Effect of Substrate Properties on Droplet Evaporation Process (Postprint)

Authors: Liu Bin, Shan Liangliang, Di Qianqian, Yang Wen-zhe, Sun Chang

Date: 2017-11-07T00:00:00+00:00

Abstract

The droplet evaporation mechanism has currently attracted widespread attention. Through investigating the evaporation process of AL2O2 droplets with a nanoparticle mass concentration of 0. 05% on iron and glass surfaces, it was found that droplets exhibit four evaporation modes on iron surfaces: constant contact line mode, constant contact angle mode, stick-slip mode, and unstable mode; whereas on glass surfaces, only the unstable mode is observed. The main reason is that when droplets evaporate on iron surfaces, the solid-liquid surface tension is greater, leading to the formation of the constant contact line evaporation mode; as evaporation proceeds, the droplet temperature decreases and the gas-liquid surface tension increases, thereby giving rise to the stick-slip mode.

Full Text

Preamble

Effect of Substrate Properties on Droplet Evaporation Process

LIU Bin, SHAN Liang-Liang, DI Qian-Qian, YANG Wen-Zhe, SUN Chang
(Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin 300134)

Abstract: The mechanism of droplet evaporation has attracted considerable research attention. By studying the evaporation process of Al O nanofluid droplets with a mass concentration of 0.05% on iron and glass surfaces, we found that droplets exhibited four distinct evaporation morphologies on iron surfaces: constant contact diameter, constant contact angle, stick-slip, and unstable morphologies. In contrast, only the unstable morphology was observed on glass surfaces. The primary reason is that during evaporation on iron surfaces, the larger solid-liquid interfacial tension leads to the constant contact diameter morphology. As evaporation progresses, droplet temperature decreases and gas-liquid surface tension increases, resulting in the stick-slip morphology.

Keywords: droplet evaporation; stick-slip morphology; substrate; nanofluid

Introduction

The evaporation of liquids is a ubiquitous phenomenon in nature and human activities that has long attracted research interest, from dewdrops on plant leaves and petals to liquid droplets on tabletops. In 1997, Deegan first reported on this seemingly common phenomenon in *Nature*, introducing the "coffee ring effect" —the deposition pattern formed during droplet evaporation. This effect is closely related to evaporation modes and the dynamic motion of the three-phase contact line. For instance, coffee-ring patterns form due to outward flow caused by fixed contact line evaporation in solutions or suspensions, uniform patterns arise from interactions between evaporation dynamics and particles at the gas-liquid interface, and concentric rings result from alternating fixation and movement of the three-phase line during evaporation. Various internal parameters and external conditions can produce different deposition patterns, with factors such as solute concentration, particle size, surfactant concentration, and ionic strength influencing particle deposition modes. However, few studies have investigated the evolution of droplet evaporation profiles under different substrate conditions. This paper experimentally examines the evaporation process profiles and contact line evolution on substrates with different surface properties (glass and iron), providing an experimental foundation for better understanding the mechanisms underlying droplet evaporation.

1. Experimental Setup

The experimental apparatus for measuring droplet evaporation is shown in [Figure 1: see original paper], comprising a constant temperature water bath (Model F12) and a droplet shape analyzer (Model DSA30) for recording and profiling sessile droplet evaporation on substrates. The analysis interface is displayed in [Figure 2: see original paper]. The surface roughness of both glass and iron substrates was measured using a surface profilometer (Model 2302A), as shown in [Figure 3: see original paper]. While the iron substrate appears smooth, actual machined surfaces exhibit micro-scale unevenness with tiny peaks and valleys. The iron substrate used in experiments had nanometer-scale roughness, whereas the glass substrate was significantly smoother.

During experiments, ambient temperature was maintained at 20 °C (±0.2 °C variation) with relative humidity at 30%. The substrate temperature was 30 °C, and the nanofluid mass concentration was 0.05%. To ensure experimental repeatability and accuracy, particular attention was paid to substrate leveling, temperature uniformity, and droplet shape recording.

2. Experimental Phenomena

2.1 Iron Substrate Observations

[Figure 4: see original paper] shows the temporal evolution of contact angle, contact line, and droplet profile during nanofluid droplet evaporation on an iron substrate. The data reveal two pronounced contact line slip events throughout the evaporation process, with the most significant contact angle jump occurring between 520-580 s. During this event, the contact angle increased abruptly while the three-phase line decreased almost instantaneously.

2.2 Glass Substrate Observations

[Figure 5: see original paper] illustrates the temporal evolution of contact angle, contact line, and droplet profile during nanofluid droplet evaporation on a glass substrate. The curves show that at a glass substrate temperature of 30 °C, the entire evaporation process was relatively uniform, with no obvious pinned three-phase line state or contact angle jumps. The contact angle gradually decreased throughout evaporation, and the three-phase line continuously receded, though the rates of change differed slightly between the early and late stages of evaporation.

3. Analysis of Experimental Results

Based on observations from the iron substrate experiments, the entire evaporation process can be divided into four morphological stages. The first stage features a fixed contact angle with continuously decreasing contact line, lasting a very short duration. The second stage exhibits a pinned contact line with continuously decreasing contact angle, representing the longest duration. The third stage shows both decreasing contact line and contact angle, lasting shorter than the second stage. The fourth stage involves stick-slip motion, where the contact line suddenly recedes while the contact angle instantaneously increases, as shown by the red profile in [Figure 6: see original paper]. This stage occurs very rapidly relative to the entire evaporation process and can be considered instantaneous. Following this, the contact line becomes pinned again while the contact angle continues to decrease until evaporation completes.

The third and fourth morphologies warrant particular attention. The first two stages correspond to constant contact angle and constant contact diameter morphologies, which have been documented in earlier literature. According to Young’ s theory, if the contact angle between droplet and surface is at theoretical equilibrium, evaporation should proceed as a dynamic equilibrium process with constant contact angle morphology. If energy imbalance at the three-phase contact line causes contact angle hysteresis, constant contact line morphology emerges. For the third morphology, where both contact line and contact angle continuously decrease without reaching equilibrium, the behavior depends on the force balance among solid-liquid, solid-gas, and gas-liquid interfaces at the three-phase line and on the evaporation rate.

[Figure 4: see original paper] also reveals two contact angle jump processes during which the contact angle increases rather than decreases, forming stick-slip motion. This stick-slip behavior makes the droplet evaporation process appear periodic. The formation of this periodic process has been analyzed in previous studies and can be determined by changes in droplet surface free energy, as expressed in Equation (1). In Equation (1), *G* represents free energy, *R* the contact line radius, and the contact angle. According to Young' s equation, cos can be expressed by Equation (2). The term _*gl* is related to droplet temperature, which in turn correlates with evaporation rate. [Figure 8: see original paper] and Equation (4) describe the energy transfer and balance during droplet evaporation on a surface.

Substituting Equation (2) into Equation (1) yields Equation (3). The energy required for stick-slip motion varies for different droplets, with the first occurrence requiring the greatest energy and subsequent events needing essentially equal energy. As shown in Equation (3), *G* is closely related to _*sl*, _*gs*, and _*gl*.

Comparing [Figure 6: see original paper] and [Figure 7: see original paper] reveals that droplet evaporation on glass surfaces follows the third morphology, where both contact line and contact angle continuously decrease without achieving equilibrium. Since all experimental conditions were identical except for the substrate, this demonstrates that the contact substrate plays a crucial role in determining evaporation morphology.

As evident from [Figure 3: see original paper], the roughness of the iron surface far exceeds that of the glass surface, resulting in much larger _*sl* for droplets on iron compared to glass. This causes the initial evaporation stage on iron to exhibit constant contact line morphology. From Equation (4), iron' s thermal conductivity is substantially higher than glass' s, leading to faster evaporation rates on iron surfaces and consequently lower droplet temperatures. Decreasing droplet temperature increases _*gl*. When _*gl* and _*sl* become imbalanced, new stick-slip motion occurs. Analysis of the stick-slip mechanism will become a focal point in microfluidic motion research.

Conclusion

Droplet evaporation is a complex process influenced by multiple factors. Through experimental observation of droplet evaporation morphologies on iron and glass surfaces, this study analyzed the mechanisms underlying different morphological formations. The main conclusions are: (1) Four distinct evaporation morphologies exist during droplet evaporation; (2) Metal surface roughness and thermal conductivity are important factors causing stick-slip morphology; (3) Droplet evaporation morphology exhibits periodic variations.

References

[1] Deegan R D, Bakajin O, Dupont T F. Capillary Flow as the Cause of Ring Stains from Dried Liquid Drops [J]. *Nature*, 1997, 389(6653): 827-829.

[2] Deegan R D. Pattern formation in Drying Drops [J]. *Physical Review E Statistical Physics Plasmas Fluids & Related Interdisciplinary Topics*, 2000, 61(1): 475-483.

[3] Sefiane K. Patterns from Drying Drops [J]. *Advances in Colloid and Interface Science*, 2014, 206(2): 372-379.

[4] Bigioni T P, Lin X M, Nguyen T T, et al. Kinetically Driven Self Assembly of Highly Ordered Nanoparticle Monolayers [J]. *Nature Materials*, 2006, 5(4): 265-271.

[5] Moffat J R, Sefiane K, Shanahan M E R. Effect of TiO Nanoparticles on Contact Line Stick-Slip Behavior of Volatile Drops [J]. *Journal of Physical Chemistry B*, 2009, (113): 8860-8868.

[6] Orejon D, Sefiane K, Shanahan M E R. Stick-Slip of Evaporating Droplets: Substrate Hydrophobicity and Nanoparticle Concentration [J]. *Langmuir*, 2015, 27(21): 34-43.

[7] Adachi E, Dimitrov A S, Nagayama K. Stripe Patterns Formed on a Glass Surface During Droplet Evaporation [J]. *Langmuir*, 1995, 11(4): 1057-1060.

[8] Vafaei S, Borca-Tasciuc T, Podowski M, et al. Effect of Nanoparticles on Sessile Droplet Contact Angle [J]. *Nanotechnology*, 2006, 17(10): 2523.

[9] Marin A G, Gelderblom H, Lohse D, et al. Evaporation Dynamics and Sedimentation Pattern of a Sessile Particle Laden Water Droplet [J]. *Physics*, 2011, (107): 502-521.

[10] Moffat J R, Sefiane K, Shanahan M E R. Effect of TiO Nanoparticles on Contact Line Stick-Slip Behavior of Volatile Drops [J]. *Journal of Physical Chemistry B*, 2009, 113(26): 8860-8868.

[11] Askounis A, Sefiane K, Koutsos V, et al. The Effect of Evaporation Kinetics on Nanoparticle Structuring Within Contact line Deposits of Volatile Drops [J]. *Colloids & Surfaces A: Physicochemical & Engineering Aspects*, 2014, 441(3): 855–866.

[12] Askounis A, Sefiane K, Koutsos V, et al. Effect of Particle Geometry on Triple Line Motion of Nano-fluid Drops and Related Deposit Nano-structuring [J]. *Advances in Colloid and Interface Science*, 2014, (222): 44–57.

[13] Askounis A, Sefiane K, Koutsos V, et al. Structural Transitions in a Ring Stain Created at the Contact Line of Evaporating Nanosuspension Sessile Drops [J]. *Physical Review E: Statistical, Nonlinear & Soft Matter Physics*, 2013, 87(1-1): 012301.

[14] Ristenpart W D, Kim P G, Domingues C, et al. Influence of Substrate Conductivity on Circulation Reversal in Evaporating Drops [J]. *Physical Review Letters*, 2007, 99(23): 234502.

[15] LIU Bin, Bennacer R, Bouvet A. Evaporation of Methanol Droplet on the Teflon Surface Under Different Air Velocities [J]. *Applied Thermal Engineering*, 2011, 31: 3792-3798.

Note: Figure translations are in progress. See original paper for figures.