passes from the warmer spherical drop and evaporates the liquid nitrogen beneath it, thereby forming a supporting nitrogen vapor layer under the sphere. The nitrogen vapor layer is, in turn, supported by the surface tension of the liquid nitrogen, which is at saturation temperature, $T_s$, of the sphere. The rate of heat change on the liquid nitrogen is
determined by assuming uniform sphere cooling in which the temperature of the sphere is inversely proportional to the thickness of the vapor gap. The evaporation rate also depends on the temperature of the sphere [15].

The rate of heat change for the vapor film can be written as

$$\frac{\partial Q}{\partial t} = -mC_p \frac{\partial T}{\partial t}|_{T \neq T_{\text{melt}}} + mL|_{T=T_{\text{melt}}}.$$  \hspace{1cm} (7)

The rate of heat change for the vapor film can be written as

$$\frac{\partial Q}{\partial t} = hA \Delta T,$$  \hspace{1cm} (8)

by considering the dominant radial component, the vapor force can be expressed as [15]

$$F_v = -0.39 \left( \frac{2 \eta_v}{\rho_v l} \right) \frac{\partial m}{\partial t},$$  \hspace{1cm} (5)

where $l$ is the film’s thickness, $ho_v$ is the vapor density, and $\eta_v$ is the vapor viscosity. The vapor force is proportional to the evaporation rate of the liquid nitrogen and inversely proportional to the thickness of the vapor gap. The evaporation rate also depends on the temperature of the sphere [15].

The heat change can be expressed in a general form:

$$\Delta Q = m \left[ L \delta (T - T_{\text{melt}}) + C_p \Delta T \right],$$  \hspace{1cm} (6)

where $\delta$ is the delta function, $T_{\text{melt}}$ is the melting temperature of the drop, $L$ is the latent heat of the drop, and $C_p$ is the specific heat of the drop at constant pressure. According to Eq. (6), the rate of heat change for the drop is

$$- \frac{\partial Q}{\partial t} = mC_p \left. \frac{\partial T}{\partial t} \right|_{T \neq T_{\text{melt}}} + mL|_{T=T_{\text{melt}}}.$$  \hspace{1cm} (10)

The rate of heat change between the drop and the liquid nitrogen is

$$hA \Delta T = L \frac{\partial m}{\partial t},$$  \hspace{1cm} (11)

where $\sigma$ is the surface tension of the liquid nitrogen.

II. THEORY

A drop of water floats on the surface of liquid nitrogen, where the sensible heat of the floating sphere evaporates the encompassing liquid. The heat passes from the warmer spherical drop and evaporates the liquid nitrogen beneath it, thereby forming a supporting nitrogen vapor layer under the sphere. The nitrogen vapor layer is, in turn, supported by the surface tension of the liquid nitrogen. The vapor film temperature, $T_f$, is assumed to be

$$T_f = \frac{T_d + T_s}{2},$$  \hspace{1cm} (1)

where $T_d$ is the temperature of the drop and $T_s$ is 77 K, the saturation temperature of the liquid nitrogen. The curvature of the liquid nitrogen under the sphere is assumed to be hemispherical, as shown in Fig. 1. Figure 1 shows a schematic diagram for the levitation of a water drop on the surface of liquid nitrogen.

The force balance, equating the weight of the sphere with the vapor force and the surface tension force, is given by a static force balance:

$$W_s = F_v + F_s,$$  \hspace{1cm} (2)

where $F_v$ represents the vapor force of the nitrogen gas and $F_s$ represents the surface tension force of the liquid nitrogen. The weight of the water drop is

$$W_s = 4 \pi R^3 \rho g d,$$  \hspace{1cm} (3)

where $R$ and $\rho dg$ are the radius and the density of the water drop, respectively. With consideration of the hemispherical shape of the liquid nitrogen under the drop, the surface tension force becomes

$$F_s = 2\pi R \sigma,$$  \hspace{1cm} (4)

where $\eta_v$ and $\rho_v l$ are the mass density and the thickness of the liquid nitrogen, respectively. The rate of heat change of the drop is

$$h = \frac{k_v}{R} + \left[ \frac{2 \eta_v \rho_v g l}{9 \eta_v R (T_d - T_s)} \left( 1 + \frac{C_p \Delta T}{2L} \right) \right]^{1/4},$$  \hspace{1cm} (9)

with $k_v$ being the thermal conductivity of the vapor, $C_p$ the specific heat of the vapor, and $T_d$ the temperature of the sphere. The rate of heat change on the liquid nitrogen, which is at saturation temperature, is

$$- \frac{\partial Q}{\partial t} = L \frac{\partial m}{\partial t}.$$  \hspace{1cm} (10)

The rate of heat change between the drop and the vapor film becomes

$$mC_p \left. \frac{\partial T}{\partial t} \right|_{T \neq T_{\text{melt}}} + mL|_{T=T_{\text{melt}}} = hA \Delta T.$$  \hspace{1cm} (11)

The rate of heat change between the vapor film and the liquid nitrogen is

$$hA \Delta T = L \frac{\partial m}{\partial t}.$$  \hspace{1cm} (12)

The vaporization rate can be determined by assuming uniform sphere cooling in which the temperature of the
sphere is the same everywhere and decreases uniformly as time goes. The evaporation rate changes with the sphere’s temperature. For the uniform drop cooling, the temperature of a water drop goes down from the initial temperature to zero Celsius, zero Celsius due to the latent heat, and then from zero Celsius to the Leidenfrost temperature at which the supporting vapor force decreases quickly. From Eq. (11), the time, \( t_{\text{sen}} \), from the initial temperature of the water drop, \( T_{\text{init}} \), to the melting temperature of the water, \( T_{\text{melt}} = 0 \) °C, is

\[
t_{\text{sen}} = \frac{m(C_p)_d(T_{\text{init}} - T_{\text{melt}})}{(hA)_d(T_{\text{melt}} - T_s)},
\]

where \((C_p)_d\) is the specific heat of the sphere. If the latent heat is considered, the time to freeze the entire sphere uniformly is

\[
t_{\text{melt}} = \frac{m_{\text{ice}}L}{(hA)_d(T_{\text{melt}} - T_s)}.
\]

With Eq. (11), the time for the sphere’s temperature to go from the melting to the Leidenfrost temperature is

\[
t_l = \frac{R(pC_p)_{\text{ice}}}{3h} \ln\left(\frac{T_{\text{melt}} - T_s}{T_{\text{LF}} - T_s}\right).
\]

As the temperature of the drop goes down, the evaporation rate goes down in three steps: the initial temperature to the melting temperature, the melting temperature to the Leidenfrost temperature, and the evaporation rate changes with the temperature of the water drop. Uniform drop cooling indicates that the temperature of the drop is the same everywhere in the sphere and decreases uniformly as a function of time, and non-uniform drop cooling exhibits a lower density compared to the liquid state. The floating time in Eq. (16) strongly depends on the size and the initial temperature of the drop.

III. EXPERIMENT

We used a typical liquid-nitrogen container to keep liquid nitrogen. A pipette was used to make water drops. The tips of the pipette had many different sizes, and the size of water drop was calculated by measuring the weight of the water drop. A hot plate was used to increase the temperature of the water in a glass container, and the temperature of the water was measured with a mercury thermometer. The bubbles generated under the surface of the liquid nitrogen reduce the floating time because they make the surface tension force and the vapor force unstable. In order to reduce the boiling of liquid nitrogen, we immersed a sheet of paper a couple of centimeters under the liquid surface. We left the water drop quickly just above the surface of the liquid nitrogen in order to measure the floating time accurately.

We measured the falling time as a function of the size of water drop as shown in Fig. 2. As the size of the drop increased, the levitation time of the drop increased. The initial temperature of the drop was 20 °C. The falling time was increased linearly with increasing size of the water drops, which is explained reasonably well by the theoretical prediction of Eq. (16) for uniform cooling of the drop. Uniform drop cooling implies that the temperature of the drop is the same everywhere in the sphere and decreases uniformly as a function of time, and non-uniform drop cooling indicates that the temperature of the drop depends on the radial distance from the center of the sphere and decreases faster on the surface and more slowly at the center of the sphere. This uniform drop cooling works for small drop radius below about 2 mm. For bigger drops, the correction for non-uniform cooling from the surface of the drop should be considered.

Figure 3 shows the falling time of water drops on
Fig. 3. The falling time of a drop is shown as a function of the initial temperature of the drop. The radius of the water drop was 1 mm. The line in the graph represents the theoretical prediction from Eq. (16). It shows the falling time increases linearly with a slope of $\frac{\partial t}{\partial T_d} = \frac{2R \rho_d (C_p) d}{3h}$ as the initial temperature increases.

IV. CONCLUSION

We have measured the floating time of water drops on the surface of liquid nitrogen as a function of the drop size and as a function of the initial temperature of the drop. The floating time increases linearly with increasing size of the water drop when the radius of the drop is below 2 mm. The floating time also increases linearly as a function of the initial temperature of the water drop. Our experimental measurement for the levitation of a water drop on the surface of liquid nitrogen is reasonably well explained by a simple heat conduction model.

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