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The effects of dissolved salt on the Leidenfrost transition

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Abstract

In this study, Leidenfrost experiments were conducted for water, NaCl, and KCl aqueous solutions at atmospheric pressure. In our tests, a 1.1 g test liquid was gently deposited on a horizontal heated aluminum surface. The evaporation time at various surface temperatures was recorded and plotted as evaporation curves. To examine the relationship between bubble coalescence, dissolved salt and the Leidenfrost transition, test surfaces were fabricated with arrays of small holes serving as artificial nucleating sites. Cavity spacing is 1 mm or 2 mm. It is demonstrated that the dissolved salt increases the Leidenfrost temperature. Mechanisms associated the Leidenfrost transition, such as suppression of bubble coalescence, variation in properties and salt deposition during the initial liquid–solid contact, are explored and accessed.

Keywords: Leidenfrost evaporation; Dissolved salt; Bubble coalescence

1. Introduction

Spray cooling is widely applied in industry for cooling of hot surfaces. In the processing of metallic alloys, the cooling rate of the process influences several properties and qualities after the process. Taking aluminum quenching as an example, it is desirable to keep the cooling process in the Leidenfrost film boiling regime for a longer period of time to ensure less warping and failure [1]. However, water used in industries usually contains dissolved gases or ionic solids from the piping system or the processing environment. It has been found that even slight variations in the water quality affect the heat treatment result [2]. Apparently, understanding the relationship between water quality and heat transfer is essential to optimize the heat treatment process.

Some earlier investigations have explored the effects of dissolved gas and salt on the Leidenfrost transition for water solution. Jeschar et al. [3] 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. [4,5], 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.

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Nomenclature

At	atomic weight of surface material
β	surface thermal parameter, $(k_s\rho_s C_{p,s})^{-1}$
C_p	specific heat at constant pressure
D	diffusion coefficient
ΔT	driving temperature
g	gravitation acceleration
H	height of the spheroid
h	latent heat
i	dissociation constant
k	thermal conductivity
q''	heat flux
R	radius of the spheroid
σ	surface tension
T	temperature
ρ	density
μ	dynamic viscosity
υ	kinematic viscosity

Subscripts

B	Berenson's model
b	boiling point
bp	bubble point (boiling point of mixture)
c	critical point
CHF	critical heat flux point
i	initial state, interface
l	saturated bulk liquid
Leid	Leidenfrost point
MFB	minimum film boiling point
ml	molality
s	solid surface
sat	saturation property
v	saturated bulk vapor
w	wall

Besides salts and gasses, there is a fair amount of literature exploring the effects of surfactants which alter the surface tension. Qiao and Chandra [6] found that the addition of surfactants lowers the surface tension and decreases the Leidenfrost temperature.

Theories based on hydrodynamic instability, homogeneous and heterogeneous nucleation, thermo-mechanical effect and wettability were utilized to construct models to predict the minimum film boiling temperature. Bernardin and Mudawar [7] summarized existing theoretical models and semi-empirical correlations for the Leidenfrost temperature and the minimum film boiling temperature for pool boiling. While some models are unable to accurately predict the Leidenfrost temperature, they offer insights about parameters affecting the transition. One of the most common Leidenfrost temperature correlations was derived by Baumeister and Simon [8]. The mathematical form is as follows:

$$T_{\mathrm{Leid}} = T_{\mathrm{l}} + \frac{0.844T_{\mathrm{c}}\left\{1 - \exp\left[-0.016\left[\frac{(\rho_{\mathrm{s}}/\mathrm{At})^{1.33}}{\sigma_{\mathrm{f}}}\right]^{0.5}\right]\right\} - T_{\mathrm{l}}}{\exp\left(3.066\times 10^{6}\beta\right)\mathrm{erfc}\left(1758\sqrt{\beta}\right)} \tag{1}$$

Berenson [9] presented a minimum film boiling model based on analysis of Taylor instability that yielded the following expression for the minimum film boiling temperature:

$$T_{\mathrm{MFB}} = T_{\mathrm{sat}} + 0.127\frac{\rho_{\mathrm{v}}h_{\mathrm{lv}}}{k_{\mathrm{v}}}\left(\frac{g(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})}{\rho_{\mathrm{l}}+\rho_{\mathrm{v}}}\right)^{2/3} \times\left(\frac{\sigma}{g(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})}\right)^{1/2}\left(\frac{\mu_{\mathrm{v}}}{g(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})}\right)^{1/3} \tag{2}$$

Henry [10] constructed his model based on the Berenson's model with wall effects. This yielded the relation

$$T_{\mathrm{MFB}} = T_{\mathrm{MFB,B}} + 0.42(T_{\mathrm{MFB,B}} - T_{\mathrm{l}}) \times\sqrt{\frac{k_{\mathrm{l}}\rho_{\mathrm{l}}C_{p\mathrm{l}}}{k_{\mathrm{w}}\rho_{\mathrm{w}}C_{p\mathrm{w}}}}\left[\left(\frac{h_{\mathrm{lv}}}{C_{p\mathrm{w}}(T_{\mathrm{MFB,B}} - T_{\mathrm{sat}})}\right)\right]^{0.6} \tag{3}$$

where the $T_{\mathrm{MFB,B}}$ is the T_{MFB} given by the Berenson's correlation, Eq. (2). Recently, Bernardin and Mudawar [11,12] presented their Leidenfrost point models by considering the cavity activation and bubble growth. Using suitable assumptions and parameters extracted from the experimental data and photography, the resulting models provide good prediction of the Leidenfrost temperature for FC-72 and water droplet with or without initial velocity on various surfaces.

As revealed by Bernardin and Mudawar [7], most current models and correlations fail to accurately predict the Leidenfrost temperature. In this study, the model proposed by Bernardin and Mudawar [11,12] was utilized to analyze the effect of dissolved salt. The Leidenfrost transition is hypothesized as the following scenario. When the liquid is first deposited, it is expected that gravity will cause the liquid to contact the surface. Upon the initial contact, bubbles nucleate and grow from the activated cavities. If the surface temperature is at or above the Leidenfrost temperature, the generated bubbles quickly merge into a vapor film which establishes a pressure field supporting the deposited liquid. Based on the bubble nucleation assumption, the amount of cavities and distance between cavities may affect the onset temperature of liquid levitation. On an extremely smooth and cavity-free surface, it is expected that the Leidenfrost temperature will be very high, almost equal to the superheat for the spontaneous nucleation. Introducing cavities and arranging those cavities in suitable spacing, bubbles are able to nucleate from the cavities, grow, merge with nearby bubbles, and form a stable film. On such a surface, the measured Leidenfrost temperature is much lower than the value on the extremely smooth surface. However, further increasing cavity density or placing excess amount of cavities does not keep decreasing the Leidenfrost temperature. A porous surface can be seen as the extreme condition where there are a huge number of cavities on the surface. Chandra and Avedisian [13] tested droplet boiling on a porous surface, and found the droplet still could not levitate when the surface temperature was 250 °C. They believed that the porous surface offers more pathways for vapor to escape, and a higher surface temperature is necessary to compensate the vapor loss. The porous surface can also be seen as a surface with high roughness. Experimental investigations [7,14–16] reported that increasing surface roughness led to a higher Leidenfrost temperature, and the trend agrees with the very high Leidenfrost temperature on a porous surface. In short, when cavity spacing is less than the bubble departure diameter, excess cavities apparently increase the surface roughness which has been shown to increase the Leidenfrost temperature. At room temperature, experimental results imply that some electrolytes do retard the coalescence [17]. Based on this observation, bubble merging may be inhibited by dissolved salt, with the effect that Leidenfrost transition cannot be achieved at the corresponding surface temperature. The net result is that a higher surface temperature is necessary to start the Leidenfrost transition. 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. [4] 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. Moreover, the dissolved salt alters some properties in the liquid–vapor system, including surface tension, saturation temperature and liquid density. Surface tension is sensitive to the type of dissolved salt and the concentration [18]. For most salts, the solution surface tension increases with increasing concentration. From Eqs. (1)–(3), it seems apparent that the Leidenfrost temperature is a function of surface tension. From experiments with addition of a surfactant [6], addition of a salt should alter the surface tension, and decrease the Leidenfrost temperature. Clearly, the Leidenfrost temperature seems to be affected by the surface tension. It is also known that salt solutions have higher boiling points and densities than pure water. Raoult's law describes the boiling point elevation of solutions in the following equation:

$$\Delta T_{\mathrm{b}} = i \cdot k_{\mathrm{b}} \cdot m_{\mathrm{ml}} \tag{4}$$

where i is the dissociation constant (2 for NaCl and KCl), k_{b} is the boiling point elevation constant (0.512 for water solutions), and m_{ml} is the solution concentration in molality (mole/kg). Berenon's, Eq. (2), and Henry's, Eq. (3), correlations are obvious functions of T_{sat} and liquid density. Due to the mechanism similarity between the Leidenfrost temperature and the minimum film boiling temperature, it is reasonable to expect that addition of salts will change the Leidenfrost temperature by raising the boiling point and the density of the solution.

In this study, the experiments conducted were specifically aimed at determining whether additives affecting the Leidenfrost transition by inhibiting the bubble merging or by other mechanisms. Three series of Leidenfrost evaporation experiments were performed. Evaporation curves were plotted, and the Leidenfrost temperatures were determined. The first series, in which water and dilute salt solutions were deposited on aluminum alloy surfaces with artificial cavity arrays, was designed to investigate the effect of the bubble coalescence. Two salts, sodium chloride or potassium chloride, and two sets of cavity spacing, 1 mm and 2 mm, formed the experimental matrix. Cavities were added to the surface to act as artificial nucleation sites during the initial liquid contact. If the spacing is close enough, two bubbles generated at adjacent sites can merge together before they depart from the surface. If the site has too large a spacing, the merging may be impossible. The two salts tested provided different levels of surface tension and bubble coalescence effects. In the second test series, droplets of water and 2-propanol aqueous solutions were deposited on an aluminum alloy surface without artificial cavities. These experiments were designed to investigate the role of surface tension by altering it with a surfactant. In the third series of experiments, distilled water tests were performed after a layer of salt was deposited on the surface. These tests of distilled water on the pre-deposited surface provided insight into the role of salt deposition. Based on the experimental results, the possible mechanisms responsible for increasing the Leidenfrost temperature for water with dissolved salt were explored and accessed. Details of the experiments are described in the next sections.

2. Experimental methods

The apparatus shown schematically in Fig. 1 was used to investigate the Leidenfrost evaporation of liquids on a heated surface. The aluminum test plate was clamped to the heater surface. Two test plates were fabricated for the Leidenfrost experiments. The plates were made of aluminum alloy 6061. The plates were 159 mm in width, 159 mm in length, and 9.5 mm in thickness. To measure the evaporation time and to avoid liquid droplets running off the surface, shallow concave spherical surface depressions which were 38 mm in radius were machined into the surfaces (see photograph in Fig. 2). Four deep holes were drilled from the sides of the plates for thermocouple installation. Two of the four thermocouple wire junctions were placed 3.175 mm beneath the central points of the two concave regions. The surface roughness for the concave region on the plates is 0.8 μm approximately.

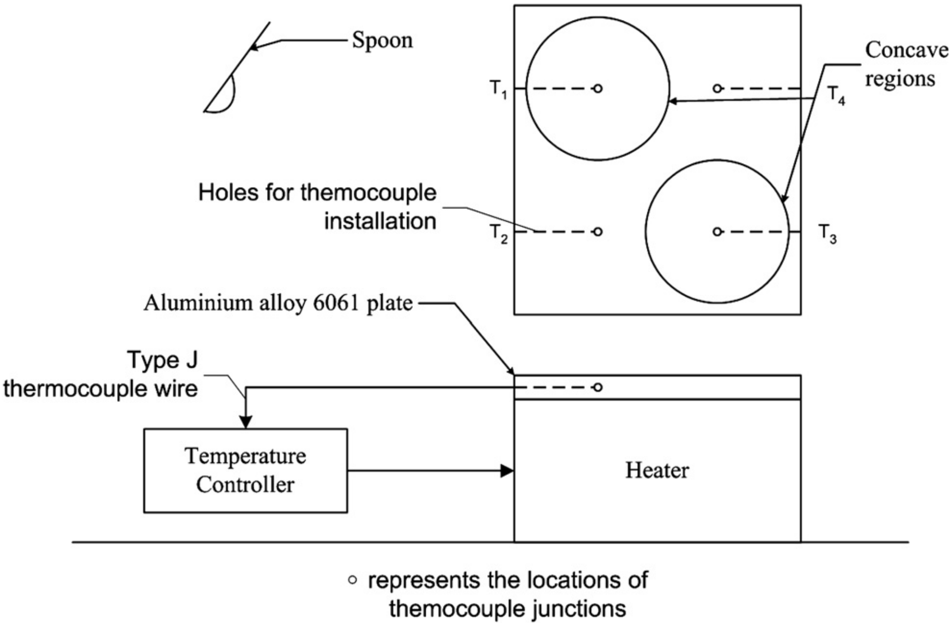

Fig. 1. Schematic diagram of the experimental apparatus.

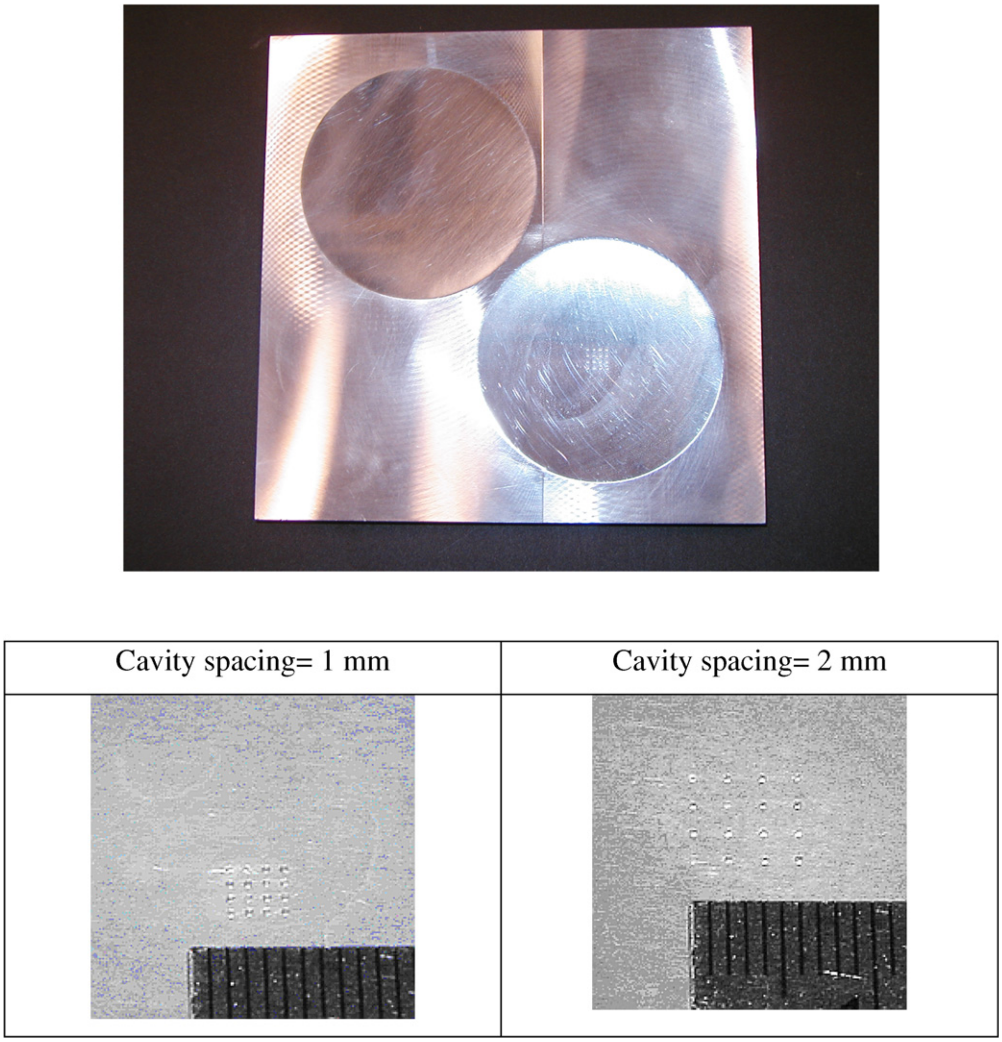

Fig. 2. (Top) Photograph of the test plate. (Bottom) Magnified view of cavity spacing.

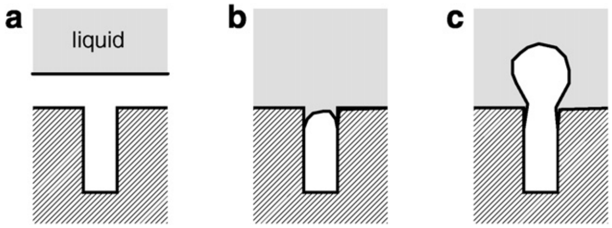

Fig. 3. Schematics of the bubble nucleation in the cavity on the concave region.

To investigate the effect of bubble coalescence, some test surfaces were manufactured with artificial cavities. Artificial cavity arrays were formed by fabricating small holes (0.5 mm in diameter and depth). The holes were expected to serve as artificial nucleation sites when the deposited liquid initially contacts the surface just after deposition. As shown in Fig. 3(a), initially the drilled cavity is dry and the droplet is not yet in contact with the surface. At $0.9T_{\mathrm{crit}}$, which is about the Leidenfrost temperature, the most dangerous wavelength for Taylor instability is about 15 mm, so the water interface is expected to bridge the drilled cavity opening when the liquid first contacts the surface. When contact is made (see Fig. 3(b)) the liquid will try to wet the wall of the drilled cavity and penetrate to the bottom. However, for the conditions near the Leidenfrost point in experiments in this study, the wall of the cavity will be very hot, and rapid vaporization of liquid near the contact line is expected to rapidly produce vapor. This will result in growth of a bubble (see Fig. 3(c)) from the mouth of the drilled cavity before the liquid penetrates all the way to the bottom. Therefore, the cavities were expected to always be active nucleation sites. Cavity arrays with different spacings were drilled on the concave region of the surface (see Fig. 2). When the spacing is shorter than the bubble departure diameter, two adjacent bubbles are likely to merge. If cavities are too far apart, the generated bubbles can depart from the cavity on the solid surface without coalescence. The different array spacings are therefore expected to produce different coalescence behavior. In this study, two cavity arrays with cavity spacings, 1 and 2 mm, were fabricated on the two concave regions of the test plate respectively.

Before the experiments, the test solution was precisely mixed using reagent quality materials. The aluminum surface temperature was controlled by a numerical temperature controller which sensed the surface temperature detected by a J-type thermocouple embedded 3.175 mm beneath the concave region where the liquid evaporation occurred. The controller modulated the on–off control for the plate heater to hold the surface temperature to within ±0.1 °C. The surface temperature was 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 or spoon, depending on amount of deposited liquid. A plastic spoon was selected because of its low surface energy and quick liquid deposition. A larger amount of liquid was used in the experiments to investigate the suppression of bubble coalescence with addition of salt. The amount was chosen so that the initial amount of liquid would cover all artificial nucleation sites. Due to the larger amount of deposited liquid, the liquid formed a spheroid, instead of a spherical droplet, when it was deposited on the surface with its temperature higher than the Leidenfrost temperature.

The uncertainty in determining the Leidenfrost temperature includes uncertainty of initial liquid amount, evaporation time, and surface temperature measurement. The spoon filled with liquid was weighed by a precision balance. In all tests, the weight of liquid deposited by spoon was 1.1 ± 0.05 g. Over the range of surface temperatures tested, which is 200–300 °C, 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, with a radius of 38 mm, on the plates.

When the liquid was deposited, a digital timer was immediately started to measure the evaporation time. The vaporization process was also visually observed or recorded by a digital video camera. 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. Aluminum, upon exposure to oxygen or dry air at room temperature, forms a thin layer of amorphous native alumina. The thickness of alumina becomes 2–4 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. For salt solution tests, salt was left on the surface after complete evaporation. In these cases, oxidation seemed more substantial, and a more thorough cleaning was necessary. The test slab was cooled, flushed with tap water to remove salt, cleaned

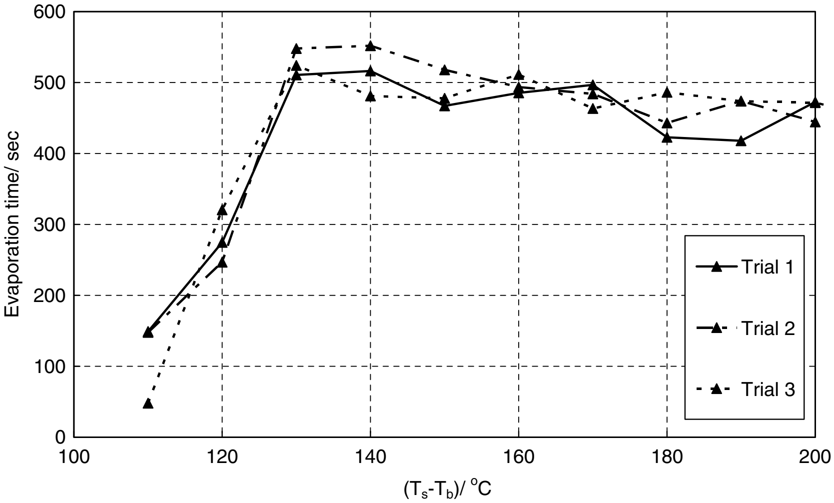

Fig. 4. Variation of evaporation time with surface superheat for three different series of experiments of distilled water deposited on an aluminum alloy 6061 surface.

with alcohol, and reheated to the desired temperature. 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. While the each evaporation curve shown in this study was from the manner described above. For each deposition liquid, multiple test series were performed. Fig. 4 shows the evaporation curves from three different series and exhibits a good repeatability.

3. Results and discussion

In previous studies reported in the literature [4], the suppression of bubble coalescence was estimated as the main reason for the elevated Leidenfrost temperature of salt solutions. To examine this hypothesis, Leidenfrost experiments were performed on surfaces with artificial cavities. With different cavity spacings, bubble coalescence was expected to occur at short cavity spacing at lower temperatures, but not occur at long spacings until higher surface temperatures were reached.

Leidenfrost experiments for distilled water were performed on the surfaces with a cavity spacing of 1 or 2 mm. Experimental results from this series of experiments were expected to provide some indications of the effects of cavity spacing and provide the baseline for later comparisons with experiments with salt solutions. Fig. 5 presents the comparison of distilled water evaporation times on surfaces with 1 or 2 mm cavity spacing. NaCl and KCl solutions were also tested on the surfaces with cavity spacings of 1 and 2 mm. The corresponding evaporation curves are shown in Fig. 6. The observed Leidenfrost temperatures for the distilled water and the salt solutions are listed in Table 1. In each cell, the value is averaged from those,

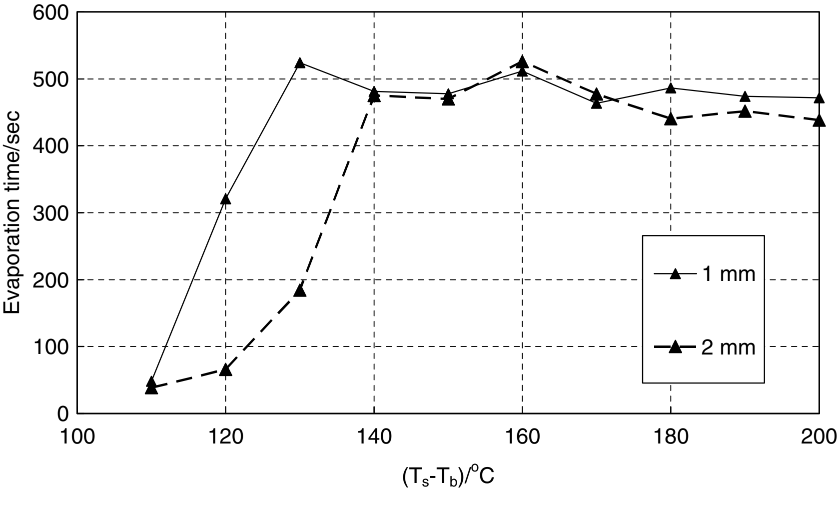

Fig. 5. Variation of evaporation time with surface superheat for distilled water deposited on an aluminum alloy 6061 surface with 1 or 2 mm cavity spacing.

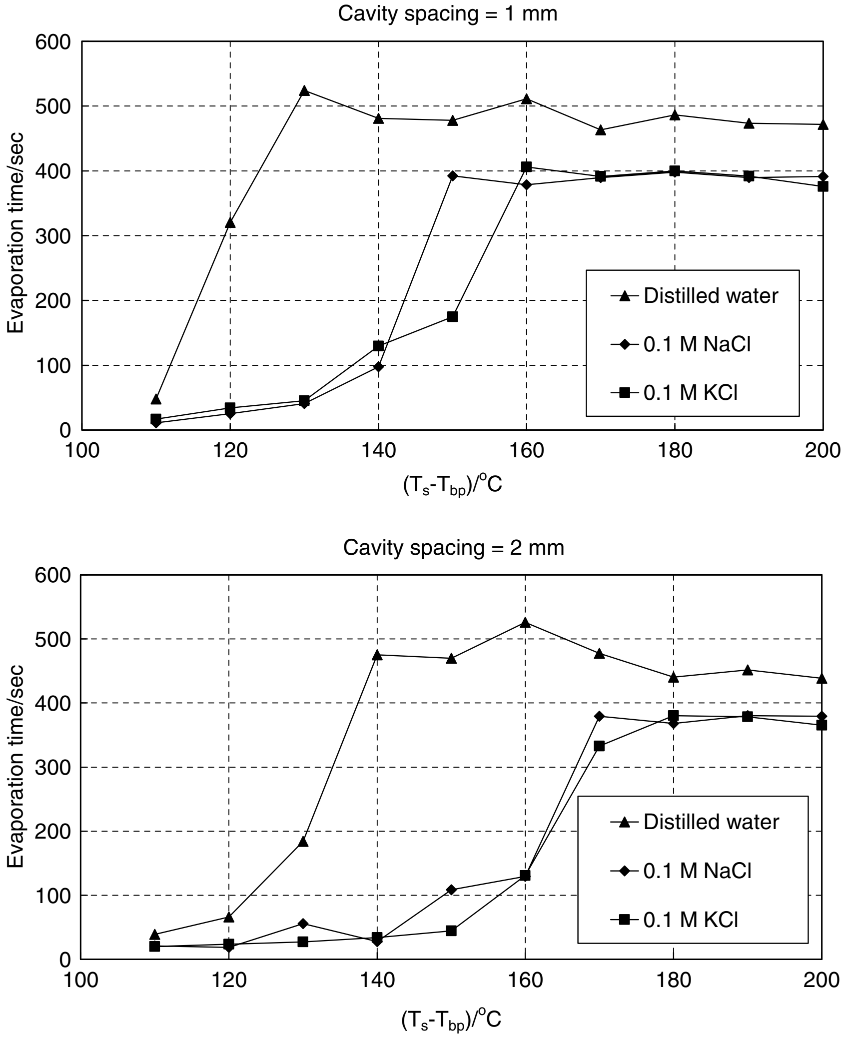

Fig. 6. Variation of evaporation time with surface superheat for distilled water and water with dissolved salt deposited on an aluminum alloy 6061 surface.

Table 1
Experimental determined Leidenfrost temperatures for various liquids

Cavity spacing, mm	The temperature of at the greatest evaporation time, °C		
	Distilled water	0.1 M (1.88×10^{-3} molar fraction) NaCl sol.	0.1 M (1.88×10^{-3} molar fraction) KCl sol.
1	240 [230, 240, 240,250]	250	260
2	243 [230, 240, 260]	270	280

which were from other series of tests, in the square brackets.

As indicated in Table 1, the average Leidenfrost temperatures for salt solutions were roughly 10–33 °C higher than the value for distilled water. The results agree with previous experimental studies. Jeschar et al. [3] conducted experiments by immersing a small nickel ball into a pool of liquid. They tested a variety of salts and found 600 mg/l NaCl solutions have Leidenfrost temperatures 30 °C higher than distilled water. Cui et al. [5] conducted droplet evaporation experiments for low concentration (<0.1 M) salt solutions deposited on a stainless steel plate and reported that solutions significantly reduce the droplet lifetime significantly in the nucleate boiling regimes. This trend is also observed in our data in the low surface temperature region of Fig. 6. Our experiments for distilled water and salt solutions show that all tested liquids on the surface with the 2 mm cavity spacing resulted in relatively higher Leidenfrost temperatures. Comparing the two salt solutions, the KCl solution produces a higher Leidenfrost temperature than the NaCl solution on both surfaces.

3.1. Bubble coalescence

Closer cavity spacing is expected to ensure that bubbles merge before departure, which tends to lower the

Leidenfrost transition temperature. Mei et al. [19] developed a model of bubble growth in heterogeneous pool boiling. They found that the bubble departure diameter for water was estimated to be 0.85 mm. Their result supports the assumption that bubble coalescence likely occurs on the surface with 1 mm cavity spacing. For the 2 mm cavity spacing, cavities apparently are too far apart for bubbles to merge before departure. This explains why the surface with 1 mm cavity spacing generally exhibited a lower Leidenfrost temperature. This also explains the smaller increment on the Leidenfrost temperature for salt solutions on the 1 mm cavity spacing surface, since the suppression of bubble coalescence by the dissolved salt will weaken the bubble merging mechanism. On the other hand, addition of salts tends to further increase the Leidenfrost temperature even on the surface with 2 mm cavity spacing, where cavities are too far apart for bubbles to easily merge.

It is noteworthy that, for each tested liquid, the difference between the Leidenfrost temperatures for the two surfaces is about 10–13 °C, despite whether bubbles are able to easily coalesce or not. This seems to suggest that, if the addition of salt does nothing but inhibit the bubble coalescence, the Leidenfrost temperature variation should be around 10–13 °C only. In contrast to 20–40 °C of the observed increment in Fig. 6, it seems to imply that the suppression of bubble coalescence by the dissolved salt is only partially responsible for the elevated Leidenfrost temperature. There should also be other mechanisms associated with the transition. Some other possible mechanisms are discussed below.

3.2. Variation of properties

For the distilled water, and the NaCl and KCl solutions, the calculated Leidenfrost temperatures and minimum film boiling temperatures from Eqs. (1)–(3) are listed in Table 2. The boiling point elevation is calculated from Raoult's law. The surface tension variations of the salt solutions are from Weissenborn and Pugh [18]. Fig. 7 shows the surface tension variations of NaCl and KCl solutions. Because of the low salt content in the two tested solutions, the variations of properties due to salt addition are small. The increment of surface tension is 0.2 and 0.18 m N/m for 0.1 M NaCl and KCl solution, respectively. The variations of liquid density and boiling point are also small.

Table 2
Comparison of distilled water, 0.1 M (1.88×10^{-3} molar fraction) NaCl and KCl solution

	Distilled water	0.1 M (1.88×10^{-3} molar fraction) NaCl solution	0.1 M (1.88×10^{-3} molar fraction) KCl solution
Density, kg/m^3	958.3	964.2	965.8
Surface tension, m N/m	58.91	59.11	59.09
Boiling point at 1 atm, °C	100.0	100.1	100.1
T_{Leid} from Baumeister and Simon's, Eq. (1), °C	156.7	156.3	156.4
T_{MFB} from Berenson's, Eq. (2), °C	186.4	186.2	186.1
T_{MFB} from Henry's, Eq. (3), °C	246.0	245.9	245.8

At 20 °C, solubility of NaCl solution: 6.11 M (9.9×10^{-2} mole fraction); solubility of KCl solution: 4.68 M (7.8×10^{-2} mole fraction).
At 100 °C, solubility of NaCl solution: 6.35 M (1.0×10^{-1} mole fraction); solubility of KCl solution: 7.15 M (1.1×10^{-1} mole fraction).

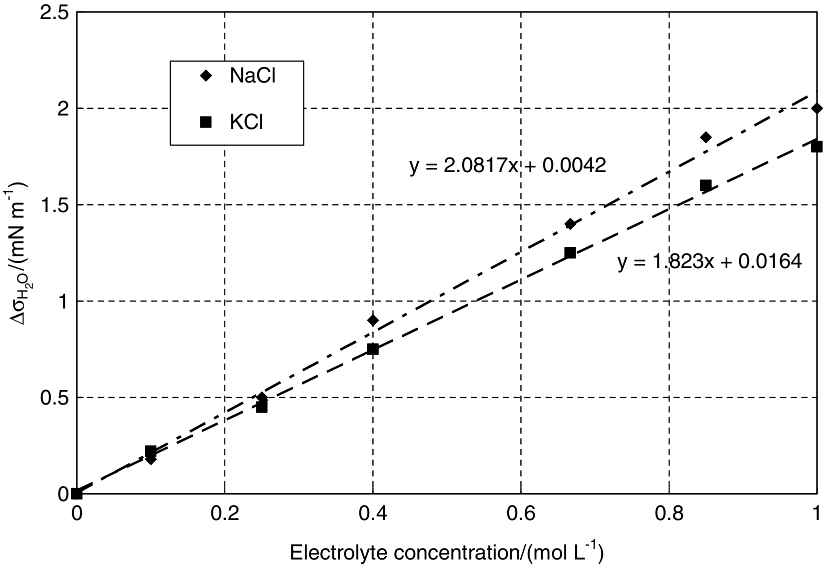

Fig. 7. Change in surface tension relative to distilled water varied with electrolyte concentration. Equations are from linear regression for the data points of the corresponding electrolyte.

From the correlations reported in earlier studies, the calculated Leidenfrost temperatures and minimum film boiling temperatures for salt solutions are predicted to be only slightly lower than the value for distilled water (see Table 2). Based on such results, those correlations seem to suggest that the addition of salt lowers the Leidenfrost temperature. This is contradictory to the trend observed in previous experimental investigations and experimental results from this study. This suggests that the current correlations lack the ability to accurately account for the addition of salt.

Qiao and Chandra [6] used sodium dodecyl sulphate as the surfactant to decrease the surface tension of water from 73 to 50 m N/m. Their tests show that the Leidenfrost temperature decreased by about 45 °C because of the 23 m N/m reduction of the surface tension. In our study, 2-propanol was selected to be the surfactant. At 0.01 mole fraction, the solution surface tension decreases by 37 m N/m. The evaporation curves of distilled water and 0.01 mole fraction 2-propanol aqueous solution are shown in Fig. 8 (For details, see [20]). Due to the addition of 2-propanol, the Leidenfrost temperature decreases by 40 °C, which is qualitatively consistent with the results from Qiao and Chandra [6]. Presumably, the proportionality between the change of the surface tension and the Leidenfrost temperature variation is the same for the 2-propanol solution and the salt solution. Based on that assumption, the Leidenfrost temperature of the 0.1 M (1.88×10^{-3} molar fraction) NaCl or KCl solution should show an increase of less than 1 °C because of the surface tension variation. At the selected salt concentration, the elevation of the Leidenfrost temperature due to the increase of surface tension is expected to be very small.

Because of the slow salt diffusion in water ($Sc = 540$), salt concentration at the liquid–vapor interface may increase substantially as the evaporation proceeds. When the liquid mass has been levitated on the vapor film, water evaporating near the bottom of the liquid mass increases the salt concentration from the liquid–vapor interface. We have used a one-dimensional transient model to estimate the concentration increase. Assuming the heat flux from the surface is 2×10^4 W/m^2 which is around the minimum heat flux in the pool boiling, the model shows that the interface concentration increases to 30 M (0.36 molar fraction) in 326.5 s. Based on Raoult's law, the boiling point elevation is around 30 °C when the concentration increases to 30 M (0.36 molar fraction). It is noteworthy that the Leidenfrost temperature difference between distilled water and salt solution (see Fig. 6) is very close to the boiling point elevation when the concentration is 30 M (0.36 molar fraction). It is also anticipated that the variations of properties are no longer negligible when salt concentration increases from 0.1 M (1.88×10^{-3} molar fraction) to 30 M (0.36 molar fraction). The details of the model and the concentration profile calculation have been documented [21].

3.3. Salt deposition during the initial liquid–solid contact

Since salt is not volatile, deposited salt residue is always generally found after the liquid mass completely evaporates. We also expect that salt may deposit on the surface during the initial contact of the liquid with the surface. To explore the effect of initial salt deposition, a pre-deposition procedure was designed to evaluate the salt deposition during the initial liquid–solid contact to determine whether it was an important factor resulting in the elevated Leidenfrost temperature. Salt solution was first deposited on a clean surface where the surface temperature was higher than the Leidenfrost temperature of the corresponding solution and concentration. In this study, 0.1 M (1.88×10^{-3} molar fraction) salt solution was pre-deposited at 280 °C, and 0.5 M (9.32×10^{-3} molar fraction) was pre-deposited at 330 °C.

Once the solution contacted the surface and appeared levitated (i.e. completion of the initial unstable period), it was blown away with an air jet. When 0.1 M (1.88×10^{-3} molar fraction) NaCl or KCl solution was

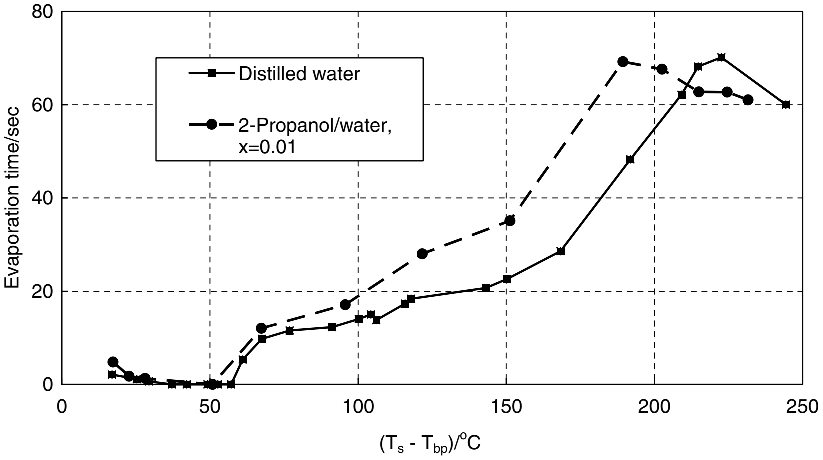

Fig. 8. Variation of evaporation time with surface superheat for distilled water and 0.01 mole fraction 2-propanol aqueous solution of 10 μl initial volume deposited on an aluminum alloy 6061 surface without artificial cavities.

used for pre-deposition, no visible salt layer was on the surface. However, after distilled water deposited and completely evaporated on the surface with performed pre-deposition, some residue could be found on the surface (see Fig. 9). It seems to imply that some invisible salt was left on the surface after the pre-deposition procedure. When the succeeding distilled water was deposited on the surface with invisible salt residue, part of the salt deposition was dissolved into the distilled water in the deposited spheroid. When 0.5 M (9.32×10^{-3} molar fraction) NaCl solution was used for pre-deposition, an obvious white residue was seen on the surface, as described before. The liquid mass was able to stably levitate on the deposition (see Fig. 9).

In Figs. 10 and 11, evaporation curves for salt solutions, and distilled water with or without pre-deposition are plotted. The deposition seems to affect the evaporation time when the surface temperature is around the Leidenfrost temperature of distilled water. Occasionally, salt deposition seemed to initialize nucleate boiling during the initial liquid–solid contact and make the initial unstable period longer. Due to the scattering and ejection in the unstable period, the size of the liquid mass appeared smaller following the unstable period. Overall, the evaporation time decreased significantly.

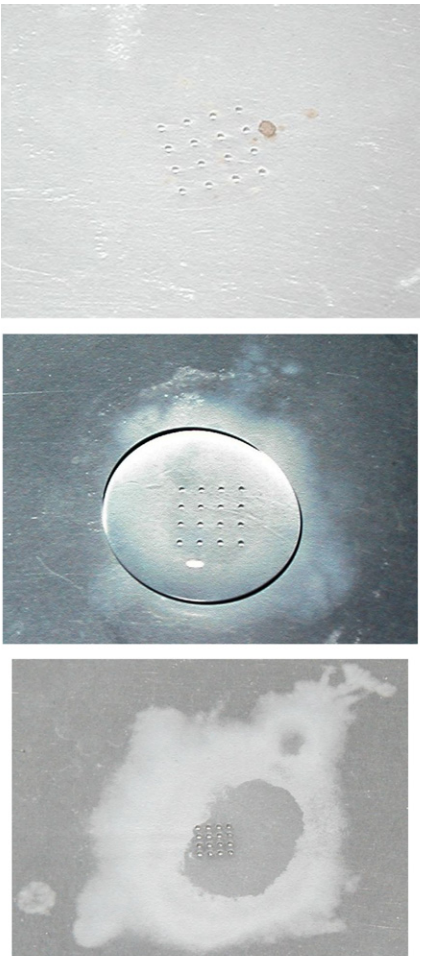

Fig. 9. (Top) The ball shape residue after complete evaporation of distilled water on the surface with performed 0.1 M NaCl pre-deposition at 330 °C (cavity spacing = 2 mm). (Middle) 0.5 M NaCl deposited at 330 °C and the salt solution levitating on the surface with visible salt deposition (cavity spacing = 2 mm). (Bottom) Salt residue formed after 0.5 M NaCl solution pre-deposition at 330 °C and partially wiped out by the initial contact of successive distilled water deposition at 240 °C (cavity spacing = 1 mm).

Comparing test results from pre-deposition by 0.1 M (1.88×10^{-3} molar fraction) and 0.5 M (9.32×10^{-3} molar fraction) NaCl solutions, higher solution concentration seems to result in greater salt deposition and a higher possibility of a shorter evaporation time. Sometimes, salt deposition may be dissolved into the liquid of the successive liquid deposition, the deposition left on the surface reduces, and the effect of changing surface condition is relatively less. The salt deposition dissolved by the successive distilled water deposition during the initial liquid–solid contact can be found in Fig. 9. The white pattern formed after a 0.5 M (9.32×10^{-3} molar fraction) NaCl solution pre-deposition at 330 °C, and the round region inside the pattern was wiped out by the initial liquid–solid contact of the successive distilled water deposition at 240 °C. When the surface temperature is higher than the Leidenfrost temperature of distilled water, the generated vapor film might be relatively thick and less affected by the salt deposition from the pre-deposition. Compared to results with 0.1 M (1.88×10^{-3} molar fraction) NaCl and KCl pre-deposition, it seems that the NaCl pre-deposition tends to produce a greater reduction in evaporation time. Except one test after 0.5 M NaCl pre-deposition, most pure water tests with pre-deposition procedure still have evaporation times longer than those for tests of 0.1 M salt solutions at the same surface temperature. In short, salt deposition during the initial liquid–solid contact clearly affects the Leidenfrost temperature. However, for the tested solution concentration, 0.1 M (1.88×10^{-3} molar fraction), the effect of this mechanism does not to be comparable to the suppression of bubble coalescence and the increasing concentration at the bottom of the liquid mass.

3.4. Revised Leidenfrost scenario

The Leidenfrost deposition process is commonly considered in the following scenario. When the liquid is first deposited, it is expected that gravity will cause the liquid to fall until it contacts the surface. When the liquid contacts the heated surface, bubble nucleation occurs at activated nucleation sites. If the surface is near the Leidenfrost transition, rapid vaporization at the surface acts to repel the liquid. If the surface temperature is high enough, vapor generated at the surface quickly merges into a vapor film, and a generation of vapor at the lower deposited liquid interface establishes a pressure field that supports the deposited liquid. The lowest temperature at which this happens is termed the Leidenfrost transition temperature. This scenario effectively describes pure liquid deposited on heated surfaces.

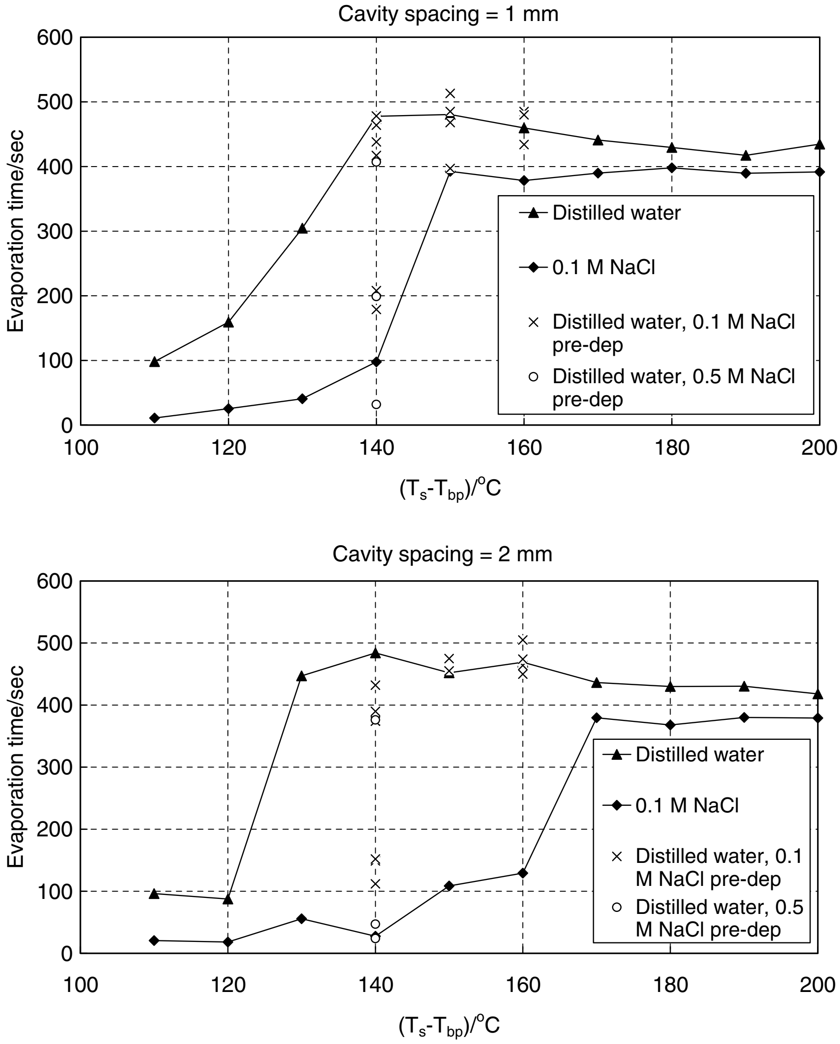

Fig. 10. Variation of evaporation time with surface superheat for distilled water and 0.1 M (1.88×10^{-3} molar fraction) NaCl solution of 1.1 g initial weight deposited on an aluminum alloy 6061 surface, × and ○ denote tests of distilled water deposited on the surface pre-deposited by 0.1 M (1.88×10^{-3} molar fraction) at 280 °C or 0.5 M (9.32×10^{-3} molar fraction) NaCl solution at 330 °C, respectively.

In experiments with salt solutions, a special phenomenon was observed that differs from distilled water evaporating on a heated surface. This situation occurred when the surface temperature was in the range between the Leidenfrost temperature of distilled water and salt solution. After the initial unstable period, the salt solution mass was levitated on the vapor film. However, as the evaporation proceeded, some unstable behavior occurred. The liquid mass seemed to intermittently contact the heated surface, and the liquid mass become more and more unstable. When pure water evaporates on a heated surface, the size reduction rate of the droplet or spheroid is nearly a constant through the evaporation process. However, for solutions with dissolved salt, the rate was first constant and then became much faster when the evaporation process approached its end. The liquid mass suddenly collapsed on the heated surface, evaporated immediately, and completed the evaporation process. In other words, the phenomenon shortened the evaporation time of salt solutions when the surface temperature was near or slightly above the Leidenfrost temperature of the distilled water. In the evaporation curve, the surface temperature with the shortened evaporation could not be explained as the Leidenfrost transition. A higher surface temperature was required to have the common length of evaporation time interpreted as the onset of the Leidenfrost temperature for the salt solution. The ordinary Leidenfrost scenario described at the beginning of this section does not conclude the above phenomena.

The scenario for liquid with dissolved salt is modified and is stated as follows. In addition to the ordinary scenario where liquid mass contacts the solid surface due to the gravity force, and bubbles nucleate to form a vapor film expelling liquid mass away, an addition to the ordinary scenario is necessary to fully describe salt solution evaporating on a heated surface. When liquid mass is able to levitate on the vapor film, solvent, water in most cases, evaporates from the bottom of the liquid mass. Salt concentration

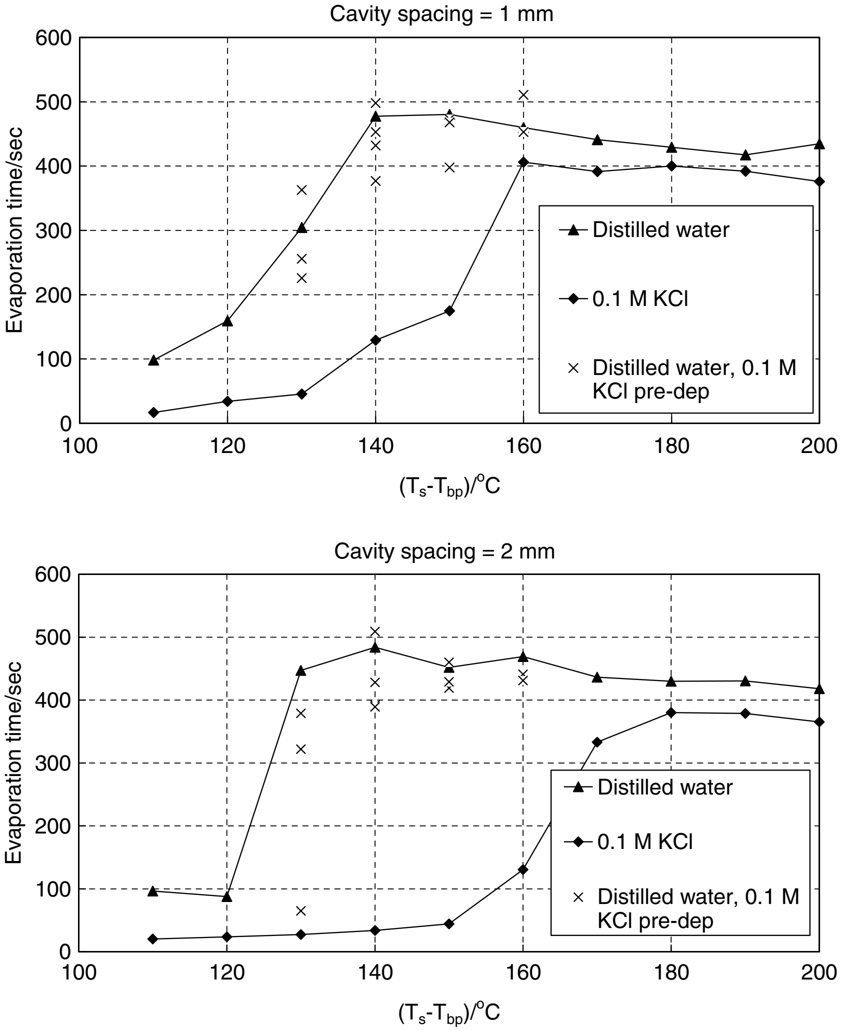

Fig. 11. Variation of evaporation time with surface superheat for distilled water and 0.1 M (1.88×10^{-3} molar fraction) KCl solution of 1.1 g initial weight deposited on an aluminum alloy 6061 surface, × and ○ denote tests of distilled water deposited on the surface pre-deposited by 0.1 M (1.88×10^{-3} molar fraction) KCl solution at 280 °C.

increases from the bottom. The concentration at the liquid–vapor interface is the highest. The increasing concentration leads to the elevation of the boiling point, surface tension, and liquid density. Biance et al. [22] presents an analytical equation to estimate the vapor film thickness beneath the evaporating spheroid.

$$\delta = \left(\frac{3k_{\mathrm{v}}(T_{\mathrm{s}} - T_{\mathrm{b}})\upsilon_{\mathrm{v}}R^2}{4h_{\mathrm{lv}}\rho_{\mathrm{l}}\rho_{\mathrm{v}}gH}\right)^{0.25} \tag{5}$$

where R and H are the spheroid radius and height respectively. For pure water, the radius decreases as the liquid evaporates. When the radius decreases to zero, it implied the completion of the evaporation process. It also implies that the film thickness decreases to zero and the liquid contacts the solid surface directly. For solutions with dissolved salt, the increase in the boiling point, surface tension and liquid density tends to decrease the film thickness more rapidly and make the vapor film thickness decrease to zero when the radius is still greater than zero. This mechanism is the major reason for the shortened evaporation time when the liquid mass is able to be levitated following the initial stage. If some salt deposition is left on the surface during the initial liquid–solid contact, those salt particles may pierce the film, and the film collapse occurs even earlier.

By considering the revised Leidenfrost transition scenario for salt solutions, the importance of the affecting mechanisms discussed in this section can be identified for each stage.

3.5. Initial stage

The liquid mass contacts the heated surface due to the gravity force. Bubbles generate from activated nucleation sites. The addition of salts inhibits the bubble coalescence and retards the formation of a stable vapor film. Some salt particles deposit on the surface, degrade the surface roughness. The combination of the two mechanisms increases the Leidenfrost temperature.

3.6. Levitated stage

After the initial stage, the liquid mass is levitated on the vapor film. Water evaporates from the bottom, and the salt concentration increases from the liquid–vapor interface. The increasing concentration causes the boiling point elevation and changes in other properties. The vapor film beneath the liquid mass gets thinner due to these changes in these properties. Eventually, the vapor film is too thin to sustain the liquid mass, or is pierced by salt deposition left at the initial liquid–solid contact. When the liquid–solid contact reoccurs, the evaporation of the small droplet becomes vary quick, and the small droplet is completely evaporated in seconds. This phenomenon causes the evaporation time to be shorter than the value for distilled water. A higher surface temperature is needed to achieve the longest evaporation time. The observed Leidenfrost temperature increases.

4. Conclusions

Comparing to Leidenfrost evaporation of distilled water masses, experimental results showed that the 0.1 M dissolved salts increased the Leidenfrost temperature by 20–40 °C. Regarding the increase of the Leidenfrost temperature for salt solutions, the suppression of bubble coalescence by dissolved salt, salt deposition during the initial contact of the deposition, and earlier collapse of the vapor film due to the increasing salt concentration at the liquid–vapor interface were studied as the mechanisms associated with the transition.

Two different cavity spacings, where one had cavities were close enough to allow bubble merging prior to bubble departure from the heated surface, were tested. It was found that the difference of the Leidenfrost temperatures where the bubble coalescence was enabled or disabled by the corresponding cavity spacing was around 10–13 °C. Compared to the measured increments of 20–40 °C, the results suggest that the suppression of bubble coalescence by the dissolved salt is only one of the mechanisms affecting the Leidenfrost transition of salt solutions.

Due to the low concentration of salt solutions, the property variation is negligible. However, the solvent evaporation from the bottom of the levitated liquid mass increases the salt concentration near the interface, and the increasing salt concentration alters some liquid properties there, and the variations in properties tend to thin the vapor film under the spheroid. The increasing salt concentration may cause the vapor film to collapse with the result that the liquid mass evaporates on the heated surface immediately. This explains the shorter evaporation time of salt solutions when the surface temperatures were slightly higher than the Leidenfrost temperature of distilled water (see Fig. 6). It is believed that the earlier film collapse due to the increasing concentration of salt at the bottom of the levitated spheroid is another important mechanism on the Leidenfrost transition of salt solutions. This mechanism is comparable in importance to the suppression of bubble coalescence.

The effect of the salt deposition during the initial liquid–solid contact of the liquid deposition was also evaluated. Salt solution was deposited on the surface at a surface temperature higher than the Leidenfrost temperature, and was allowed to rapidly evaporate. This procedure deposited a layer of salt deposition on the surface, simulating the salt deposition during the initial solid–liquid contact. Experimental results showed that the evaporation time after performing the pre-deposition procedure was sometimes shorter. For tests pre-deposited by 0.1 M (1.88×10^{-3} molar fraction) NaCl solution, 15–20% of tests showed an evaporation time 50% lower than the measured values without the pre-deposition procedure. With 0.1 M (1.88×10^{-3} molar fraction) KCl solution pre-deposition, less then 15% of tests showed an evaporation time 50% lower. If 0.5 M (9.32×10^{-3} molar fraction) NaCl solution was used to pre-deposit, 50–67% of tests showed an evaporation time of 50%. The experimental results imply that some salt deposition is left on the surface during the initial liquid–solid contact. The salt deposition may serve as nuclei to initiate nucleate boiling during subsequent contact. Higher surface temperature is necessary to form a vapor film thicker than the height of the salt deposition, and the observed Leidenfrost temperature increases. The salt deposition during the initial contact of the deposition is believed to be one of the reasons for the elevated Leidenfrost temperature observed for salt solutions. While it is found that, for 0.1 M tests, the effect of salt deposition during the initial contact is apparent only in 20% of tests, it is estimated that the influence of this mechanism is not as important as the suppression of bubble coalescence by dissolved salt or the increasing salt concentration at the bottoms of the liquid mass.

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