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Nucleate boiling inside small evaporating droplets: An experimental and numerical study

Gui Lu [a,b], Xiao-Dong Wang [a,b,*], Wei-Mon Yan [c]

[a] Research Center of Engineering Thermophysics, North China Electric Power University, Beijing 102206, China
[b] School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China
[c] Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 10608, Taiwan

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ABSTRACT

Evaporating and boiling of droplets on heated surfaces are widely involved in many industrial applications. In this work, the phase change characteristics inside the small droplets in the nucleate boiling regime are studied experimentally and numerically. Confined by the free surface of the droplet, the bubble dynamics in the small evaporating droplet is found experimentally to be greatly different from those observed in pool boiling. After the droplet is deposited on the heated surface, nucleate bubbles generate immediately on the droplet bottom, and then they grow fast and coalesce into large bubbles. However, unlike pool boiling, once the bubbles grow to a specific size, they stop growing and always attach to the heated surface until the droplet evaporates to a thin liquid film, subsequently the bubbles start shrinking, collapsing and finally disappearing due to the confined effects induced by the thin film free surface. With such bubble dynamics, the heat transfer rates of the fast initial bubble nucleation stage and the last thin film evaporation stage are almost four times as large as the middle stable bubble stage. A numerical model is proposed to understand the confined boiling mechanisms with flow and temperature details. The results show that the confined boiling can be attributed to either the evaporation-condensation competition, or the jetting flows induced by the Marangoni convection inside the droplet. The bubble bottom evaporates while the top condensate when its top enters the droplet subcooled region; thus, the bubble seems to stop growing. The jetting flow due to the Marangoni flows further inhibits the bubble growing by pumping the cooled liquids from the top of the droplet onto the bubble surface. For hydrophobic surfaces, the Marangoni effect dominates the bubble dynamics within the evaporating droplet. For hydrophilic surface, the evaporation-condensation competition dominates the bubble dynamics inside the evaporating droplet.

1. Introduction

Droplet evaporating or boiling on heated surfaces is a fundamental process in a wide variety of practical applications, ranging from the traditional spray cooling, ink-jet printing, to the state of art technologies, such as droplet manipulation in DNA chips, protein crystallization, electronic cooling and many others [1–4].

Most available investigations on droplet boiling focused on the macroscopic heat and mass transfer characteristics for the spray cooling process. The heat and mass transfer can be characterized by the droplet boiling curve with the relations of the droplet life time and substrate temperatures, rather than the relation of the heat flux and the surface temperature in the pool boiling curve. Tamura and Tanasawa [5] firstly mapped the droplet boiling curve based on the diversified phase change behaviors. The boiling curve divides the droplet phase behaviors into four regimes, free surface evaporation, nucleate boiling, transition boiling and spheroidal boiling. The boiling curve can describe the boiling morphologies, phase change regimes and heat and mass transfer characteristics of the boiling droplets [6–8]. Many other efforts [9–16] have been devoted to study various effects on the statistical boiling characteristics for a large number or the droplet stream impinging on the heated surface, including ambient pressure, liquid types, initial volume, impacting velocity, surface roughness, temperatures or materials and many others. The deliveries are to propose heat transfer empirical correlations of the time or space average heat transfer characteristics for the droplet impinging, evaporating or boiling [17–19] on heated surfaces. These heat flux versus wall

* Corresponding author at: Research Center of Engineering Thermophysics, North China Electric Power University, Beijing 102206, China.
E-mail address: wangxd99@gmail.com (X.-D. Wang).

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temperatures correlations depict the cooling performance of the evaporating or boiling droplets, which do not need to consider the phase change behaviors of a single droplet. Actually, as a fundamental element of the spray droplets, one single boiling droplet successively experiences impacting, spreading, evaporating and internal boiling processes. The heat and mass transfer characteristics are diversified between these processes. In addition, as the dominant process, the internal boiling process also exhibits versatile phase change characteristics during different stages [20–22]. Therefore, the time and space average of heat transfer empirical correlations are not able to depict precisely the boiling process, especially if the droplet lifetime is long enough. However, few available literatures studied the dynamic phase change behavior inside the droplets. Actually, Studies of internal phase change of a single droplet not only provide the microscopic insight into the heat and mass transfer mechanisms of the spray cooling, but also are of practical interests, especially in the microfluidic or lab-on-chip devices whose characteristic length is as large as the evaporating or boiling droplet. The heat or mass transfer plays a significant role and must be well understood, predicted, and controlled in such small devices. For a single droplet, most studies were focused on the free surface evaporation regime, in which the moderate phase change occurs at the liquid-vapor interface. Extensive experimental and numerical studies have been devoted to exploring the droplet evaporation process, ranging from the heat and mass transfer characteristics [22–26], to the internal flows within the droplet and the "coffee ring" phenomena [27–31].

The bubble dynamics inside the evaporating droplet is affected by the small droplet size (space), as well as the temperature non-uniformity caused by the free interface evaporation (external conditions). Therefore, the phase change inside the evaporating droplet differs from that of traditional pool boiling [32,33]. In addition, the complex external conditions will also make the phase change characteristics inside the evaporating droplet differ from other kinds of space-confined boiling phenomena [34–36]. The new boiling phenomena and their corresponding mechanisms are still unclear, which motivates this work. The confined bubble characteristics inside a 2 mm evaporating and boiling droplet in the nucleate boiling regime were studied experimentally and numerically. The new confined boiling phenomena and their corresponding mechanisms were revealed and discussed with visualization phenomena, flow and heat transfer details. The deliveries might help to understand the bubble dynamics inside the confined space with complex external conditions, as well as to provide methods to control and manipulate the bubble dynamics according to the input heat flux in microfluidic devices.

2. Experiments

2.1. Experiment setups and methods

Fig. 1 shows the experiment setup. The boiling droplets were deposited on a 50 × 50 × 2 mm^3 polished silica surface. The silica surface was heated by the copper heater. The silica surface temperatures changed from 373 K to 383 K, with the fluctuation of ±0.5 K. The glass enclosure was used to prevent the surrounding influence. T-type thermocouples of 0.3 mm in diameter were used to measure the surface temperatures, loaded under the silica surface where the droplet was deposited. The uncertainty of temperature measure was ±0.25 K. Two high speed CCD camera, with maximum photo capture rate of 16,000 frames per second, and a zoom lens of 20–50 times in magnification, were used to record the dynamic and delicate phase change behaviors from the top view and the side view. The experiments were performed at atmospheric pressure and a room temperature of 298 K. When the test surface was heated to a specified temperature, a 3 μL deionized water droplet was gently deposited on the heated plate from a micro-syringe placed at about 20 mm above the silica surface. The phase change imagines and the solid surface temperatures were recorded synchronously.

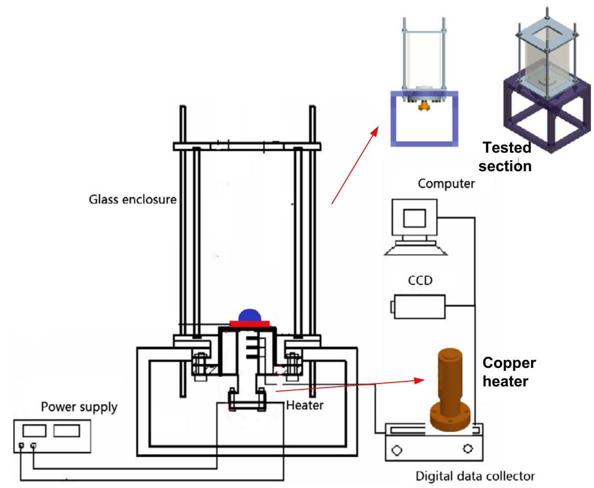

Fig. 1. Experimental setup of droplet boiling.

2.2. Experiment results

Fig. 2 shows the phase change characteristics of a water droplet on the heated silica surface. The droplet boiling experiments were conducted on various solid surfaces, including copper, stainless steel, silica and aluminum surfaces. The bubble dynamics inside the evaporating droplet on these surfaces is similar [21]. The surface roughness, rather than the surface materials greatly affect the bubble dynamics inside the droplet. To eliminate the effects of surface roughness, the polished silica surfaces were used in this work. The solid surface temperature was maintained constant prior to the droplet depositing using a proportional–integral–derivative (PID) controller, ranging from 373 K to 383 K. The droplets exhibit the same phase change characteristics for this temperature range, which can be classified as the nucleate boiling regime. Therefore, we take the case of the 378 K substrate temperature as an example here to show the typical phase change behaviors for the droplet boiling. The droplet spreads, evaporates and then dries out on the heated surface. The lifetime of the droplet is 19 s. The droplet spreads to the equilibrium contact area in a very short time (less than 0.3 s) after depositing on the surfaces. The droplet is pinning to the solid surface with a constant contact area during most of the droplet life time (16 s). The height of the droplet continuously decreases due to the evaporation of free surface. Several tiny nucleate bubbles with diameters of 0.1–0.2 mm, immediately generate at the bottom interface when the droplet contacts with the heated surface. The nucleate bubbles gradually grew up with uniform diameter of 0.3–0.4 mm. The bubbles attach to the heated surface throughout the whole droplet lifetime, rather than departing from the surfaces as occurred in the pool boiling. The wetted area within the bottom of the droplet is covered with bubbles with uniform diameters. These uniform large bubbles can sustain for several seconds, without growing or collapsing. Since the height of the droplet keeps decreasing due to the free surface evaporating, the inside bubbles gradually shrink and collapse when the free surface of the droplet approaching the bubbles. In the last stage, the droplet becomes a thin film without any bubbles inside at all. Finally the contact line shrinks and the droplet gradually dries out.