Evaporation rate of drop arrays within a digital microsystem.

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Abstract

One essential advantage of digital lab-on-chips (LOC) is based on massive parallelization of biochemical functions achieved from moving drops by surfaces acoustic waves or electrowetting (EW). This paper aims at characterizing the evaporation rate of a population of drops in EW-based microsystems due to their relevant applications. Up to now, and despite its importance for end-users, the evaporation rate of one target drop selected among a population of drops has never been measured. This is essentially due to the difficulty of developing imaging of a time-dependent drop size under evaporation in confined microsystems. Interferometry, jointly used with EW in the oscillating regime [1], is proposed as a new (non-imaging) evaporation rate measurement method fully compatible with EW-based LOCs and easy to be integrated into closed or open geometries. In this paper, we investigate the impact on drop evaporation of different arrangements of drops and different degrees of confinement.

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1. Introduction

In the past years, more and more applications of digital microfluidics using electrowetting on dielectrics (EW) have emerged. Besides drop-based lenses and displays, the main users for this technique are lab-on-a-chips (LOC) [2]. Recently, an application of EW for cooling of processor units was published [3]. For the last two techniques, evaporation is either not wanted or deliberate, respectively. In either case, it is important to evaluate the evaporation in these microsystems. They involve normally not only one single drop, as their strong point is the possible parallelization of multiple drops in a drop array, which makes it eventually difficult to properly evaluate evaporation in the system via imaging.

Here, evaporative mass transfer of a \( \mu \text{L} \)-sized drop in a drop-array environment is investigated. Different drop patterns are proposed to compare the mass transfer of a drop in the center or at the edge of
a pattern. Different confinements are studied to examine the effects of a reduced drop array volume. The methodology is based on coplanar EW [4] and interferometry, to measure evaporation of a sessile drop, based on former work of the authors [1]: Use is made of dual-frequency electrowetting (DF-EW), adjusting the contact angle to a value of $\theta = \pi/2$ during the evaporation process. This constant contact angle mode of evaporation is described by the evaporation law $R(t)^2/R_0^2 = 1 - t/\tau_{\text{evap}}$ [5], where \( \tau_{\text{evap}} = R_0^2 \rho [2D_{\text{vap}} (c_0 - c_f)] \) is the evaporation time scale, \( R_0 \) the initial radius, \( \rho \) the water density, \( D_{\text{vap}} \) the diffusion coefficient of water vapor in the ambient air, \( c_0 \) and \( c_f \) are the concentrations of water vapor at the interface and far from it, respectively. The drop is brought to oscillate by perturbation of the actuation voltage between the EW electrodes. The resonance spectrum of the capillary oscillation depends on the radius, which is calculated progressively in the course of evaporation. An advantage compared to the imaging method is the measurement of evaporation in a confined environment with a drop distribution, which might hinder imaging. This is usually encountered in LOCs, since parallelization of tasks is one of the goals of these systems. The technique is compatible with integration requirements for digital LOCs.

2. Interferometry, electrowetting, liquid and geometries

A dedicated Michelson interferometer is developed for measurement of the vertical drop apex motion. All details on interferometry and EW technology are described in [1]. The water drops with an initial volume of 1.5 $\mu$L have a surface tension of 57 mN/m. The EW chip is positioned on a Plexiglas support, which can be covered by a Plexiglas lid (53x56 mm$^2$ bottom area, cf. figure 1b). The lid has an opening of 12 mm$^2$ above the measured drop to allow the laser beam to pass. Into the lid can be inserted slides of different thickness to adjust the vertical confinement. Four confinements are tested: a) no confinement (no lid), b) a confinement of 12 mm, c) 6.5 mm and d) 3 mm. The different drop arrays are shown in figure 1a). A single drop, a line of three drops and a die-like five arrangement are chosen. The drop patterns are as follows: 1) single drop, 2) line of three drops, 3) five drops (die, measurement in the center), 4) five drops (die, measurement at the corner) and 5) single drop with a water-filled U-shaped channel (figure 1b(5)). In addition to this, for drop pattern 3), drops are added on the EW chip in a 4x5 square grid with 3 mm side length to have a total of twenty drops on the chip, as seen in figure 1b). In order to estimate the impact of the inter-drop distance, drop pattern 3) is modified by doubling (pattern 7) and reducing to the half (pattern 8) the distance between the drops (8.5 mm and 2 mm, respectively). The drops are deposited with a pipette and the lid is closed immediately. The ambient relative humidity and temperature throughout the experiments are between 56% to 60%, and 25.3°C to 26.8°C.

3. Results and discussion

The different drop patterns, 1 to 8, are tested with different confinements, a to d, and the results are presented in figure 2. The curves are non-dimensionalized by the initial radius, which has been extrapolated by a linear fit of $R(t)^2$. A distinct decline of mass loss due to evaporation is demonstrated when diminishing the vertical confinement from no confinement to 5 mm (a to c). Beyond the confinement c, the slower evaporation rate is only significant for a small number of sacrificial drops.

**Drop patterns and confinements:** The comparison between four sacrificial drops (pattern 3), and a single drop with a filled water bath, (pattern 5), is only significant for low confinements (confinement a (no lid) and confinement b (12 mm)). The water bath is less efficient than four sacrificial drops placed near the measurement site. For stronger confinements, water bath and sacrificial drops nearly exhibit the same efficiency in preventing evaporative mass loss ($\tau_{\text{evap}}^{\text{d-3}}/\tau_{\text{evap}}^{\text{d-5}} = 1.3$).
The 20 drop pattern with water bath (d-6), which exhibits the slowest evaporation kinetics, has a six-fold slower evaporation kinetics than a single drop without confinement, $\tau_{\text{evap}}^{d-6}/\tau_{\text{evap}}^{a-1} = 6.3$. Considering the influence of the position on evaporation, one may compare drop patterns 3 to drop patterns 4. For weak confinements (a and b), there is a great difference in evaporation kinetics, whereas for strong confinements (c and d), the position of the drop does not strongly influence the mass loss.

**Evaporation kinetics:** Concerning evaporation kinetics of the different patterns and confinements, one recognizes two different kinetics during the measurement, translated by the slope of the evaporation curves: When placing the lid onto the support, the drops will follow their non-confined evaporation regime, as long as the humidity under the lid will not change significantly. As this point is reached, the evaporation regime will change until a new equilibrium is found: the vapor exchange of the drop surfaces and the water channel (for some drop patterns) is equal to the vapor exchange between the inside and the outside of the lid, through the laser hole. The initial evaporation regime is entirely characterized by the pattern a-1. As the confinement and total initial water-air interface area is raised, the different evaporation kinetics will tend to the kinetics of pattern d-6, which for the geometry of the confinement discussed here, represents the slowest possible evaporation dynamics.

**Inter-drop distance:** Concerning the study on the inter-drop distance, one may refer to the drop patterns c-3, c-7 and c-8, represented in figure 3a). In comparison to the initial drop pattern c-3, drop pattern c-7 exhibits a time ratio of $\tau_{\text{evap}}^{c-7}/\tau_{\text{evap}}^{c-3} = 0.7$ (shorter evaporation time). Drop pattern c-8 exhibits a time-ratio of $\tau_{\text{evap}}^{c-8}/\tau_{\text{evap}}^{c-3} = 1.2$ (longer evaporation time). The inter-drop distance thus impacts significantly on the evaporation time scale. This is though only true for a strong enough vertical confinement. In these cases, evaporation might be considered being constrained to a horizontal 2D plane [21], which is a significant parameter for evaluating the effects of a modified inter-drop distance.

**Physical interpretation:** Fig. 3b) shows the evaporation curves, non-dimensionalized by $\tau_{\text{evap}}$ and the fitted initial radius. This graph shows that the evaporation law is valid for describing the evaporation of a population of drops in our confined system. The evaporation law is based on diffusion kinetics of the water vapor in the ambient gas phase. This leads to the time scale, $\tau_{\text{evap}} = R_0^2/\rho(2D_{\text{vap}}(c_0-c_f))$. When the inter-drop distance is altered, the governing factor for the evaporation time scale is the ambient vapor concentration $c_f$. This vapor concentration far from the drop surface is expected to rise when approaching the drops. It is expected to fall when increasing the distance between them, depending on the environment within the drop array. Other factors like $D_{\text{vap}}$ and $c_0$ should not be influenced so significantly.

4. **Conclusions**

Interferometry of drop shape oscillations is shown to be a convenient measurement and transduction mechanism to capture the evaporation dynamics of an evaporating drop in a closed microsystem. It is found that evaporation of drops inside a microsystem is difficult to predict unless the volume is completely sealed and the atmosphere is pre-humidified. Otherwise, an initial diminution of the drop volume can not be avoided. This is especially important for biological applications, for which the concentration of molecules as a control parameter is of utmost importance.

In this work, the impact of evaporation upon a single drop within a drop array environment has been examined with respect to the number of drops, the proximity of neighboring drops and the vertical confinement in the array. The efficiency of limiting evaporation by making use of a water bath or sacrificial drops is strongly dependent on the confinement. For biological applications, the vertical confinement needs to be smaller than 6 mm and any opening in the system leads inevitably to
evaporation-driven mass loss, even for multiple drop patterns. For cooling applications involving phase change of drops, the confinement should be no less than about 12 mm, in order not to influence the evaporation kinetics and to deliver an efficient cooling effect. The influence of the inter-drop distance has been evaluated for three distance values at a strong enough confinement. Its effect upon evaporation kinetics is significant, since the confinement gives rise to a quasi-two-dimensional evaporation process. Finally, the evaporation of a drop at the edge of a drop pattern is significantly faster for weak confinements while being no longer significant for strong confinements.

Fig. 1: A) Drop patterns: a black blank circle corresponds to a drop, a red shady circle corresponds to the measured drop. B) A sketch of the chip support: 1, lid; 2, confinement disk; 3, connection part for EW voltage; 4, EW chip; 5, chip support/water bath.

Fig. 2. All evaporation dynamics at a glance: the confinement is distinguished by letters a-d, the configuration by numbers 1-6.

Fig. 3. a) Evaporation dynamics for drop patterns 7, 3, 8 (confinement of 6.5 mm): The inter-drop distance is adjusted to 2 mm, 4.25 mm and 8.5 mm, respectively; b) Presentation of all experimental curves in non-dimensionalized form.

References