The Effects of Nanoparticles on the Leidenfrost Phenomenon

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ABSTRACT

In this study, Leidenfrost experiments were conducted for water, Al_2O_3, and TiO_2 (0.1% and 0.4%) nanofluids. In our tests, a 20 μl test liquid is gently deposited on a horizontal heated aluminum surface. The evaporation time at various surface temperatures was recorded and plotted as evaporation curves. It is demonstrated that, for most nanofluids, the nanoparticles increase the Leidenfrost temperature and shorten the evaporation time. However, 0.1% TiO_2 nanofluid exhibits a Leidenfrost temperature lower than that of pure water and a longer peak evaporation time. Some explanations of this interesting discovery are explored and accessed. The effects of nanoparticles on the surface tension of the nanofluid and the particle diffusion of the nanofluid are discussed.

Keywords: Leidenfrost phenomenon, droplet evaporation, nanofluid

1 INTRODUCTION

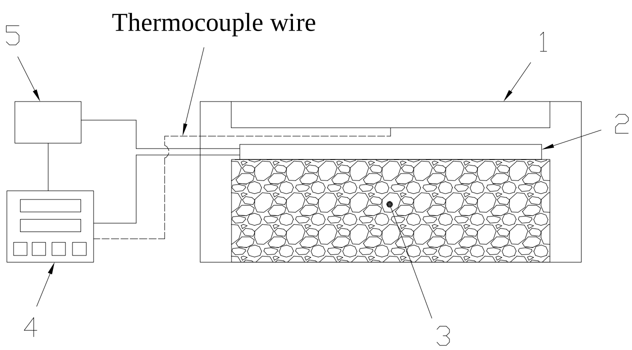
When small amount of liquid mass is deposited on a hot enough solid surface, the liquid may not evaporate rapidly as we expect. Instead, the liquid mass evaporates slowly with a vapor film beneath. This is called the Leidenfrost phenomenon. When the surface temperature is higher than the Leidenfrost temperature, the liquid mass evaporates slowly and can be explained as slow heat transfer. On the other hand, when the surface temperature is below the Leidenfrost temperature evaporates very quickly and represents a high heat transfer rate. Consequently, the Leidenfrost temperature defines the boundary between transition boiling regime with at least partial wetting of the surface, and film boiling regime in which the liquid is separated from the surface by a vapor film. The phase change heat transfer before the Leidenfrost transition is orders of magnitude higher than the value after the Leidenfrost phenomenon starts. Parameters influencing the Leidenfrost transition include size of the liquid mass, deposition velocity, liquid subcooling, solid thermal properties, surface roughness, liquid surface tension and additive. Also, Leidenfrost experiment can be an alternative solution for the pool boiling experiment, since it is easy to convert the evaporation curves derived from Leidenfrost experiments to the boiling curves from pool boiling experiments. The Leidenfrost experiment is also considers as a better simulation for the spray cooling. Overall, Leidenfrost phenomenon is not only a special behavior of liquid, but also a good performance evaluation of phase-change heat transfer.

Various nanoparticles have been added into fluids to form nanofluids. While most added nanoparticles are good thermal conductors, most nanofluids exhibits higher conductivities and/ or higher convection heat transfer coefficients. Little Leidenfrost experiments for nanofluids have been reported. In fact, some earlier investigations have explored the effects of dissolved gas and salt on the Leidenfrost transition for water solution. Jeschar et al. [1] designed quenching experiments by submerging a small nickel ball into solutions to determine the Leidenfrost temperature for a variety of water solutions with dissolved salt or gas. They found that all salts added lead to an increase in the Leidenfrost temperature, and the Leidenfrost temperature decreased with increasing amount of gas. While they offered a model for the formation and break down of the vapor film, and discussed the effects of dissolved gases, they did not explain the reason for the elevated Leidenfrost temperature resulting from the addition of salt. The effects of dissolved solids and gases on droplet boiling were comprehensively investigated by Cui et al. [2, 3], who observed the effect of dissolved Na_2CO_3, $NaHCO_3$, NaCl, Na_2SO_4, $MgSO_4$ and CO_2. The addition of salts was found to prolong the evaporation time when the surface temperature was too low to initiate nucleate boiling, but dramatically decreased the droplet lifetime in the nucleate boiling region. Suppression of bubble coalescence by the dissolved salt was suggested as the main reason for the nucleate boiling enhancement. In the film boiling regime, the evaporation curves for salt solutions were not shown due to severe droplet scattering. Besides salts and gasses, there is a fair amount of literature exploring the effects of surfactants which alter the surface tension. Qiao and Chandra [4] found that the addition of surfactants lowers the surface tension and decreases the Leidenfrost temperature. Due to the fast evaporation during the initial contact, it is also expected that some salt molecules do not diffuse fast enough and deposit on the surface. Cui et al. [2] estimated that the salt particles precipitating from the evaporating droplet serve as nuclei to trigger bubble formation and promote the nucleate boiling heat transfer. In addition, the deposition equivalently degrades the surface roughness and raises the Leidenfrost temperature.

In this study, experiments are intended to simulate Leidenfrost's original experiment to observe the effects of nanoparticles on the Leidenfrost phenomenon. Two kinds of nanoparticles, TiO_2 and Al_2O_3, are added into distilled water at two levels of concentration, 0.1 wt% and 0.4 wt%. Prepared fluids are deposited on a polished aluminum alloy 6061 heated surface. A precision syringe is used to deposit and control the droplet volume at 20 μl.

2 EXPERIMENTAL METHODS

The apparatus shown schematically in Figure 1 was used to investigate the Leidenfrost evaporation of liquids on a heated surface. The aluminum test plate was clamped to a 150 Watt plate heater. The plate is made of aluminum alloy 6061, and 150 mm in width, 150 mm in length, and 12 mm in thickness. To measure the evaporation time and to avoid liquid droplets running off the surface, a shallow concave spherical surface depression which were 50 mm in radius were machined into the surface. A hole is drilled from the back side of the plate and a groove are made for thermocouple installation. The thermocouple wire junction is placed 4 mm beneath the center of the concave region. The surface roughness for the concave region on the plate is 0.4 μm approximately. The schematic of the experimental apparatus is shown in Figure 1.



1: Test plate, 2: Heater, 3: Insulation Material, 4: PID Controller, 5: Solid-State Relay

Figure 1: Schematic of the experimental apparatus.

Before the experiments, the test solution was precisely mixed using reagent quality nanoparticles. Al_2O_3 and TiO_2 nanoparticles are chosen for this study due to its availability and good suspension in water. The diameter is 10-15 nm for Al_2O_3 particles, and 20 nm for TiO_2 particles. Referring to previous works in literatures, 0.1 and 0.4 % mass fraction are selected. After adding precise amount of nanoparticles, the nanofluid is processed with an ultrasonic resonator for the uniform dispersion of nanoparticles inside the nanofluid. The aluminum surface temperature is controlled by a numerical PID controller which senses the surface temperature detected by a K-type thermocouple installed 4 mm beneath the concave region where the liquid evaporation occurs. The controller modulates the on-off control for the plate heater to hold the surface temperature to within +/- 0.1˚C. The surface temperature is read from the display of the controller, and the accuracy is +/- 1˚C according to the manufacturer specification. For the initial experiments, the surface temperature was set in the nucleate boiling region. Once the set point temperature was achieved and the surface temperature was stable, liquid was deposited by a micropipette (precision syringe). The liquid volume for each droplet deposition is chosen as 20 μl. When the liquid was deposited, a digital timer was immediately started to measure the evaporation time. When experiments were completed at one surface temperature, the surface temperature was set 10°C higher, and the process was repeated until the surface temperature was high enough to result in a point in the stable film boiling region. When the surface temperature is higher than the Leidenfrost temperature, the deposited liquid forms a sphere or a spheroid, as shown in Figure 2.

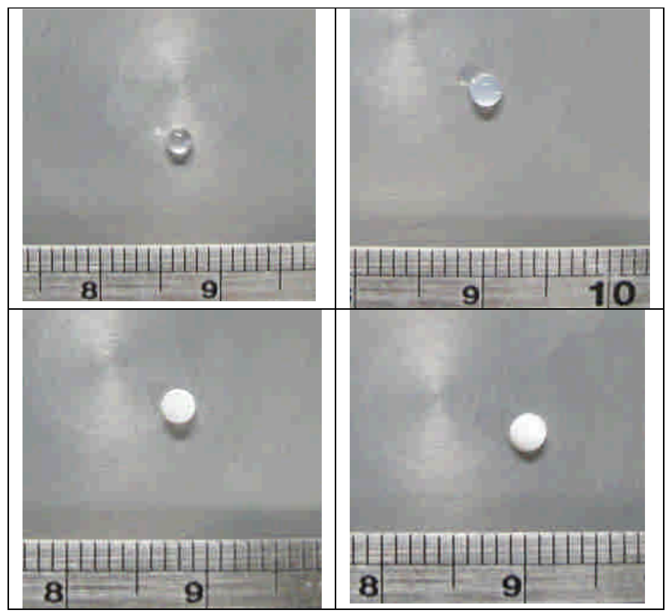


Figure 2: Photos of Leidenfrost droplets (top left: 0.1% Al_2O_3, top right: 0.4% Al_2O_3; bottom left: 0.1% TiO_2, bottom right: 0.4% TiO_2).

The uncertainty in determining the Leidenfrost temperature includes uncertainty of initial liquid amount, evaporation time, and surface temperature measurement. According to the manufacturer specification, each droplet is 20 μl with an accuracy of +/- 2% and a precision of +/- 1%. Over the range of surface temperatures tested, the uncertainty of temperature measurement is estimated as +/- 0.5 ˚C based on performance data for the numerical temperature controller. The surface temperature drop during the initial contact was less than 2°C. The maximum temperature drop happened in the nucleate boiling regime, and the temperature recovery time was one half of the evaporation. The time-averaged temperature drop is estimated as 0.5°C. The initial drop should be considered in the calculation of the temperature uncertainty. Overall, the temperature uncertainty in this study is estimated as +/-1°C. The uncertainty of evaporation time involved the final visible size of the liquid and how long it takes to evaporate. It is estimated that the uncertainty is less than 5%. After the equilibrium was achieved, temperatures at the four locations of the plate were recorded. The temperature difference from the four measurement locations of the plate provides the information to evaluate the surface temperature uniformity. It was estimated the surface temperature variation is less than 2˚C within the concave region on the plate.

Aluminum, upon exposure to oxygen or dry air at room temperature, forms a thin layer of amorphous native alumina. The thickness of alumina becomes 2 to 4 nm over several hours, and reaches a value of about 5 nm after a long time. Because of the oxide accumulation, various methods were tried to keep the surface condition consistent. Soft cloth cleaning with alcohol was utilized between each test. To avoid surface condition variation over time, test series with a particular solution were performed sequentially in rapid succession and series comparisons were performed back to back. Each evaporation curve shown in this study was from the manner described above. For each deposition liquid, multiple test series were performed.

3 RESULTS AND DISCUSSION

Results for pure water and the four nanofluids are exhibited as evaporation curves as shown in Figure 3 and Figure 4. The temperature of rapid raise of curves or the peak of the curve defines the Leidenfrost temperature. The acquired Leidenfrost temperatures and the corresponding evaporation times are listed in Table 1.

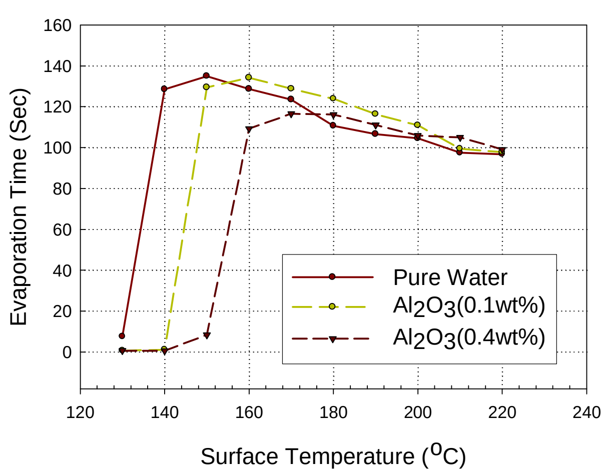


Figure 3: Evaporation curves of pure water and pure water with Al_2O_3 nanoparticles.

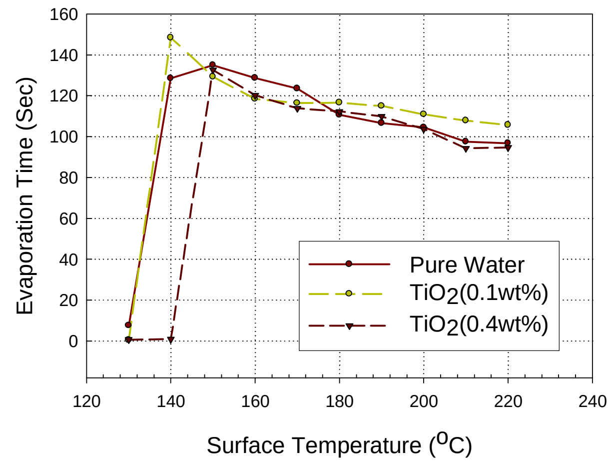


Figure 4: Evaporation curves of pure water and pure water with TiO_2 nanoparticles.

Table 1: Leidenfrost temperatures and the corresponding evaporation times of nanofluids tested in this study

Fluid	Leidenfrost Temperature (°C)	Leidenfrost Evaporation Time (sec)
Pure Water	150	135
Al_2O_3 (0.1%)	160	134
Al_2O_3 (0.4%)	170	117
TiO_2 (0.1%)	140	148
TiO_2 (0.4%)	150	133

Except 0.1% TiO_2 nanofluid, experimental results show that nanoparticles increase the Leidenfrost temperature, and decrease the evaporation time. It is noted that the short evaporation time of nanofluids should not be explained as a higher heat transfer rate. The decrease of evaporation time is mainly due to the increase of particle concentration near the bottom of the droplet and the subsequent vapor film collapse [5]. For both nanoparicles, it seems that higher nanoparticle concentrations lead to higher Leidenfrost temperatures and shorter evaporation times. For the same concentration, TiO_2 nanoparticles exhibit lower Leidenfrost temperatures and longer evaporation times.

Like salts, nanoparticles cannot be evaporated, and the residue can be found on the heated surface after the completion of the evaporation process. It is expected that nanofluids should have a Leidenfrost transition similar to water with dissolved salt. Huang and Carey [5] mentioned that the addition of dissolved salts increases the Leidenfrost temperature, and decreases the evaporation time. For the two nanoparticles tested in this study, Al_2O_3 shows a trend similar to the dissolved salts. However, TiO_2 nanofluid exhibits an unusual behavior. 0.1% Surprisingly, TiO_2 nanofluid even decreases the Leidenfrost temperature and prolongs the evaporation time.

Since the concentrations of nanofluids in this study are so low that they do not change any thermal properties too much, it is believed that the heat transfer area difference during the evaporation process is the key point to exhibit the variation of evaporation time. It is noted that 0.1% TiO_2 nanofluid keeps spherical during the evaporation time, but other nanofluids form a spheroid when the evaporation process is almost to the end. When the spheroid droplet evaporates completely, the residue is like a thin disk, as shown in Figure 5 and Figure 6. However, a spherical droplet leaves a solid ball-like residue as the 0.1% TiO_2 nanofluid shown in Figure 6. The heat transfer area for a sphere is less than a spheroid, and it seems to explain why the 0.1% TiO_2 exhibits the longest peak evaporation time.

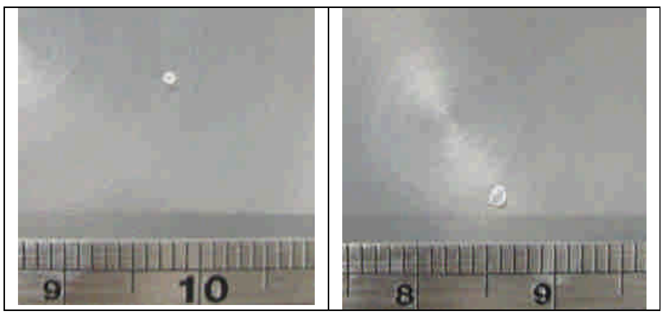


Figure 5: Residue after the complete evaporation of a Al_2O_3 nanofluid droplet (left: 0.1%, right: 0.4%)

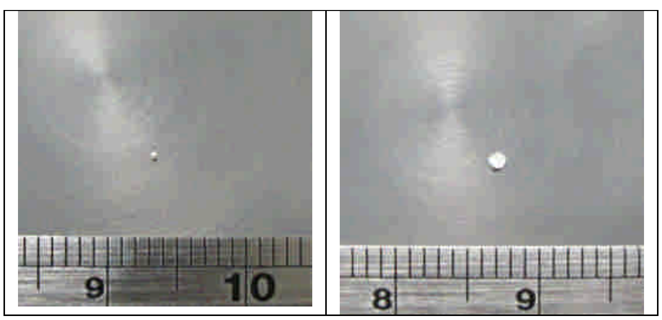


Figure 6: Residue after the complete evaporation of a TiO_2 nanofluid droplet (left: 0.1%, right: 0.4%)

The shape of the deposition droplet is mainly determined by the surface tension of the nanofluid. TiO_2 nanofluid may have a special surface tension to ensure spherical droplet at the 0.1% concentration. Or, the spherical form is from a special nanoparticle concentration inside the droplet.

The diffusion of nanoparticles inside the nanofluid droplet also affects the residue left during the initial liquid-solid contact. It has been found that the solid deposition during the initial contact may serve as the nucleation sites, inducing nucleate boiling and making the Leidenfrost transition starting at a higher surface temperature [2, 5]. It seems like the diffusion rate of TiO_2 nanoparticles in water is higher than that of Al_2O_3. Consequently, TiO_2 nanoparticles diffuse into the rest liquid part during the initial liquid-solid contact more successfully, and the nanoparticle residue left is less. The less initial contact residue helps to exhibit a lower Leidenfrost temperature, which can be seen in Figure 4.

4 CONCLUDING REMARKS

Al_2O_3 and TiO_2 nanofluids are used to performed the Leidenfrost experiments. Results are shown in evaporation curves, and the Leidenfrost temperature are determined. According to the results, some conclusions are following:

(1) The effects of nanoparticles are almost similar to the effects of dissolved salts to the Leidenfrost phenomenon. The Leidenfrost temperature increases, and the evaporation time decreases.

(2) 0.1% TiO_2 nanofluid forms a sphere during the whole evaporation process, and the spherical shape is believe as the reason of longer evaporation time.

(3) TiO_2 nanoparticles seem to have a better diffusion rate in water. It is then believed that the better diffusion leads to less initial residue and lower Leidenfrost temperature.

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