Evaporation of liquid microdroplets levitated above a solid surface heated below the saturation temperature

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Abstract. This paper presents a study of the interaction of liquid microdroplets falling on a solid surface whose temperature is varied from 75 °C to 155 °C. It has been shown for the first time that droplet levitation above a solid surface is possible at a temperature below the saturation temperature. It has been found that for levitated droplets, the specific evaporation rate is constant in time, but for sessile droplets, it increases sharply. The evaporation rate for sessile droplet was found an order of magnitude higher than that for levitated droplets.

1. Introduction
Effective solutions for removing high-density heat fluxes are systems based on gas-droplet flows or sprays [1, 2, 3] as well as systems using two-phase flow in a microchannel [4, 5, 6]. The effectiveness of these methods can be impaired by the Leidenfrost effect [7]. Liquid microdroplets may not reach the heating surface, which can affect the cooling capacity. The behavior of liquid microdroplets falling on a solid surface heated below the Leidenfrost temperature (about 200 °C for water) is not well understood. At relatively low temperatures, droplet levitation [8, 9] can have a significant effect on the performance of two-phase cooling systems.

The objectives of this work were to study the properties of liquid microdroplets levitated above a solid surface heated below the saturation temperature and to compare the evaporation rate for levitated and sessile microdroplets.

2. Experimental setup and methods
The experimental setup is shown schematically in Fig. 1. The working section is made of stainless steel with an embedded copper rod with dimensions of 10x10 cm². The surface was heated by a Nichrome coil supplied with current from a power source. Substrate surface temperature was measured by thermocouples embedded in the copper rod. The surface temperature of the copper rod varied from 75 to 155 °C. The experiments were performed in the working section open to the...
atmosphere at an air temperature of 25–27 °C. Liquid microdroplets with a size of the order 10 µm were applied on the working surface by a spray device placed a few centimeters above the heating area. Droplets were examined over the surface of the copper rod. Room-temperature nanofiltered distilled water was used as the working fluid. The radius of droplets was varied from 5 to 23 µm and was measured from images obtained with a FASTCAM SA1.1 high-speed camera (5600 fps at a resolution of 1024x1024 pixels) coupled with a microscope objective. The optical resolution of the system was 0.78 µm/pixel.

![Figure 1. Schematic diagram of the experimental setup.](image)

### 3. Results

It has been found that microdroplets with size of the order 10 µm can levitate above the surface heated below the saturation temperature. The minimum recorded substrate temperature at which droplet levitation occurred was 75 °C, which is far below not only the Leidenfrost temperature for water but also the saturation temperature. Figure 2 shows a photograph of levitated droplets at a substrate temperature of 75 °C. Due to evaporation, the droplet size decreases with time. Depending on the substrate temperature the droplet life changes from 0.01 to 1 second.

![Figure 2. Levitated microdroplets and their reflection from the heated surface (for a droplet located at the center: r=5.4 µm, h=3.5 µm) at a substrate temperature of 75 °C.](image)
Figure 3 shows plots of the radius of an evaporating droplet versus time for different surface temperatures and initial droplet sizes. The plots were well fitted by linear relations. It can be seen that increasing the substrate temperature increases the slope of the plot and decreases the droplet lifetime.

![Figure 3](image-url)

**Figure 3.** Radius of a levitated droplet versus time at a substrate temperature $T= 155 \, ^\circ\text{C}$ (1), $135 \, ^\circ\text{C}$ (2), $93 \, ^\circ\text{C}$ (3), and $80 \, ^\circ\text{C}$ (4).

In Fig. 4, lines 2, 3, 4 and 5 show the specific evaporation rate of a droplet (droplet weight loss per unit time per unit surface area) versus time constructed from the approximating straight lines presented in Fig. 3. It can be seen that for levitated droplets, the specific evaporation rate does not change throughout the droplet evaporation process (for ease of comparison, the data in Fig. 4 are shown up to 0.01 second only). At the same time, the nominal value increases with increasing temperature. For comparison, the evaporation rate for a sessile droplet at the same surface temperature of $135 \, ^\circ\text{C}$ is plotted (line 1). It can be seen that the evaporation rate of the levitated droplet is an order of magnitude lower than that of the sessile droplet, which can significantly affect the performance of spray cooling systems. In the case of sessile microdroplets, the specific evaporation rate is not constant but increases rapidly with time. An increase in the specific evaporation rate was also observed in [10, 11] for relatively large sessile droplets (droplet size of several mm).
Figure 4. Specific evaporation rate of a droplet per unit surface area for a sessile droplet (1) at a substrate temperature of 135°C and for a levitated droplet at a substrate temperature of 155 °C (2), 135 °C (3), 93 °C (4), and 80 °C (5).

4. Conclusions

Liquid microdroplets falling on a solid surface have been studied experimentally and the following results have been obtained.

(1) Microdroplets with a size of order 10 µm can be levitate above a solid surface heated below the saturation temperature. The minimum temperature at which levitated droplets were observed was 75 °C, which is far below not only the Leidenfrost temperature, but also saturation temperature.

(2) For sessile microdroplets on the surface, the specific evaporation rate increases rapidly with time, while for levitated droplets, it is constant in time. The evaporation rate of levitated droplets is an order of magnitude lower than that of the sessile droplet.

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