Heat transfer and evaporation rates of small liquid droplets on heated horizontal surfaces

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Abstract

The evaporation rates of small liquid droplets were observed and quantified in order to measure heat transfer rates when individual droplets evaporate on a horizontal heated surface. Single water droplets with a post-impact diameter of approximately 1 mm and *n*-heptane droplets approximately 5 mm in diameter were gently placed on aluminum and copper surfaces that were maintained at temperatures below the saturation temperatures of the liquids, and the evaporation was observed at atmospheric pressure. The droplets were videotaped throughout the entire evaporation process and transient variations of the diameter, height were measured. From the measured quantities, the contact angle and evaporation rates were calculated and used to predict the heat transfer rate on the surface. The results show that the trends in the wetted diameter, height and contact angle for water droplets are fundamentally different than the geometric changes for heptane droplets. Even though the evaporation rates of the *n*-heptane droplets were an order of magnitude greater than the water droplets, the heat fluxes for the *n*-heptane droplets are approximately an order of magnitude less than the water drops. The experimental results are compared with recent analytical models which predict the evaporation rates of small liquid droplets.
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1. Introduction

The volumes of the small liquid droplets examined in this study were approximately 0.45 mm^3 for the water drops and about 2.5 mm^3 for the *n*-heptane drops. These volumes correspond to a droplet diameter of about 1 mm for the water drops and 5 mm for the *n*-heptane drops after they spread on the surface. A study of small diameter drops is of particular interest, because a thin liquid layer formed by numerous small droplets provides greater heat transfer rates than thicker layers, which possess greater thermal resistance. This study concentrates on determining evaporation and heat transfer rates for single, small, gently deposited liquid drops of water and *n*-heptane.

Of the papers written about evaporation and heat transfer characteristics of droplets that change phase on heated surfaces, several have focused on small drops on the order of 1 mm in diameter. These studies have been carried out due to interest in the high heat transfer rates that can be achieved when thin liquid films change phase on a surface. Other studies have explored the phase change of liquid hydrocarbon fuels due to interest in the design of combustion systems, in general, and fuel injectors in particular.

Some of the more basic studies of the phase change of small liquid droplets have dealt with the measurements and prediction of the geometric changes that the droplets experience as they impact or evaporate on the heated surface. In particular, several studies have investigated the variations in the droplet diameter and the contact angle that is formed by the liquid at the heated surface.

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Nomenclature

d_o	original diameter of droplet after spreading on surface
h_{fg}	latent heat of vaporization of liquid
$\dot{m}$	evaporation rate of liquid
q''	heat flux

T_s	surface temperature of heater

Greek symbol

θ_o	original surface contact angle of droplet after spreading on surface

Some papers have considered evaporation on high conductivity metallic surfaces while others have been limited to surfaces that would be classified as thermal insulators.

Several related studies involving evaporation of small, gently deposited drops include one by Wachters and Westerling [1] who performed one of the earlier experiments involving impinging water drops. In their study, approximately 2 mm drops impacted a hot (up to 370 °C), polished gold surface at various velocities. More recent experiments conducted by Kurokawa and Toda [2] studied the dynamics of single droplets as they impacted on a glass surface at room temperature. Chandra and Avedisian [3] studied the evolution of droplets shapes when *n*-heptane drops struck a heated surface. They showed that the wetted area and the spreading rate of the drops are independent of surface temperature during the early period of impact. Several investigators including Qiao and Chandra [4] experimentally measured the influence of a surfactant on the evaporation rates of liquid drops. The presence of a surfactant greatly reduced the droplet evaporation times and increased the surface heat transfer rate. Xiong and Yuen [5] studied the impact of liquid drops with diameters less than 1 mm, including water and several hydrocarbon fuels. The droplets impacted on a stainless steel plate heated to temperatures up to the Leidenfrost temperature. Tartarini et al. [6] used gently deposited water drops on both metallic and ceramic surfaces heated between 100 and 200 °C. Makino and Michiyoshi [7] studied boiling of gently deposited water droplets on several metallic surfaces that were initially maintained above the saturation temperature of water and the final temperature was greater than the Leidenfrost temperature. They used drops with pre-impact diameters between 2.5 and 4.5 mm. di Marzo and Evans [8] studied softly deposited water droplets on an aluminum surface that was maintained at temperatures up to the saturation temperature. Drops were released from a hypodermic needle that was positioned less than 1 cm above the surface. Their results showed that during evaporation the drop diameter remained relatively constant as the contact angle continually decreased. Once a critical angle was reached, the contact angle became fixed while the diameter decreased.

2. Experimental apparatus

All experiments were carried out at one atmosphere pressure and the heater temperatures were always maintained at less than the saturation temperature of the liquid. Two heater materials, aluminum (Alloy 6061-T6) and copper (Alloy C145), were maintained at 60, 80, and 95 °C for the water droplets and 60 and 75 °C during the *n*-heptane experiments. Droplet diameter and height were measured by examining individual frames of videotape that were recorded throughout the evaporation process. Measurements verified that the free surface was a spherical shape throughout the lifetime of both the water and *n*-heptane droplets. Knowing that the droplets were spherical in shape, instantaneous value of the contact angle between the evaporating droplets and the heater surface, evaporation rate, and spatially averaged heat flux could be calculated solely from the diameter and height measurements.

Both heaters used in the evaporation experiments were cylindrical (diameter of heated surface, 9.53 mm; length, 44.5 mm) and were designed to be heated to a constant, uniform temperature by a 25 W cartridge heater that was inserted into the base of the cylinder. The heated surfaces had three thermocouples located along the axis of the metallic cylinder at 2, 6 and 10 mm from the upper surface. The output of the top thermocouple was used in conjunction with an automatically temperature-controlled, regulated power supply that maintained the surface temperature to within ±0.2 °C. The temperatures indicated by the other two thermocouples were extrapolated to the surface and the extrapolated temperature was used as a measure of the interface temperature of the droplet during entire evaporation process. A schematic of the experimental apparatus is shown in Fig. 1. A more detailed description of the apparatus and a comprehensive discussion of the test protocol are given in [9].

The spatial and temporal temperature variations at the droplet-heater interface were non-existent, because the droplets were very small, both heaters were composed of high conductivity materials and the external surfaces of the heaters were covered with a layer of insulation. The heated surface was polished to a mirror-like finish with 400, 600, and 1500 grit sandpaper, and
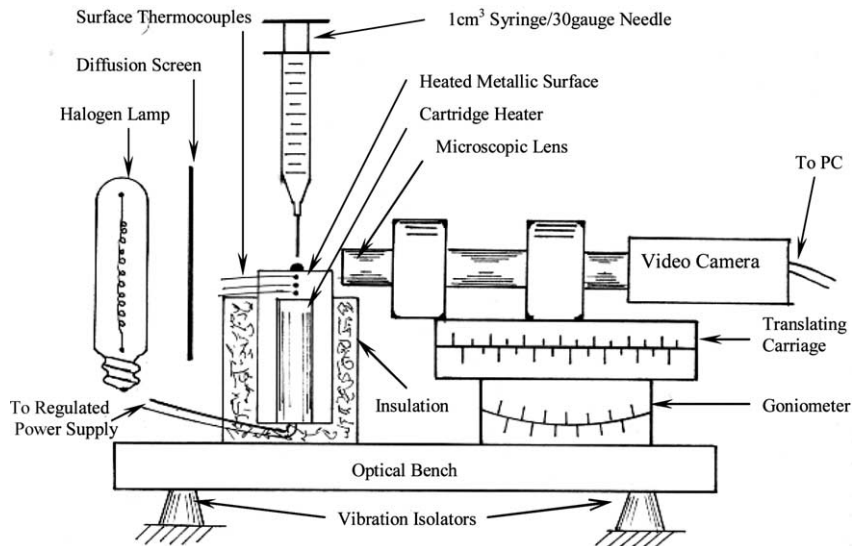
Fig. 1. Schematic of droplet generator, heated surface and video equipment.

scratch remover acrylic polishes were applied to eliminate small surface scratches. The polishing process was completed only once to prepare both the aluminum and copper surfaces for all measurements. However, prior to each experiment, the surfaces were sequentially cleaned with metal polish, acetone, ethyl alcohol, isopropyl alcohol, and purified, de-ionized water. The surfaces were then dried with a soft, non-scratching cotton cloth and finally compressed air was used to eliminate any remaining lint or dust.

All droplets were formed at the end of a 30-gauge stainless steel blunt needle that was attached to a 1 cm^3 syringe. In order to consistently place the droplets directly in the center of the field of view of the video camera, the syringe was suspended by a device that was able to lower the syringe until the droplet that was suspended from the needle gently touched the heated surface. Once the drop touched the surface, the syringe was quickly withdrawn, leaving the droplet on the surface and the subsequent evaporation process was recorded.

The shape of the droplets was continually recorded using a progressive scanning double-speed video camera, adapted to a microscopic lens that magnified the images. The camera and lens were attached to three rack-and-pinion dovetail stages and a goniometer that were mounted on a rigid foundation. This configuration allowed the camera to be moved in the three coordinate directions as well as to be rotated in one angular direction. For the images shown in this paper, the camera was always oriented horizontally in the plane of the heated surface. The foundation that supported the camera and the heater was mounted on elastic vibration isolators so

that structural vibrations in the building did not affect the shape of the evaporating drops.

The images of the droplets were recorded on videotape at a rate of 30 frames per second. Images were recorded from the time that the drop was formed on the end of the needle until it had completely evaporated. A time generator, connected to the VCR and television monitor, placed a time stamp on each frame of videotape so that the time from the start of evaporation could be accurately determined for each frame. The droplets were illuminated by a 150 W halogen bulb that was placed about 300 mm from the drop. A translucent screen was used to diffuse the light so the droplet was uniformly illuminated. The presence of the screen, the large distance between the drop and the light source, the very small droplet size and the relatively short lifetime of the drop help to minimize the radiant heating of the droplet. A 25 mm diameter glass reticle with a smallest division of 0.1 mm provided a calibration scale for objects recorded on the videotape. An image of the reticle was recorded on each segment of videotape to provide a measure of magnification for the height and diameter measurements. In order to limit ambient air movement in the vicinity of the droplet, a thin plastic film was placed around the entire experimental apparatus so that any air currents in the room were minimized at the location of the evaporating drop.

The spread of the droplets and the motion of the liquid within the drops as they were placed on the surface were relatively short, because the droplets were gently placed on the surface. The spreading process for gently deposited drops is observed to be typically less than 0.25 s for the water drops which has been verified in

[12,13]. Observed spreading times were nearly identical to those stated in [10] where water droplets were dropped from about 10 mm above an aluminum surface. Measurements were recorded only after the droplet came to rest (defined as time = 0) and gross motion of the exterior surface of the drop ceased. At this time, the initial droplet diameter on the surface, d_o, was recorded. Pre-impact diameters were not recorded, because the drops were always in contact with either the needle or the heated surface and they were not observed during free-flight conditions. However, the pre-impact diameter can be estimated by multiplying the values of d_o by a factor of 0.66–0.83 which are the inverse of the spreading ratios reported in [8]. Measurements were terminated when three-dimensional, nonsymmetrical evaporation effects within the drop were evident. At this time oscillations occurred in the surface of the droplet and the motion of the outer diameter of the droplet become very erratic. Terminating the measurement in this way led to height, diameter and contact angle measurements that apply only during the gradual two-dimensional evaporation phase. This measurement philosophy led to initial contact angles that are referred to as "quasi-static advancing contact angles" and initial droplet diameters that are termed "quasi-mechanical equilibrium diameters" in references [10,11]. The measurements were terminated prior to reaching the receding contact angles described in [15].

Throughout the entire lifetime of the drops, the free surface of the liquid was assumed to be a segment of a sphere which is a shape of small liquid droplets verified by others [14]. This assumption was also verified in [9] by comparing the surface profiles of a number of both water and *n*-heptane drops with locus of a sphere. Measurements showed that the droplets remained spherical-shaped throughout their lifetime until three-dimensional effects were observed, at which time the surface of the droplet began to oscillate and the measurements were terminated. The oscillatory nature of the surface of the drop late in its lifetime has also been verified in a study of water droplets evaporating on a non-wetting surface [14] and water droplets evaporating on a stainless steel surface [15].

Relative humidity of the air within the room was measured prior to each experimental test and the values remained constant throughout each test. While there were slight variations in humidity over the entire span of this study, they were not sufficient to have a significant effect on the measured evaporation rates. Therefore, the relative humidity of the ambient air is not reported in the data that follows, but humidity data can be found in [9].

Evaporation measurements were carried out for both water and *n*-heptane droplets. The water used was purified, reagent grade de-ionized water and a vacuum was drawn on the water samples to remove dissolved air. The *n*-heptane had 99.3% purity with less than 0.0001% residue after evaporation. The fluid properties shown in Table 1 illustrate the notable differences between the water and *n*-heptane droplets. Liquid *n*-heptane, with a surface tension that is only about one-fourth that of water at 60 °C, tends to spread and form large, thin drops with very small contact angles when compared to water under the same conditions. Heptane drops with comparable pre-impact diameters possess evaporation times that are significantly less than water drops due to their more volatile behavior at elevated temperatures and their greater exposed surface area. Water has a latent heat of vaporization that is nearly seven times that of heptane, so even though the evaporation rate typically was greater for the heptane drops, they produced heat transfer rates that fell far short of the heat transfer rate for water droplets.

An error analysis showed that the height and diameter of the water drops could be measured with a precision of ±0.01 mm. The much thinner *n*-heptane droplets made the task of measuring the size of the droplets much more difficult. As a result the precision for the height and diameter measurements for the *n*-heptane drops was ±0.02 mm. These values translate to an accuracy of the calculated contact angles to within ±3°. They also resulted in a measurement error for both the evaporation rates and calculated heat transfer rates of 3.9% for water and 4.4% for *n*-heptane. The precision values were determined by repeating the height and depth measurements twenty five times on the same drop at two different times during the evaporation process. A statistical analysis of the array of data verified that the experimental technique could provide evaporation and heat transfer rates that were repeatable within the stated experimental errors.

Table 1
Properties of water and *n*-heptane at various temperatures

Fluid	Boiling point, 1 atm (°C)	Temperature (°C)	Density (kg/m³)	Surface tension (mN/m)	Heat of vaporization (kJ/kg)
Water	100	60	983	66.2	2359
		80	972	62.7	2309
		95	962	59.9	2270
n-Heptane	98.4	60	645	16.3	344
		75	632	14.9	334

3. Results

The diameter and height of each droplet were measured for three temperatures for water and two temperatures for *n*-heptane while they were placed on both the aluminum and copper surfaces. From the measured values of droplet height and diameter, values for contact angle, droplet volume and evaporation rate were calculated by applying the assumption of a spherically shaped free-surface. Values for heat flux were then determined from the calculated evaporation rate, and the liquid latent heat of vaporization, assuming the surface heat transfer was entirely due to the phase change of the liquid on the surface.

The motion of the droplet early in its lifetime was very gradual. By contrast, toward the end of the evaporation process, three-dimensional effects became apparent, and the motion of the droplet became very erratic and unpredictable. For water, the occurrence of three-dimensional effects was easily determined from an examination of the images on the videotape. However, given the limited sensitivity of the video equipment, the broader and thinner *n*-heptane droplets were much more difficult to observe during the latter stages of evaporation as the droplet height approached zero. Therefore, for the *n*-heptane droplets, observations were continued until the height of the droplet became too small to observe on the video tape.

3.1. Water

Four typical video frames of a water droplet evaporating on the aluminum surface are shown in Fig. 2. For these images the surface was maintained at 60 °C and the maximum diameter of the drop corresponded to the frame shown in Fig. 2(a). After about 27 s had tran-

spired, asymmetric effects were observed; the last frame of the axisymmetric evaporation is shown in Fig. 2(d). These four images are representative video frames of the entire extent of the two-dimensional evaporation process.

The heights of several size water droplets are shown as a function of time on a 60 °C aluminum surface in Fig. 3(a) and a copper surface in Fig. 3(b). The height is normalized with respect to the maximum-recorded droplet height during the evaporation process. The height of the water droplets decreases nearly uniformly during the axisymmetric evaporation process with the larger drops showing longer evaporation times. The effect of heater material on the height of the droplet is practically non-existent. The data in Fig. 3 can be extrapolated to zero height to estimate the evaporation times for drops with a known diameter even though the measurements were terminated prior to complete evaporation. For example, in Fig. 3b the droplet with an original maximum equilibrium diameter of 1.13 mm (pre-impact diameter approximately 0.94 mm and a drop volume of 0.43 mm^3) has an evaporation time of about 45 s. This value is significantly less, as expected, than the evaporation time of 140 s reported in [4] which was measured for larger water drops with pre-impact diameters of about 2 mm when it evaporated on a stainless steel surface at 60 °C.

Typical trends in the normalized diameter of water droplets evaporating on the aluminum surface at 60 °C are shown in Fig. 4. A more extensive set of diameter measurements is provided in [9]. For the larger water drops studied, the droplet diameter remains practically constant over a significant fraction of the lifetime of the drop. Only near the end of the drop's lifetime does the diameter show an appreciable decrease. This trend has also been reported in [8]. As the original droplet

(a) 0 s

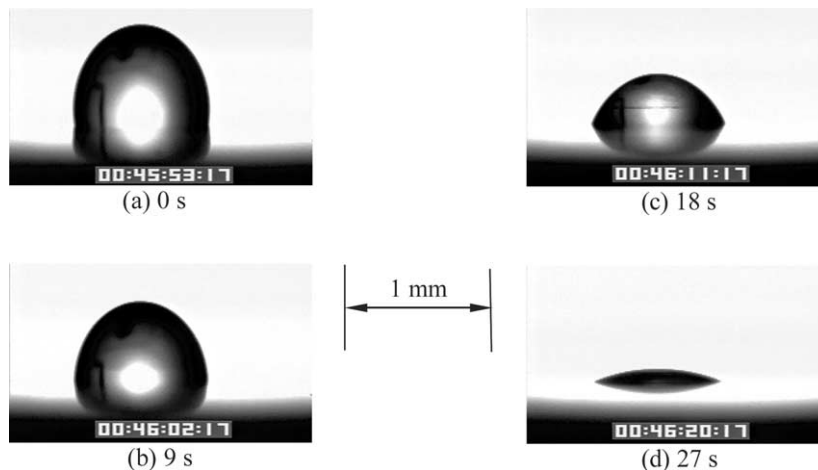(b) 9 s

(c) 18 s

(d) 27 s

1 mm

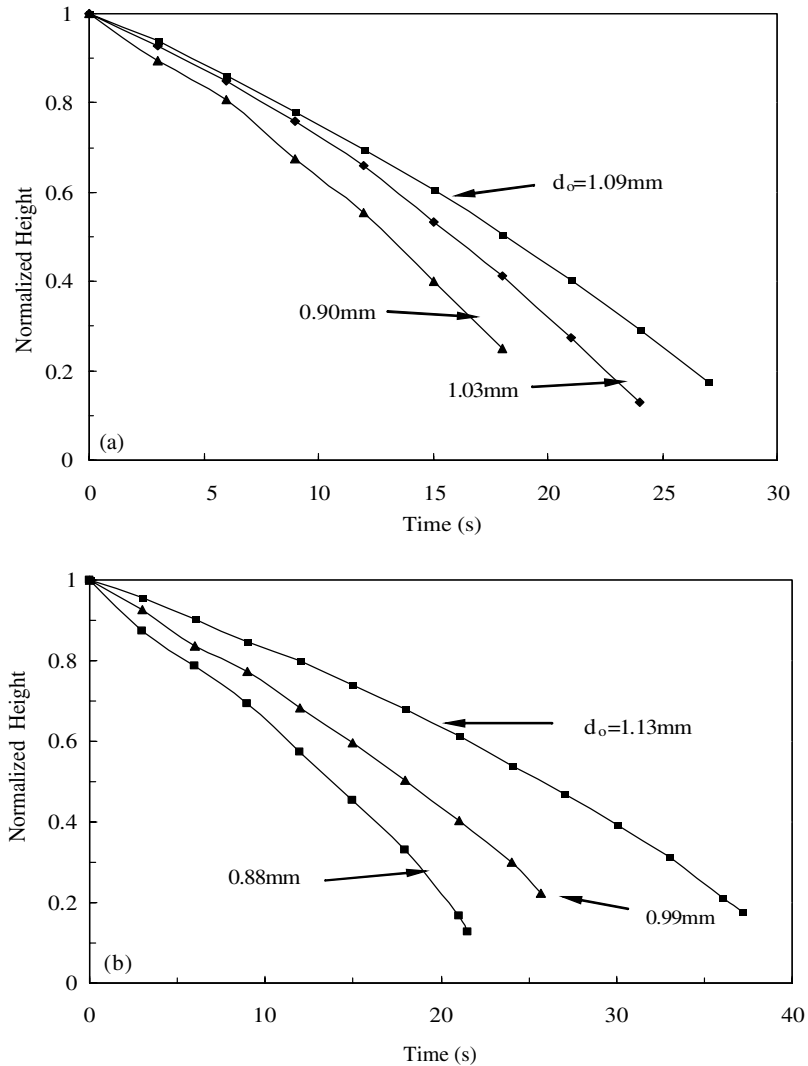Fig. 2. Sequence of water droplets on an aluminum surface at 60 °C.

Fig. 3. Normalized height for water droplets at 60 °C on (a) an aluminum surface and (b) a copper surface.

diameter decreases, the diameter shows a somewhat more gradual decrease with time. This trend may be due to increased capillary forces for the smaller drops that would cause the droplets to experience a greater tendency to shrink during the evaporation process.

The contact angles between the tangent to the spherical free surface of the drop and the plane of the heater as a function of time were calculated from the instantaneous measurements of the droplet diameter and height. Fig. 5 shows droplet contact angles as a function of time for water droplets on the aluminum and copper surfaces at 60 °C. The contact angle continually decreases throughout the portion of the evaporation process that was observed, and it decreases faster as the droplet approaches a thin film where three-dimensional

motion of the droplet begins to occur. Measurements were terminated before the receding contact angle reported in [15,16] was reached. The contact angle decreases faster for droplets with smaller initial contact diameters indicating an increased evaporation rate. The initial contact angles have a slightly greater spread for the droplets on the aluminum surface.

Taken together, the transient measurements of height, diameter and contact angle show that during the evaporation process, the water droplets have a relatively constant diameter as the droplet height and contact angle both continually decrease. The initial contact angles of water droplets placed on an aluminum surface at 60 °C are only slightly greater than the contact angles that have been reported in [4,10,15]. The outer diameter
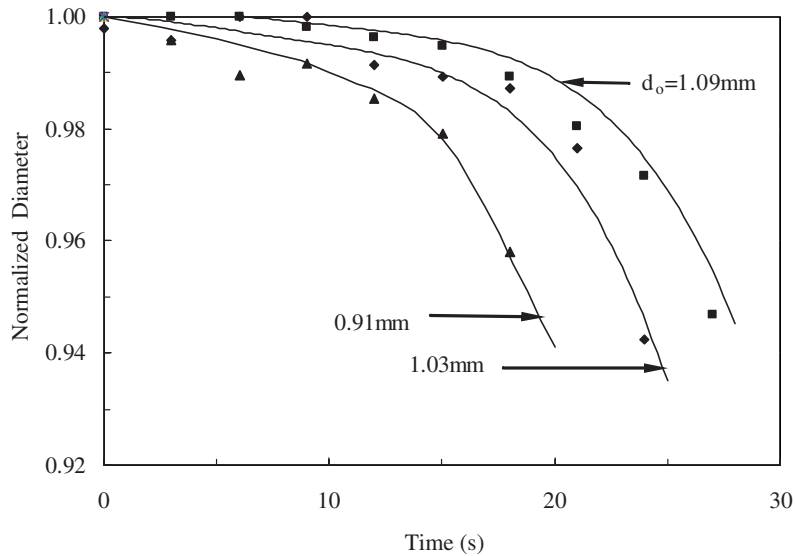
Fig. 4. Normalized diameter for water droplets on an aluminum surface at 60 °C.

of the liquid contact line appears to be anchored to the surface at a position close to its original location while the mass of liquid leaves the free surface and the drop becomes thinner. Only after the drop reaches a contact angle in the range of about 20–40° does the diameter begin to show a significant decrease. This range of receding angles is somewhat greater than the value of 10° for water on aluminum surfaces that has been reported in [4,10].

The effect of heater temperature on droplet height is shown in Fig. 6 for water droplets on an aluminum surface. The three curves for temperatures of 60, 80 and 95 °C are provided for drops with essentially the same original diameter. As expected, the results show that the surface temperature has a significant effect on the life expectancy of the drops. For example, the evaporation time necessary to reach a normalized height of 0.1 decreased by about a factor of four when the drop temperature was increased from 60 to 95 °C.

Evaporation rates were calculated from the geometric changes of the drops and are plotted in Fig. 7 for water droplets placed on the aluminum surface at 80 °C. As the droplet diameter increases, the evaporation rate increases slightly due to the increased surface area of the larger drops. Over the limited range of droplet sizes that were placed on the heated surface, the evaporation rate increased nearly linearly with an increase in the post-impact diameter of the drop.

The calculated evaporation rates were used to estimate the heat flux on the surface area originally covered by the drop, by assuming the heat is removed solely due to the phase change of the drop. This assumption is particularly valid for small droplets, because the sensible energy required to heat the drop from the ambient temperature to the temperature of the heater is typically less than 10% of the heat required to vaporize the drop. Heat flux values are shown in Fig. 8 for the water droplets on the aluminum surface at 80 °C. The area used to calculate the heat flux was a constant and equal to the original surface area covered by the drop (that is, a circle with diameter d_o) after spreading had ceased. That is,

$$q'' = \frac{\dot{m}h_{fg}}{\pi d_o^2/4} \tag{1}$$

In contrast to the trend of the evaporation rate, the heat flux increases as the contact diameter decreases. This result shows that it is preferable to cover a heated surface with a thin film of liquid consisting of numerous, small drops rather than fewer, large drops if increased heat transfer rates are desired. The heat flux values shown in Fig. 8 are about twice the values reported in [8]. Their study used much larger water droplets that had post-impact diameters of about 5 mm and the metallic surface was heated between 75 and 100 °C.

The experimental results presented here can be compared to a limited number of computational studies that have modeled the evaporation of small gently deposited water drops on heated surfaces. However, comparisons are complicated by the large number of variables involved in a study of this complexity and the relatively few studies that contain overlapping values for the test conditions. di Marzo and Evans [8] have provided plots of normalized volume as a function of normalized time where the normalizing time factor was the total evaporation time for the drop. Their computational predictions
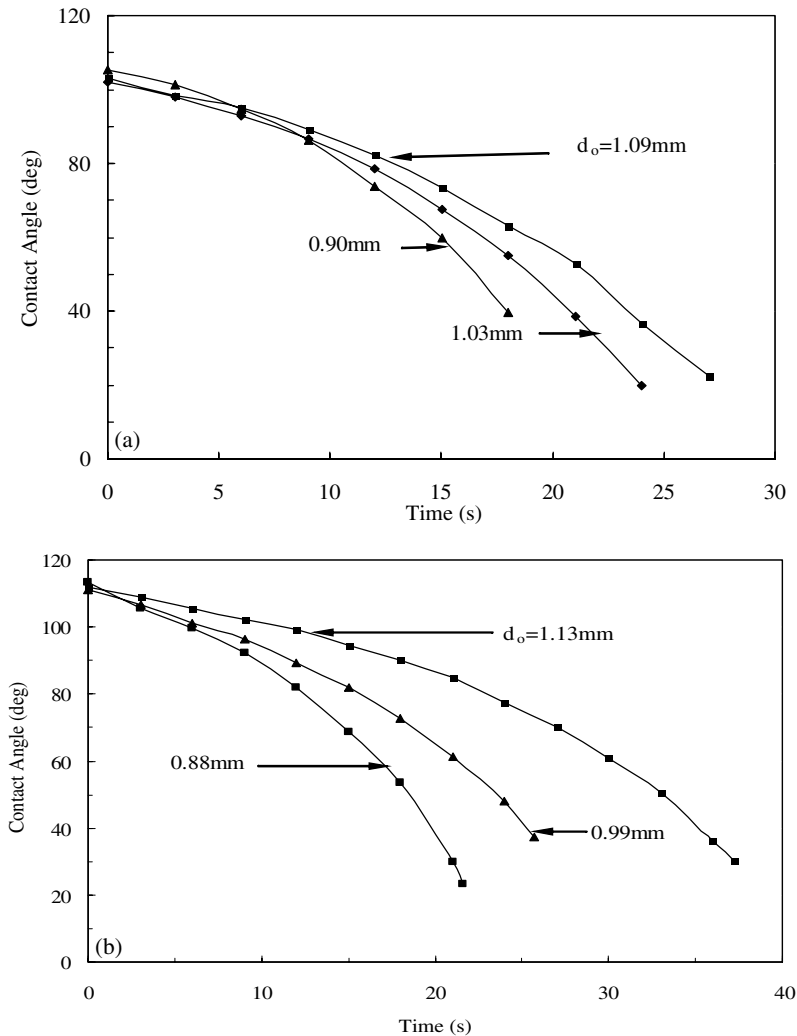
Fig. 5. Contact angles for water droplets at 60 °C on (a) an aluminum surface and (b) a copper surface.

were reported for water evaporating on a high thermal conductivity surface at a temperature of 98 °C. The volume of the drop was reported to be 30×10^{-9} m^3. They also provided experimental measurements which closely matched the computational results. The volume ratios from the present study were measured on a copper surface at 95 °C and the pre-impact volume was 0.19×10^{-9} m^3 which is about 160 times smaller that the drops used by di Marzo and Evans. A comparison between their dimensionless droplet volume and values measured in this study are shown in Fig. 9. di Marzo and Evans found that the drop volume decreased slightly faster toward the end of the evaporation process, whereas the measurements carried out in this experiment determined that the volume decreases nearly linearly throughout the evaporation process until the drop becomes a thin film and the contact line moves to the droplet center. Therefore

measurements could not reveal the precise shape of the curve when the last portion of the droplet evaporated. Several reasons can be proposed to explain the gross differences in the dimensionless volume curves. The much smaller drops used in this study have a significantly smaller conductive resistance and therefore, for a given heater temperature, the free-surface temperature of the drops are higher for the smaller drops. The reduced conductive resistance tends to accelerate the evaporation rate of the smaller drops which reduces the dimensionless volume. Furthermore, the smaller drops possess a smaller ratio of volume to surface area and this trend also tends to increase the evaporation rate which reduces the dimensionless volume below the dimensionless volume reported for larger drops.

An axisymmetric numerical model proposed by Ruiz [12,13] provides another comparison for the experi-
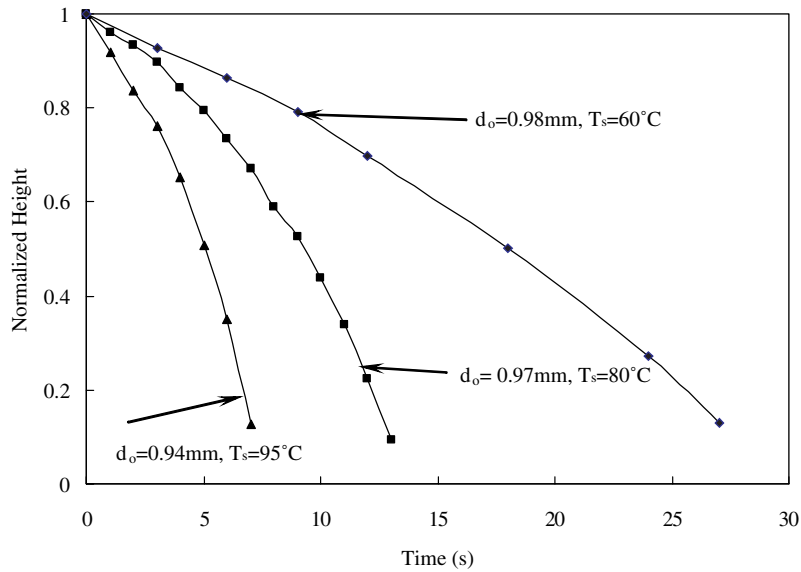
Fig. 6. Effect of temperature on the height of water droplets on an aluminum surface.
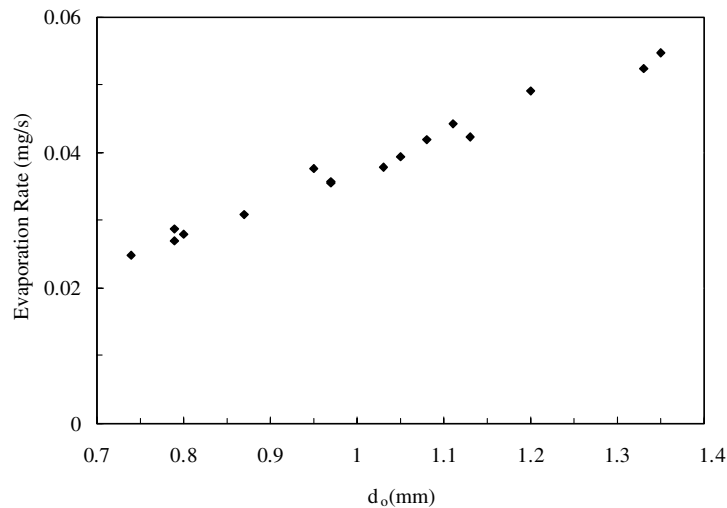

Fig. 7. Evaporation rate as a function of water droplet diameter on an aluminum surface at 80 °C.

mental results. This computational model simulates the evaporation of gently deposited water droplets and it predicts the decrease of droplet volume as a function of time. It is the first analytical model to consider evaporation at the free surface and motion of the liquid within the drop due to Marangoni forces. The circulation of the liquid suggests a greater evaporation rate than previous models and it predicts a linear volume change as a function of time. Simulations that include fluid motion indicate that the flow field has a substantial effect on the temperature distribution in the drop and the mass flux at the free interface is very different from the flux predicted

by a model based on pure conduction in the drop [12]. In Fig. 10 a comparison of the decrease in dimensionless droplet volume predicted by Ruiz' model shows excellent agreement with the measurements of this study.

3.2. n-Heptane

A few of the experimental measurements for *n*-heptane are summarized in Figs. 11–13, and a more complete set of data is presented in [9]. Gently placed *n*-heptane droplets were observed evaporating on the polished aluminum and copper surfaces at 60 and 75 °C. For
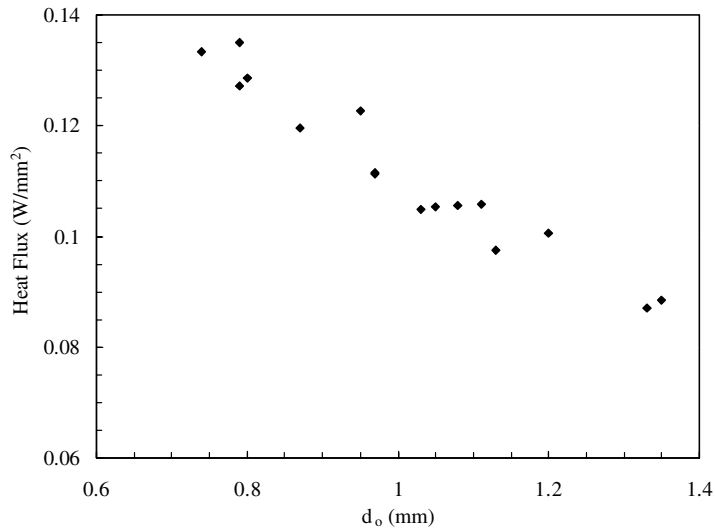
Fig. 8. Heat flux as a function of water droplet diameter on an aluminum surface at 80 °C.
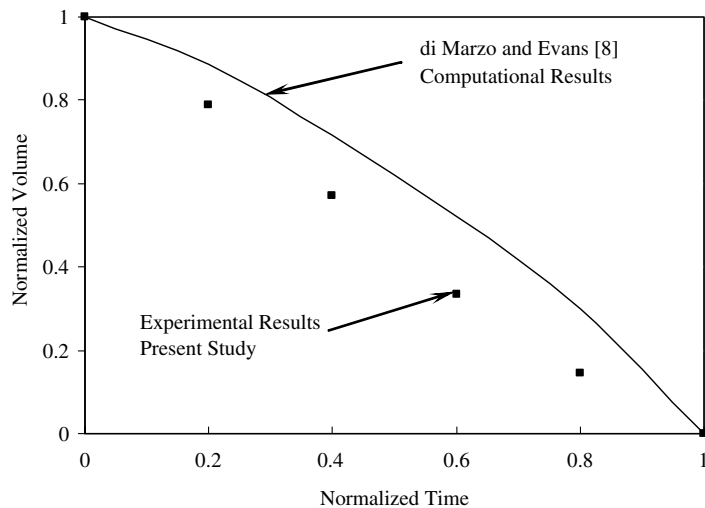

Fig. 9. Comparison of evaporation rates for water drops on a copper surface at 95 °C compared with a computational model from [8].

n-heptane droplets evaporating on the aluminum surface at 60 °C, normalized diameters are plotted as a function of time in Fig. 11. Contrary to the behavior of the evaporating water droplets, the *n*-heptane drops showed a continual decrease in diameter during evaporation while the diameter of the water drops remained relatively constant during their lifetime. Similar to the behavior of the water droplets, however, the height of the *n*-heptane droplets continually decreased during evaporation (see Fig. 12).

The calculated contact angles as a function of time for *n*-heptane droplets on the aluminum surface at 75 °C

are provided in Fig. 13. The contact angles fluctuated between a narrow range of about 12° and 16° but they remained fairly constant throughout the evaporation process, considering the measurement uncertainty of ±3°. Taken together, the measurements indicated that the heptane drops continually shrank in diameter and depth such that the contact angle remained practically constant throughout the evaporation process.

The calculated evaporation and heat transfer rates for the *n*-heptane droplets are shown in Fig. 14 and Table 2, respectively. Evaporation rates for the thinner, broader heptane drops generally exceed those of water
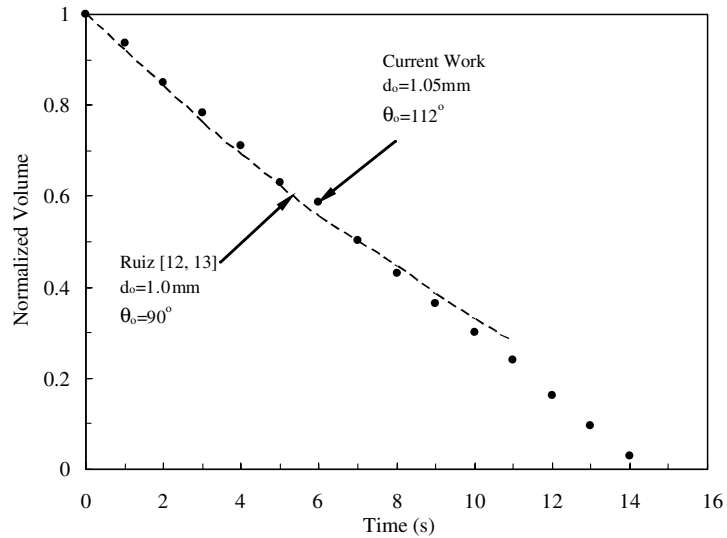
Fig. 10. Comparison of instantaneous volume of water drop on an aluminum surface at 80 °C with numerical model from [12,13].
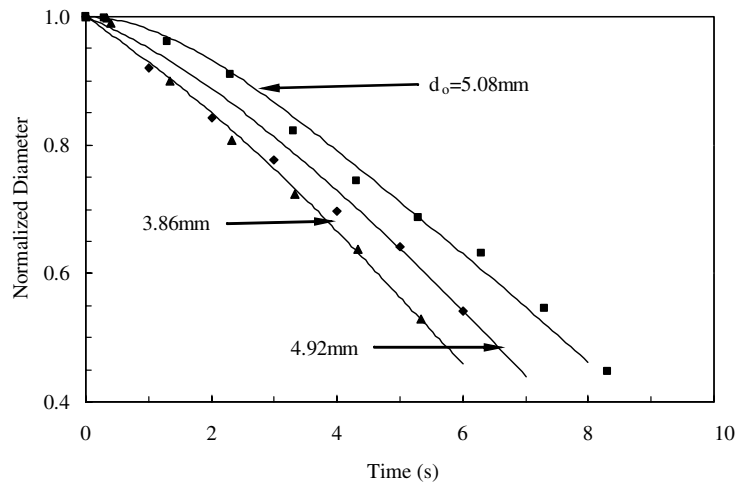

Fig. 11. Normalized diameter for heptane droplets on an aluminum surface at 60 °C.

for the same conditions. However, the heat transfer rates for the heptane drops are quite small compared to the water drops mainly because the latent heat of vaporization of water is nearly seven times that of heptane (see Table 1). Similar to the calculations with water, the heat flux values in Table 2 are based on the initial post-impact droplet diameter and the initial evaporation rate.

4. Conclusions

Observation of the evaporation process of small water droplets on both the aluminum and copper sur-

faces have led to the following conclusions. The initial contact angle for water droplets was between 102° and 113° and this range of angles was independent of the initial droplet size. The contact angle and droplet height continually dropped during the evaporation process while the diameter remained relatively constant until three-dimensional effects became evident. The evaporation rates of the water droplets were equivalent for the aluminum and copper surfaces and they remained essentially constant throughout the lifetime of the drop. Evaporation rates increased linearly with increasing original post-impact droplet diameter. Measured heat flux values based on the original wetted area covered by
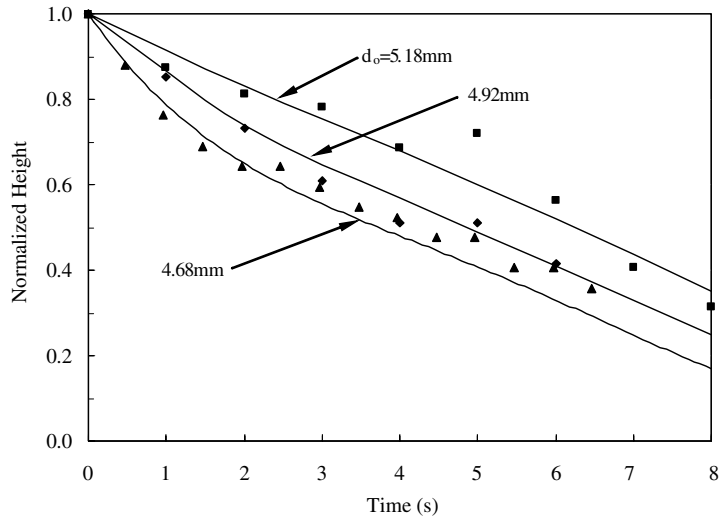
Fig. 12. Normalized height for heptane droplets on an aluminum surface at 60 °C.
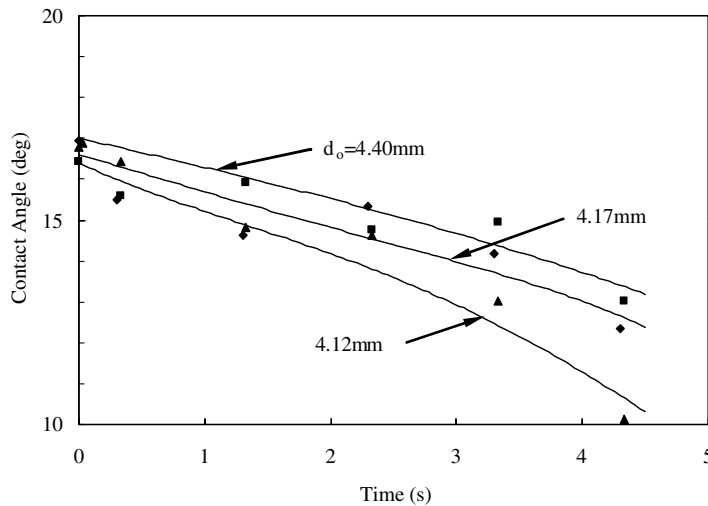

Fig. 13. Contact angle for heptane droplets on an aluminum surface at 75 °C.

the drop ranged between 0.050 and 0.25 W/mm² for both surfaces when heated between 60 and 95 °C. Heat flux values decreased as the droplet size increased.

The evaporation of small *n*-heptane drops showed different characteristics than experienced with water drops. The diameter and height of heptane droplets decreased during evaporation and the contact angle remained relatively constant near 15° until three-dimensional effects became apparent. Evaporation heat transfer rates were nearly an order of magnitude less than the water drops when they evaporated on the same surface at the same temperature. Heat fluxes for the heptane droplets ranged between 0.0074 and 0.012 W/mm² for heater surface temperatures between 60 and 75 °C.

The experimental data for evaporation rates compare well with a theoretical axisymmetric model that accounts for both conduction and convection in the drop. Measured evaporation rates suggest a nearly linear curve of the droplet volume as a function of time. Very small drops therefore appear to evaporate faster than larger drops that have been shown to follow a D-squared model.
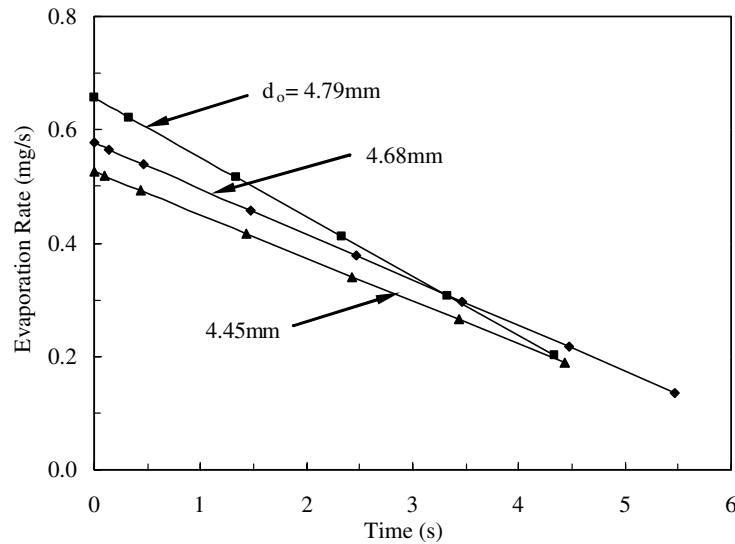
Fig. 14. Evaporation rates as a function of heptane droplet diameter on an aluminum surface at 75 °C.

Table 2
Heat flux as a function of droplet diameter for heptane on aluminum and copper surfaces at 60 and 75 °C

Heater surface	Heater temperature (°C)	Initial contact diameter (mm)	Evaporation rate (mg/s)	Heat flux (W/mm^2)
Aluminum	60	4.92	0.406	0.0074
	75	4.49	0.657	0.0122
Copper	60	4.62	0.363	0.0075
	75	4.40	0.494	0.0109

References

[1] L.H.J. Wachters, N.A.J. Westerling, The heat transfer from a hot wall to impinging water drops in the spheroidal state, Chem. Eng. Sci. 21 (1966) 1047–1056.

[2] M. Kurokawa, S. Toda, Heat transfer of an impacted single droplets on the wall, in: ASME/JSME Thermal Engineering Proceedings, vol. 2, 1991, pp. 141–146.

[3] S. Chandra, C.T. Avedisian, On the collision of a droplet with a solid surface, in: Proceedings of the Royal Society of London, vol. 432, 1991, pp. 13–41.

[4] Y.M. Qiao, S. Chandra, Evaporative cooling enhancement by addition of a surfactant to water drops on a hot surface, HTD-Vol. 304, in: ASME National Heat Transfer Conference, vol. 2, Portland, Oregon, August 6–8, 1995, pp. 63–71.

[5] T.Y. Xiong, M.C. Yuen, Evaporation of a liquid droplet on a hot plate, Int. J. Heat Mass Transfer 34 (7) (1991) 1881–1894.

[6] P. Tartarini, G. Lorenzini, M.R. Randi, Experimental study of water droplet boiling on hot, non-porous surfaces, Heat Mass Transfer 34 (1999) 437–447.

[7] K. Makino, I. Michiyoshi, The behavior of a water droplet on heated surfaces, Int. J. Heat Mass Transfer 27 (5) (1984) 781–791.

[8] M. di Marzo, D.D. Evans, Evaporation of a water droplet deposited on a hot high thermal conductivity surface, Trans. ASME, J. Heat Transfer 111 (1989) 210–213.

[9] Elyssa Farah Crafton, Measurements of the Evaporation Rates of Heated Liquid Droplets, Masters Thesis, George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, April 2001.

[10] J.D. Bernardin, I. Mudawar, C.B. Walsh, E.I. Franses, Contact angle temperature dependence for water droplets on practical aluminum surfaces, Int. J. Heat Mass Transfer 40 (5) (1997) 1017–1033.

[11] T.A. Elliott, D.M. Ford, Dynamic Contact Angles, Part 7—impact spreading of water drops in air and aqueous solution of surface active agents in vapor on smooth paraffin wax surfaces, J. Chem. Soc. Faraday Trans. I 9 (1972) 1814–1823.

[12] O.E. Ruiz, Numerical Analysis of the Dropwise Evaporation Process, Doctoral Thesis, George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, April 2000.

[13] O.E. Ruiz, W.Z. Black, Evaporation of water droplets placed on a heated horizontal surface, Trans. ASME, J. Heat Transfer 124 (5) (2002) 854–863.

[14] G. McHale, S.M. Rowan, M.I. Newton, M.K. Banerjee, Evaporation and wetting of a low-energy solid surface, J. Phys. Chem. B 102 (1998) 1964–1967.

[15] S. Chandra, M. di Marzo, Y.M. Qiao, P. Tartarini, Effect of liquid–solid contact angle on droplet evaporation, Fire Safety J. 27 (1996) 141–158.

[16] M. di Marzo, P. Tartarini, Y. Liao, D. Evans, H. Baum, Evaporative cooling due to a gently deposited droplet, Int. J. Heat Mass Transfer 36 (17) (1993) 4133–4139.