EXPERIMENTAL AND NUMERICAL STUDIES OF EVAPORATION OF A SESSILE WATER DROP ON A HEATED CONDUCTIVE SUBSTRATE

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Experimental and theoretical studies of evaporating droplets of relatively large volume are conducted. Two numerical models are presented and their predictions are discussed in detail. Experiments on droplet evaporation on two substrates of the same chemical composition but different degrees of roughness, produced by spray Teflon and spin Teflon on glass, were conducted with the objective of understanding the effect of roughness and contact angle hysteresis. The influence of the substrate temperature was investigated, showing much faster evaporation for higher temperatures. Droplets under similar conditions were then studied on a more thermally conductive stainless steel substrate, such that the effects of substrate conductivity could be investigated.

KEY WORDS: evaporation, thermocapillarity, convection, contact line pinning, partial pinning and de-pinning, substrates with different wettability, contact angle hysteresis, theory and experiment

1. INTRODUCTION

Studies of evaporating droplets on solid substrates have been motivated by several different applications. For example, in the development of DNA microarray technology, droplets of DNA solution are deposited on functionalized glass slides. The chemical reaction between the molecules in the solution and the molecules of the substrate can then be used to identify the components of the solution provided that the DNA concentration near the substrate is sufficiently uniform. In the absence of heating and convective flow in the gas phase, the sessile droplet dynamics is mostly governed by the diffusion of vapor through air. Detailed investigations of this diffusion process and its coupling to the evolution of the droplet’s shape have been performed both experimentally and numerically (Deegan et al., 2000; Bhardwaj et al., 2010; Picknett and Bexon, 1977; Hu and Larson, 2002; Popov, 2005). Recent studies of sessile droplets under ambient conditions have focused on the role of substrate wettability, clarifying the dependence of the evaporation rate on the contact angle (Sobac and Brutin, 2011; Song et al., 2011). In recent years, the classical models of diffusion-driven evaporation were also modified to address the issues from several emerging novel applications involving non-Newtonian fluids such as colloidal suspensions or blood (Brutin et al., 2011) as well as deformable viscoelastic substrates (Lopes and Bonaccurso, 2012).
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>droplet surface area</td>
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<tr>
<td>$C$</td>
<td>concentration</td>
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<tr>
<td>CAH</td>
<td>contact angle hysteresis</td>
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<td>$D$</td>
<td>diffusion constant</td>
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<td>$h$</td>
<td>droplet height</td>
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<td>evaporative flux</td>
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<td>$L$</td>
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<td>$\dot{M}$</td>
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### Greek Symbols

<table>
<thead>
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<tr>
<td>$\alpha$</td>
<td>heat transfer coefficient</td>
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<tr>
<td>$\theta$</td>
<td>contact angle</td>
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<tr>
<td>$\kappa$</td>
<td>thermal conductivity</td>
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<tr>
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<td>density</td>
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<tr>
<td>$\sigma$</td>
<td>surface tension</td>
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### Subscripts

- $g$: gas
- $l$: liquid
- liq: liquid
- mix: gas–vapor mixture
- sur: surface
- $v$: vapor
- $w$: wall

In the field of heat and mass transfer, evaporating sessile droplets have been studied in the context of thermal management applications. For example, in spray cooling (Kim, 2007) the significance of the contact line length per unit area of the heated surface is often emphasized in the discussion of heat transfer efficiency. The spray–wall interaction is a complex set of phenomena since the liquid–gas interface deformations are coupled to the liquid flow, heat transfer, and phase change. However, there are flow regimes involving surfaces covered by individual droplets that do not merge as they evaporate and spread. Clearly, understanding the evolution of the size and shape of an evaporating sessile droplet on a heated surface is important in determining the overall heat transfer rates in such spray cooling regimes, as well as in interpreting the data on the dependence of the heat transfer coefficient on the contact line length. Two-phase flow in a rectangular cross-sectional channel is another configuration that can be used in thermal management applications. For several experimentally observed flow regimes, the gas phase in the channel remains separated from the channel walls by liquid films. However, recent experimental studies (Chinnov and Kabov, 2011) have shown that these films can break up into individual droplets. The intensity of the evaporation of these droplets is an important factor in the overall heat transfer in the system.

In the presence of substrate heating, the main driving force for evaporation is still determined by the vapor concentration gradient at the droplet surface; however, other factors also play an increasingly important role as the substrate temperature increases. These factors include Marangoni stresses at the liquid–gas interface; heat transfer in the liquid, gas, and substrate; and convective flow in the gas phase.

Next, we will discuss the key studies that have elucidated the role of these factors and their coupling to the diffusion process and wettability effects. The temperature along the droplet surface is non-uniform due to evaporation, leading to the Marangoni effect, which is usually modeled through a linear dependence of the surface tension on the local temperature. Detailed studies of the Marangoni effect were carried out by Hu and Larson (2005) using finite-difference simulations. Note that these stresses affect both the liquid motion and heat transfer.

Evaporation also can lead to local cooling of the substrate under the droplet. Several models investigate this effect. Sodtke et al. (2008) developed a model of a thin evaporating droplet that predicts the local depression of the temperature profile near the contact line and conducted experimental measurements using thermochromic liquid crystals, which confirmed this result. However, this work was limited to the case in which the gas phase above the droplet was pure vapor (Ajaaev, 2005). For the case of evaporation into a gas–vapor mixture, detailed investigations of the effects...
of substrate thermal conductivity were carried out by Dunn et al. (2009). They approximated the local concentration of the vapor near the interface as a linear function of temperature, while the latter temperature was found through the solution of the coupled heat transfer problem. Both theoretical results and experiments (David et al., 2007) indicate that higher thermal conductivity leads to faster evaporation of the droplet. This is expected since vapor diffusion in the ambient gas is determined by the vapor concentration near the liquid–gas interface. This local saturation concentration at the interface depends on the local interface temperature and local pressure in the gas phase. The interface temperature, in turn, depends on the heat transport in both the droplet and substrate. Evaporation is accompanied by the cooling of the interface due to the latent heat. If the thermal conductivity of the substrate is low, then the heat transport between the droplet and the substrate is slow and there is stronger cooling of the droplet than in the case of a substrate with high thermal conductivity. The lower interfacial temperature corresponds to the lower saturation concentration of the vapor, and therefore to the lower diffusion rate in the gas and lower evaporation rate of the droplet.

A more recent study pointed out that the quantity called effusivity should be used instead of thermal conductivity to describe the effects of heat conduction in the substrate (Sobac and Brutin, 2012). This study also emphasized the effects of unsteady heat conduction. Note that many previous studies assumed that temperature fields in the substrate and droplet, as well as the vapor concentration field in the gas phase, are all quasi-steady. To justify these assumptions, the characteristic times of heat conduction (or vapor diffusion) were estimated based on the characteristic size and thermal diffusivity (or vapor diffusion coefficient). These times often turned out to be much smaller than the total evaporation time. However, the aforementioned assumption does not hold for the case where the heat transfer coefficient between the back side of the substrate and the ambient gas is low, which is typical in situations involving free convection. In the limiting case of insulating substrates, the temperature at longer times changed linearly with time. Moreover, the temperature field in the steady state is determined by the thermal conductivities of the phases involved. The influence of thermal effusivity on the droplet dynamics discussed in Sobac and Brutin (2012) is a clear indication of the effect of transient heat conduction on the evolution of an evaporating droplet. Further numerical studies of coupling between vapor diffusion and substrate conductivity were carried out by Ait Saada et al. (2013). Gatapova et al. (2014) focused on the combined effects of substrate heating and wettability. They carried out experimental and theoretical studies on the evaporation of water droplets on a heated solid substrate with relatively large drops and large temperature differences between the substrate and ambient air. Different values of wettability were considered and the three modes of evaporation (pinned, receding contact line, and stick–slip) were analyzed. It was reported that the specific evaporation rate is inversely proportional to the contact radius and it increases drastically at the final stage of the drop’s life, particularly in small contact angle hysteresis (CAH). The rate diverges at the end when the radius tends to zero. Good agreement between the experimental and theoretical results was demonstrated.

The question of the impact of the gas phase on the temperature distribution and evaporation intensity is still unclear and requires more analysis. For the relatively large temperature difference between a heated substrate and ambient gas ($T_w - T_g$), the convective thermal transport in the gas phase becomes of great importance and should be carefully investigated. An empirical model that takes into account the combined diffusive and convective transport was developed by Kelly-Zion et al. (2011) and Carle et al. (2013). The convective contribution to the evaporation rate was estimated by a correlation with the Grashof number. In Gatapova et al. (2014), the heat exchange with the gas phase and evaporation was analyzed and the importance of the heat exchange with ambient gas was shown.

The objectives of the present study are twofold. First, we provide a detailed discussion of two recently developed models of evaporating sessile droplets. Second, we investigate experimentally how the surface temperature and roughness affect the droplet evaporation for surfaces of identical chemical properties, with a focus on the effects of contact line hysteresis.

2. MATHEMATICAL MODELS

2.1 Modeling with the Contact Angle of Quasi-Stationary Evaporation

The evaporation process is modeled using an ellipsoidal cap shape coupled with the heat and mass transfer problem and considering heat conduction and diffusion equations with appropriate boundary conditions. The time dependence is modeled using the calculation of the evaporated liquid volume for each step. The droplet shape is defined by the
function \( S(r, t) \):

\[
S(r, t) = b \sqrt{1 - \frac{r^2}{a^2}} - \frac{h^2}{r_b \tan \theta - 2h}
\]

For \( r \leq r_b \), where \( h \) is the height of the droplet

\[
a = \frac{r_b (r_b \tan \theta - h)}{\sqrt{r_b \tan \theta (r_b \tan \theta - 2h)}} \quad \text{and} \quad b = \frac{h (r_b \tan \theta - h)}{r_b \tan \theta - 2h}
\]

are the semi-major and semi-minor axes.

The heat and mass transfer described by the diffusion and heat conduction equations in the wall and liquid phases are

\[
\Delta T = 0 \\
\Delta C = 0
\]

The heat exchange with the gas phase at liquid–gas interface \( S \) is described as follows:

\[
-\kappa_i \frac{\partial T}{\partial n} = L J + \alpha (T - T_g)
\]

where \( L \) is the latent heat of evaporation, and \( \alpha \) is the heat transfer coefficient. This condition can be interpreted as the energy balance at the liquid–air interface and indicates that the heat flux from the liquid droplet goes to the phase change at the interface and heat loss goes to the air. The evaporative mass flux is specified using the concentration at the liquid–gas interface:

\[
J = -D \frac{\partial C}{\partial n}
\]

where the equilibrium concentration at the liquid–gas interface depends on the temperature:

\[
C(T) = C_0 + C_1 (T - T_g)
\]

Far away from the droplet surface in the gas phase the concentration and temperature of the vapor in air is known, where \( T_w \) is the temperature of the wall.

The model is valid for any contact angle. One of the goals is to investigate liquid droplet evaporation when the size of the drop is relatively large, such that the contact radius of the droplet is larger than the capillary length. The peculiarity of our problem is that the temperature difference between the solid substrate and the atmosphere \((T_w - T_g)\) is in the range of 0°–90°C.

In order to calculate the local mass flux \((J)\), we organize the iterative procedure. For the first step in the calculation, the evaporative mass is assumed to be very small (an order of magnitude less than the minimum value of the specific evaporation rate at the beginning of droplet evaporation). Then, in the second step we calculate the temperature profile on the droplet surface \( T(S) \). Knowing the temperature profile on the droplet surface we find the local evaporation mass flux \((J)\), global evaporation rate \((\dot{M})\), and evaporated volume \((V_i)\). Then, we turn to the second step. Since we know evaporated volume \(V_i\), we define the droplet shape for the next step. Here, we note that for the case of a small contact angle the temperature at the liquid surface can be written as follows:

\[
T(S) = \frac{\kappa_i T_w + S(r) (\alpha T_g - L J)}{\alpha S(r) + \kappa_i}
\]

It should be pointed out that for this formulation of the problem the temperature field is dependent on the droplet profile, and as a result the mass flux strongly depends on the droplet profile and temperature.

Figure 1(a) illustrates the droplet surface temperature profiles at different temperature differences. There is a noticeable increase in the temperature close to the periphery of the droplet near the contact line [Fig. 1(a)]. This leads to an increase in the evaporative mass flux near the contact line [Fig. 1(b)]. It is important that the concentration...
distribution on the liquid–gas interface strongly depends on the drop surface temperature distribution. The size and volume of the drop can be relatively large, which implies that there is an inhomogeneous temperature distribution. This can strongly affect the evaporation intensity. Based on our model, we conclude that heat transfer to the gas phase influences the droplet surface temperature and evaporation flux due to the energy balance on the liquid–gas interface, and this should be properly incorporated into the model.

The results of the proposed approach were compared with the experimental data. The specific evaporation rate (evaporation speed) is defined as the ratio of global evaporation rate $\dot{M}$ to droplet surface area $A$. The global evaporation rate is calculated as a surface integral of local mass flux $J$ over the surface of the drop, $A$. The calculated specific evaporation rate was in excellent qualitative and quantitative agreement with the experimental data (Gatapova et al., 2014). The present model of drop evaporation allows us to estimate the value of the specific evaporation rate.

### 2.2 Thin Evaporating Droplet

Since the problem of coupling between heat transfer in the substrate, fluid flow and evaporation in the droplet, and diffusion of gas above the droplet is rather difficult to ascertain mathematically, we start with a simple configuration that involves a droplet with a wetted radius much larger than its maximum height, which is referred to as thin droplet. The treatment here is based on the recently developed numerical approach applied to the conditions when the contact line is pinned. For the sake of completeness, we repeat several aspects of the method here.

Let us introduce the concentration variable $C$ defined as the ratio of the dimensional value of the concentration to the concentration at ambient temperature far away from the droplet. The nondimensional temperature is defined as the dimensional value scaled by the ambient temperature. The scaled governing equations are then written in the following form:

\[
\begin{align*}
C_t &= D \nabla^2 C \\
T_t &= \nabla^2 T
\end{align*}
\]

where the first equation refers to the dynamics of the vapor concentration in air and the second one refers to the heat conduction in the substrate. The geometry is assumed to be axisymmetric, with the cylindrical coordinates $r$ and $z$. 

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**FIG. 1:** The influence of the temperature difference at contact angle is 67° on a water droplet: (a) temperature along the droplet surface at different substrate temperatures; (b) mass flux at the liquid–air interface.
scaled by the substrate thickness. The standard adiabatic boundary conditions are imposed at the side boundaries of a cylindrical computational domain of radius $R$ that is much larger than the wetting radius of the droplet. The value of the scaled concentration away from the droplet is given by the fixed value of the relative humidity ($H$) such that

$$C \rightarrow H, \quad \text{as} \quad \sqrt{r^2 + z^2} \rightarrow \infty$$

At the axis of symmetry, the conditions for both concentration and temperature take the following form:

$$C_r = 0, \quad T_r = 0, \quad \text{at} \quad r = 0$$

The coupling between diffusion and heat transfer at the liquid–gas interface is described by the following interfacial conditions:

$$\mathbf{n} \cdot \nabla T = \hat{E} \mathbf{n} \cdot \nabla C$$

$$C = 1 + \alpha (T - 1)$$

$$\hat{E} = \frac{k_l T^*}{LDC_0}$$

$$\alpha = \left. \frac{T^*_\infty dC}{C_0 dT} \right|_{(T= T^*_\infty)}$$

The first of these equations relates the heat flux at the interface and the mass flux in the vapor phase, while the second equation defines the local concentration as a function of the temperature using a linear approximation.

The solid substrate is assumed to be insulated at the side boundaries, such that

$$T_r = 0 \quad \text{at} \quad r = R$$

while the bottom temperature is fixed:

$$T = T_b \quad \text{at} \quad z = -1$$

The temperature is continuous at the solid–liquid boundary, while the heat losses from the liquid to the gas phase are modeled using a Biot number:

$$T_z = Bi (T - 1) \quad \text{at} \quad z = h(r,t)$$

On the dry portion of the substrate, no penetration condition is satisfied, such that

$$C_z = 0 \quad \text{for} \quad z = 0, \quad r > R_w$$

where $R_w$ is the wetted radius of the droplet. The droplet evolution is described by the equation for its nondimensional height

$$h_t + J + (3r)^{-1} \left[ r h^3 (h_{rr} + r^{-1} h_r) \right]_r = 0$$

with the condition of the pinned contact line [$h(R_w) = 0$] and the symmetry conditions

$$h_r = h_{rr} = 0 \quad \text{at} \quad r = 0$$

Initially, the temperature is assumed to be equal to the ambient temperature, and the concentration is the value determined by the ambient gas humidity ($H$).

### 2.3 Numerical Procedure and Results

The governing equations are discretized using uniform finite-difference methods, and the evolution over time is then traced using the method of lines with standard backward differentiation formula solvers for stiff systems of differential equations. The diffusion equation is discretized using the centered-difference approximation, and the same approach is taken for the heat equation. The result is a banded system of ordinary differential equations, which is then solved using
the SUNDIALS package (Lawrence Livermore National Laboratory, Livermore, CA, USA). Nonuniform mesh is used such that one-half of the radial grid points are located in the first 10% of the radial length. Extensive convergence studies were conducted to verify the accuracy of the numerical package by grid refinements. The convergence results are in agreement with the theoretical predictions. Typical simulation results based on this model are shown in Fig. 2, which illustrates a concentration snapshot as a function of spatial coordinates. Figure 2 clearly shows a high spatial gradient in the concentration field in the region where the local evaporative flux reaches its maximum, i.e., near the contact line.

The changes in droplet size as a result of evaporation were analyzed. Typical results are shown in Fig. 3 for the volume of the droplet as a function of time for different liquids. It is interesting to point out that the overall behavior of the volume is not very sensitive to the liquid properties when the time is scaled appropriately, even though the details of the flux distributions seen in the simulations are. Also, it is important to note that dimensional time scales of evaporation can be significantly different for different liquids.

The substrate conductivity is an important parameter since it defines the rate of evaporation. Figure 4 shows the simulation results for several different substrates. First, we note that all metals are highly conductive substrates, such that the liquid–solid temperature for all of them can be assumed to be nearly constant. Thus, the rate of evaporation and the resulting shape changes tend to be very similar, as seen in the comparison of the radius curves corresponding to different metals in Fig. 4. Note that initially the contact line is pinned, and then it is unpinned as a result of evaporation. The glass substrate is much less thermally conductive, resulting in a different droplet radius curve.

**FIG. 2:** Concentration distribution obtained from the thin droplet model at \( H = 0.4 \)

**FIG. 3:** Dimensional volume as a function of scaled time for four different liquids
3. EXPERIMENTAL EQUIPMENT, MATERIALS, AND METHODS

3.1 Experimental Setup

The tests of water drop evaporation into the atmosphere were carried out at the experimental setup shown in Fig. 5. The test section was a 50-mm-thick aluminum plate; the heater was located on its lower side. A 40 × 40 mm² Peltier element was used as a heater. The tested substrate in the form of a 52-mm-diameter and 3.2-mm-thick disk was mounted on the upper side of the aluminum plate. The temperature of the substrate was measured by a flat thermocouple fixed at a distance of 1–2 mm from the contact line of a liquid drop. The temperature under the substrate was measured by two K-type thermocouples. These thermocouples were located at different radial distances from the center of the disk and allowed the measurement of the temperature distribution along the substrate radius. Three different substrates were used in the studies. Two substrates were made of float glass with a nano-coating, consisting

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**FIG. 4:** Dimensional radius as a function of time for water droplets on five different substrates

**FIG. 5:** Sketch of the experimental setup
of optical quality metal (gold or aluminum): the spin Teflon coating was obtained by centrifuging the drops of molten Teflon (the hysteresis of the contact angle is determined as the difference between the advancing and receding contact angles, \( \Theta_h = \Theta_a - \Theta_r = 122.5^\circ - 112.7^\circ = 9.8^\circ \)); and the spray Teflon coating was deposited by spraying Teflon particles (\( \Theta_h = 119.9^\circ - 90.6^\circ = 29.3^\circ \)). The third substrate of stainless steel had a developed rough texture of the working surface, which was obtained by bombarding the surface with calibrated aluminum oxide particles. The roughness of this surface was about 5 µm. The relative air humidity in the room during the experiments was 20%–30%.

Two optical methods were used in the experiments. The first one was the shadow method, which used a telecentric light source and camera. A red light-emitting diode (Thorlabs) and a lens system, which created a parallel light beam at the outlet, were used as the light source. A NIKON D200 camera with a macro-lens Nikon 105 mm f/2.8G IF-ED AF-S VR Micro-Nikkor was used in the regime of 1:1 to shoot the profile of the studied object in the light. The spatial resolution of this system was 6 µm/pixels and the shooting frequency ranged from three to eight frames per second. The shadowgraphs of the liquid drop profile were obtained by the shadow method. The images were processed by the software package Drop Shape Analysis developed by KRUSS. The shadowgraph was used to choose the drop profile by the Young–Laplace method. Then, the geometrical parameters of a liquid drop, such as the base and maximal diameters, height, volume, contact angles, surface area, and base area were determined. The second optical technique used a digital video camera (Imaging Source with a resolution of 5 megapixels), which was placed above the liquid drop and allowed visualization of the evaporation process from the top and control of the drop symmetry. If the drop lost its symmetry, the experiment was repeated.

The experiment started with pretreatment of the substrate; the working surface was thoroughly cleaned, and then the entire substrate was placed into a tank filled with distilled water for a day. Thereafter, in order to remove residual water from the surface, the substrate was blown by clean compressed air used to clean the optical components. A liquid drop of the predetermined volume was placed on the surface and heated to the desired temperature by an electronic syringe. The shadow method lens was focused (the depth of the field was a few millimeters), and then periodic shooting was done with steps of 10 seconds until the liquid drop was completely evaporated. The upper camera was switched on in advance and registered the evaporation process at a frequency of 1 Hz.

### 3.2 Experimental Results

The accuracy of the measurements of the key quantities characterizing the droplet, such as the volume and contact angle, depends on accurate optical recording of the droplet. Figure 6 shows a sample set of optical recordings of droplet shapes for three substrates studied, taken at different times. The difference in the contact angles between the different substrates is clearly seen.

Let us now separately discuss the results for the different substrates. We start with the set of experiments designed to investigate how the substrate roughness affects the dynamics of evaporation for substrates with the same chemical composition. Two Teflon substrates were compared: a spray Teflon and a spin Teflon. Figure 7 illustrates the key parameters of evaporation plotted as a function of time for the spray Teflon. Let us discuss each plot. The contact angle plot [Fig. 7(a)] shows the two-stage dynamics seen in other experiments and predicted by the models: slow variation initially followed by rapid decay at the final stages of droplet lifetime. The base diameter [Fig. 7(b)] is important to evaluate the degree of pinning of the droplet. Clearly, for spray Teflon the contact line is only pinned during an initial time interval, on the order of 200 s, and is mostly independent of heating. After that, the contact line is not pinned and the base diameter is in a nearly linear fashion until rapid dynamics is observed at the final stages of the droplet lifetime. Both the height and volume of the droplets start off in a nearly linear fashion, but then the decrease in height slows down while the decrease in volume speeds up as the base diameter of the droplet decreases sharply. When the evaporation rate is divided by the surface area, as shown in Fig. 7(e), the result shows a sharp increase at the later stages of the droplet lifetime. The nature of this physical phenomenon is, in fact, similar to the case of spherical droplets surrounded by gas. The latter have been studied extensively and the experimental data are well described by the theories based on a simple view of diffusion-dominated evaporation.

The results of the corresponding measurements for spin Teflon are shown in Fig. 8. The decrease in the contact angle is much sharper and the contact line stays pinned for a significantly longer period of time. We note that the
FIG. 6: Evolution of droplets during evaporation on different surfaces with the same temperature $T_s = 65^\circ$C

<table>
<thead>
<tr>
<th>t, s</th>
<th>Spin Teflon</th>
<th>Spray Teflon</th>
<th>Stainless Steel</th>
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chemical composition and the thermal properties of the two substrates are similar; therefore, the only possible explanation for the observed stronger pinning has to do with changes in the surface roughness and corresponding CAH. Sharper reduction in height is seen than in Fig. 7, while the dynamics of the volume change is qualitatively similar. Finally, the effect of a sharp increase in the evaporation speed (rate per unit surface area) is seen in the case of spin Teflon as well.

In order to better understand the difference between the two substrates discussed previously, we investigated their properties using microscopy. Figure 9 illustrates the results of this study. Spray Teflon clearly shows a significant degree of roughness, which is related to the production method involving spraying of small particles.

Clearly, the substrate temperature has a significant effect on the droplet’s dynamics. Therefore, Fig. 10 shows the dynamics of the droplet evolution for the two surfaces considered at the same temperature, in which a corresponding plot of the highly conductive stainless steel substrate is added to clarify the effect of substrate conductivity. We first note that the droplets evaporate significantly faster on the steel substrate. This can be explained by the fact that the higher thermal conductivity of the material implies that the temperature of the solid surface under the droplet, including the contact line region, leads to higher evaporation rates. There is also significantly stronger pinning for the stainless steel substrate. The volume evolution is nearly linear since the substrate temperature under the droplet remains nearly constant due to the relatively high thermal conductivity of the substrate.

4. CONCLUSIONS

We conducted numerical simulations and experimental studies of evaporating droplets on different substrates. The coupled effects of droplet wettability and heat conduction in the substrate are discussed, with emphasis on how they influence the heat and mass transfer and evaporation rate of the droplets. The first mathematical model is based on a coupled description of vapor diffusion and heat transfer when the heat loss to air is incorporated at the liquid–gas interface. The droplet shape is parametrized by an analytical expression and the concentration of vapor is assumed to depend on the surface temperature. The droplet surface temperature is found to increase near the contact line, giving an increase in the mass flux near the contact line. The second model assumes the droplet is thin, making it easier to
**FIG. 7:** Characteristics of evaporating droplets as a function of time for the spray Teflon substrate, where different curves correspond to the following: 1, surface temperature $T_s = 55^\circ$C; 2–5, $T_s = 65^\circ$C (four runs); 6, $T_s = 75^\circ$C; 7, $T_s = 85^\circ$C
FIG. 8: Results for spin Teflon: 1, surface temperature $T_{sb} = 65^\circ$C; 2, $T_{sb} = 75^\circ$C; 3, $T_{sb} = 85^\circ$C
study coupling between vapor diffusion and substrate heat conduction. The results from the computations based on the model show strong evaporation near the contact line and a higher droplet radius for less conductive substrates.

The experimental studies of evaporation of droplets on different surfaces show much faster evaporation on more conductive surfaces. The temperature of the substrate is found to play an important role in the evaporation intensity and droplet lifetime. We note that the droplets evaporate significantly faster on a steel substrate than on glass with Teflon coating. This is explained by the fact that the higher thermal conductivity of the material implies that the temperature of the solid surface under the droplet, including the contact line region, leads to higher evaporation rates. The droplet on the stainless steel substrate shows also significantly stronger pinning. For the relatively high thermal conductivity the substrate temperature under the droplet remains nearly constant which leads to nearly linear evolution of the droplet volume.

A comparison between spin Teflon (with low CAH) and spray Teflon data is used to illustrate the effect of the wetting properties of the substrate at different temperatures of the substrate. A much sharper decrease in the contact angle and longer contact line pinning are found for spray Teflon, which is explained by the larger CAH.

**FIG. 9:** Microscopic images of the substrate with Spray Teflon coating at optical magnification of 500 (a) and 1000 (b)

**FIG. 10:**
FIG. 10: Comparison of the results on different surfaces, where the droplet evaporated at $T_s = \text{65°C}$: 1–3, spray Teflon (three runs); 4, spin Teflon; 5–7, stainless steel (three runs); the results show the following quantities as a function of time: (a) contact angle; (b) base diameter; (c) height; (d) volume; (e) base area; (f) evaporation speed

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