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Evaporation of a sessile drop with pinned or receding contact line on a substrate with different thermophysical properties

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ABSTRACT

Effect of substrate thermophysical properties on the evaporation of a sessile drop of water in surrounding moist air is investigated by means of a quasi-steady state diffusion model. The situation of a non-heated solid substrate is invoked and both pinned and de-pinned drops are considered. The used numerical approach allows a full coupling between the three coexisting phases by solving water vapor diffusion equation in the surrounding air and heat conduction equation in all three phases. Results show that, for both pinned and de-pinned drops, a decrease in thermal conductivity of the substrate or an increase of its thickness has a cooling effect on the drop and expands the cold zone close to the liquid–gas interface. Furthermore, the overall heat and mass transfer rates at the liquid–gas interface vary between two limiting values. The maximum evaporation rate is obtained when the drop is on a substrate with very high thermal conductivity or on a very thin substrate. In this case, the drop is mainly supplied with heat from the substrate. The minimum evaporation rate is obtained when the drop is on a perfectly insulating substrate or a very thick substrate. In that case, the needed energy for evaporation is taken mainly from the gas phase. The numerical predictions also highlight different evaporation rate and evaporation flux for pinned or de-pinned drop and they depict a higher evaporation time for the latter.

1. Introduction

Evaporation of liquid drops on solid substrates is a fundamental phenomenon in nature and a process which is very often encountered in industry. The physics of evaporation in presence of three phases, solid, liquid and gas with different thermophysical properties is very complex because of the coupling between hydrodynamics, heat and mass transfer. Understanding the basics of a sessile drop evaporation is essential to handle more complex situations encountered in industry such as in biochemical and pharmaceutical processes, deposition of DNA/RNA micro-arrays, painting, spray cooling, inkjet printing technique in microelectronics, thin film coating and many others.

Various physical aspects like surface wettability, fluid thermophysical properties effect and dynamics of the contact line were previously explored [1–15]. Other studies [20–29] dealt with cooling of the drop surface and conduction heat transfer in the substrate. Convective heat transfer induced by surface tension gradients and due to temperature gradients in the liquid drop [21–23] as well as buoyancy convection in the gas [26,27] were also investigated. A review of published papers on the topic over a period of 120 years was recently presented by Erbil [1]. Most of the review was devoted to the discussion of basic theory on the effects of initial contact angle, drop cooling and substrate thermal conductivity. Picknett and Bexon [2] were the first to report on the substrate effect. They also distinguished between the constant base area evaporation and the constant angle mode and they proposed a theory to predict the evaporation rate in terms of a function of the contact angle $f(\theta)$. Thereafter, other experiences were carried out to study the wettability effect. Some authors proposed approximate solutions for $f(\theta)$ [3,4,9] whereas others [5–8] developed diffusive evaporation models ignoring the $f(\theta)$ factor. Recently, Song et al. [9] experimentally investigated the evaporation of water drops on hydrophilic and hydrophobic surfaces. They observed both the pinned and receding contact line evaporation. Their results illustrated the surface roughness effect on the evaporation rate. They proposed a more accurate empirical linear function $f(\theta)$ for hydrophilic and hydrophobic surfaces rather than using previous theoretical models [2–4]. Hu and Larson [10] investigated the evaporation of a pinned sessile drop by applying both analytical theory and numerical computations. They found that the evaporation rate remains almost constant with time for initial contact angle lower than 40°. They also showed that the evaporation flux increases along the drop surface from the apex to the contact line. Such distribution of the evaporation flux generates

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Nomenclature

c_p	specific heat, J/kg K
C	concentration, kg/m^3
C_v	saturated vapor concentration, kg/m^3
D	vapor diffusion coefficient in gas, m^2/s
g	gravitational acceleration, m/s^2
h	height of the drop surface
H_α, H_β, H_ϕ	dimensionless metric coefficients according to α, β, ϕ, respectively
$h_{\ell g}$	latent heat of vaporisation, J/kg
H_a	relative humidity
Ja	Jacob number, $h_{\ell g}/(c_{pg}T_\infty)$
k	thermal conductivity, W/m K
Le	Lewis number, α_{Tg}/D
J	evaporation flux, kg/m^2 s
$\dot{M}$	overall evaporation rate, kg/s
q	local heat flux, W/m^2
Q	overall heat flux, W
Rc	thermal conductivity ratio, k/k_ℓ
R	contact radius, m
r, z	cylindrical coordinates, m
r', φ	spherical coordinates, m
S	surface of the drop, m^2
V	volume of the drop, m^3
T	temperature, °C

Greek symbols

ΔC	concentration difference, $(1 - H_a)\ C_v(T_\infty)$
α, β, ϕ	toroidal coordinates, rd
α_T	thermal diffusivity, m^2/s
ρ	density, kg/m^3
μ	dynamic viscosity, kg/m s
θ	contact angle, °

Subscripts

s, ℓ, g	solid, liquid, gas
0	beginning of the evaporation
∞	at the infinite in the gas region

Superscripts

$*$	dimensionless variable

flow inside the drop, which transports solid particles to the edge of the drop [11–15]. In this context, the thin liquid film evaporation near the contact line may play an important role in sessile drop evaporation. Plawsky et al. [16] presented a review on the current state of the art in nanoscale surface modification as applied to the enhancement of evaporative processes that occur at contact line. Other authors [17–19] discussed the effects of temperature-dependent thermophysical properties, liquid velocity slip and interface temperature jump on the thin film evaporation.

Many experiments have demonstrated that the evaporation phenomenon is an endothermic process causing cooling of the liquid–gas interface. The resulting temperature gradients on the drop surface can induce convective flow in the drop due to thermocapillary or buoyancy effects. While the cooling effect is only determined by the evaporation rate for an isolated spherical drop, it can also be linked to thermal properties of the substrate in the case of a sessile drop. David et al. [20] were the first to show that the drop evaporation induces an important cooling effect when the substrate is a thermal insulator. They conducted experiments using small droplets of three different liquids (acetone, methanol and water) on thin substrates made of aluminum, titanium, macor and PTFE. No surface cooling was noticed for aluminum or titanium substrates, but a maximum cooling of 1.6 °C was measured on PTFE substrates. Ristenpart et al. [21] investigated theoretically and experimentally thermocapillary convective flow inside sessile drops of organic liquids. They established criteria for flow direction and magnitude according to the contact angle and the ratio of substrate and liquid thermal conductivities. Numerical predictions of Hu and Larson [22] showed that the flow direction reverses at a critical contact angle. Xu et al. [23] added that the flow direction is also dependent on the ratio of the substrate thickness to the base radius of the droplet. Dunn et al. [24] formulated and solved a mathematical model for the quasi-steady diffusion-limited evaporation of a thin axisymmetric sessile drop with a pinned contact line. The predictions of the model allowed capturing the experimentally observed dependence of the evaporation rate on thermal conductivity of the liquid and the substrate and on the atmospheric pressure. These authors used their previous model to analyze the quasi steady evaporation of a thin liquid droplet on a thin substrate with a high thermal resistance [25]. Dunn et al. [26] generalized their model to study the case of a bigger droplet on a thick substrate. In addition, they showed that including two ad hoc improvements to the model, namely a Newton's law of cooling on the nonwetted surface of the substrate and the buoyancy of water vapor in the atmosphere, gave excellent quantitative agreement for all of the combinations of liquids and substrates considered. Ait Saada et al. [27] analyzed the effect of buoyant convection in the surrounding air. They developed a mathematical model that takes into account the cooling of the surface of an evaporating drop on a substrate of infinite thermal conductivity. Their numerical predictions showed that the rate of evaporation of a water drop on a solid surface is underestimated by more than 8% while using a diffusion model. Sefiane et al. [28] investigated the effect of different surrounding gases on the evaporation of a water drop on different substrates. The effect of environment pressure was analyzed and an important cooling of the order of 20 °C was reported at 40 mbar. Recently, Sefiane and Bennacer [29] used an electrical analogy to predict the evaporation rate reduction due to cooling effect and proposed a correlation, based on linear or quadratic dependency of concentration on temperature. Referring to the works of Dunn et al. [24–26] and Sefiane et al. [28,29], it appears that the study of thermal effect is limited to cooling of the drop surface and heat conduction in the substrate in the case of pinned contact line during evaporation. The receding contact line is another evaporation mode for which the drop cooling can behave differently depending on the substrate thermal conductivity. This aspect was never studied in the literature and it will be addressed in the present work. As the evaporation rate of a drop was shown to be dependent on the substrate thermal conductivity [20,26], it could be evidenced that it depends also on the substrate thickness. In addition, heat transfer in the gas phase is not taken into account in the proposed theoretical models [26,29] whereas it can contribute to evaporation particularly near the contact line where the heat and mass exchanges are strong [27]. Thus limiting the thermal analysis to the temperature field only is not sufficient to show the importance of thermal effects. It is necessary to complete this by the analysis of the heat transfer rate at local and global scale on both sides of the drop surface.