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Dynamic behavior with rapid evaporation of an inkjet water droplet upon collision with a high-temperature solid above the limit of liquid superheat

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ABSTRACT

The dynamic behavior of the rapid evaporation of an inkjet droplet of water upon collision with a high-temperature silicon substrate has been investigated experimentally. The colliding droplet spreads into a thin disk-shaped liquid film and then splashes away. The splashing behavior depends on the solid temperature, which varies significantly due to nucleation and evaporation while spreading along the solid surface. Even when the temperature of the contact interface of the substrate, as estimated by transient heat conduction, significantly exceeds the kinetic limit of liquid superheat, numerous fine bubbles are simultaneously generated, presumably by spontaneous nucleation, beneath the liquid film and break up the film, which is dispersed into fine droplets. The surface temperature at the collision point is measured using a small platinum film sensor and exhibits a significant decrease compared to the heat conduction to the liquid for this peculiar nucleation.

1. Introduction

The evaporation of liquid droplets upon collision with a high-temperature material is closely related to technological applications of spray/mist cooling of high-temperature materials and power-dissipation devices, vaporization of fuel droplets in fuel-injected engines, fire extinguishment, and vapor explosion [1,2],. As such, a number of studies have examined this phenomenon, including reviews of the important issues of impact dynamics, heat transfer, and measurement [1–6]. When a colliding liquid droplet directly contacts a hot material having a temperature far exceeding the boiling point of the liquid, rapid boiling initiated on the contact interface may significantly affect the subsequent process of evaporation heat transfer. In particular, when the temperature T_c at the contact interface between a semi-infinite solid and a semi-infinite liquid derived from the one-dimensional transient heat conduction theory, which is expressed as

$$T_c = \{T_s\sqrt{(\rho c_p k)_s} + T_l\sqrt{(\rho c_p k)_l}\}/\{\sqrt{(\rho c_p k)_s} + \sqrt{(\rho c_p k)_l}\}, \qquad (1)$$

is so high as to exceed the limit temperature of liquid superheat, spontaneous bubble nucleation due to molecular density fluctuation in the liquid and the resultant rapid vapor generation on and in proximity to the contact interface may immediately hinder the liquid–solid contact. Although for values of T_c equal to the superheat limit temperature of water, the solid temperatures T_s are several tens of Kelvins higher than the superheat limit temperature for common solid metals, Nishio [7,8], reported that the limiting temperature of the solid for contact between a hot solid (stainless steel and brass) and a water droplet (with a diameter of 3.6 to 5.1 mm), where the electrical conductance between these surfaces is lost during droplet impact (with a velocity of 0.5 to 1.0 m/s) (the corresponding Weber number, We = 14–58), is as much as several hundred Kelvins higher than the temperature of the superheat limit and varies significantly with the liquid temperature on the order of hundreds of Kelvins. Nishio et al. [9] also revealed, based on their observation of wetting of the hot surface with a water droplet (with a diameter of 4.1 mm) dropped on a hot quartz glass (from a height of 37 mm) (the corresponding Weber number, We = 42) using total internal reflection imaging, that, even for a solid at a temperature so high that the contact interface temperature estimated using Eq. (1) exceeds the limit temperature of liquid superheat by as much as several tens of Kelvins, liquid remains in contact with the glass surface over an extensive area (1.5 to 2 times the droplet diameter) for approximately 20 ms before transition to the spheroidal vaporization state. These results imply that the limit of liquid superheat does not necessarily restrict the liquid–solid contact or the subsequent wetting processes.

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Nomenclature

c_p	specific heat at constant pressure [J/(kg·K)]
d	droplet diameter [m]
J	homogeneous nucleation rate per unit volume [1/(cm^3 s)]
k	thermal conductivity [W/(m·K)]
k_B	is the Boltzmann constant [J/K]
l_v	heat of vaporization per molecule [J]
m	molecular mass [kg]
N	number of molecules per unit volume [1/cm^3]
p	ambient pressure [N/m^2]
p_{sat}	saturation vapor pressure at a flat interface [N/m^2]
T_c	interface temperature at liquid-solid contact due to heat conduction [°C]
$T_{L,\ r}$	dynamic Leidenfrost temperature [°C]
T_l	liquid temperature [°C]
T_{ls}	temperature of liquid superheat limit [°C]
T_s	solid temperature [°C]
T_{sat}	saturation temperature [°C]
ΔT_{cond}	surface temperature decrease at liquid-solid contact due to heat conduction [K]
ΔT_{de}	surface temperature decrease at droplet collision [K]
u	colliding velocity of the droplet [m/s]
We	Weber number (=$\rho u^2 d/\sigma$)
We_v	Weber number corresponding to velocity normal to the solid surface (=$\rho u_v{}^2 d/\sigma$)
ρ	density [kg/m^3]
σ	surface tension [N/m]
τ_{re}	time required for the surface temperature to recover to the initial value [s]

Subscripts

l	liquid
s	solid
v	vapor

On the other hand, Okuyama et al. observed the nucleation phenomenon on a platinum film heater that was immersed in a test liquid and subjected to pulse heating high enough to generate a rate of temperature increase of from 10^6 to 10^8 K/s and measured the surface temperature at nucleation [10]. Numerous fine bubbles (on the order of several micrometers), presumably generated by spontaneous nucleation, were produced at the temperature of the superheat limit of the liquid and then coalesced in a short period of time (around 1 μs) into a thin vapor film that prevented the liquid from being in contact with the entire heated surface. However, a pulse heating system is different from a liquid droplet collision system with respect to the development of the superheated liquid layer on the contact surface. For a pulse heating system (usually a rectangular pulse), a superheated liquid layer develops to store the superheat energy at an approximately constant rate until the heated surface reaches the nucleation temperature. In contrast, for a system in which the liquid is separated prior to the contact with a hot solid, the liquid temperature at the contact interface increases stepwise to the nucleation temperature before the superheated layer develops. Therefore, the nucleation and the subsequent evaporation process at the liquid–solid interface in the droplet collision system will obviously be different from that of the pulse heating system.

In a liquid droplet collision system, when the theoretical contact interface temperature is close to or slightly higher than the superheat limit temperature, violent evaporation at the liquid–solid interface and subsequent dynamic fluid phenomena, such as jetting of the secondary droplets upward from the top of the primary droplet, have been observed [5,11],. However, most experimental studies that investigated the collision of droplets on a hot solid focused primarily on the dynamic behaviors of the droplet in the impact regimes (deformation, deposition, rebound, disintegration including splashing with thermal interaction, etc.), the influences of parameters, the criteria for regime transition, and heat transfer from the hot surface, which is closely associated with the regime [1,3,6,12],. The observations were conducted at scales of 0.1 to 1 mm and 0.1 to 10 ms, which are much larger than those of spontaneous nucleation (which are on the orders of nanometers and nanoseconds, respectively [13]). For larger droplets, the observation of the contact behavior with the solid surface will be hindered by splashed liquid and/or the boiling bubbles produced in the droplet. In addition, as the droplet size is increased, the contact situations (local surface temperature and fluid flow) will change significantly in the course of the extension along the solid surface due to the convection and phase-change heat transfer processes.

In the present study, the collision of a small inkjet droplet of water onto a hot surface, the temperature of which exceeds the limit of liquid superheat, is investigated experimentally. The liquid–solid contact and the subsequent evaporation process are observed through the thin liquid film that is formed upon collision, at the microsecond and micrometers scales, which are close to the scales of spontaneous nucleation. The time variation of the solid surface temperature upon collision is measured using a small film sensor. The surface temperature at which numerous bubbles, presumably generated by spontaneous nucleation, are produced and the subsequent temperature variation are examined.

2. Experimental apparatus and procedures

Fig. 1(a) shows the experimental apparatus. A single droplet of distilled water of 60 μm in diameter is ejected at room temperature from a nozzle (50 μm in diameter) of an inkjet print head (HP51604 A), which is located 7.0 mm in height above a solid test surface placed horizontally and is driven by a power amplifier (NF4025, frequency band width: DC to 1 MHz). The droplet collides with the solid surface at an angle of 45°. The flying velocity just before collision is 10.88 m/s (under the condition without heating), and the corresponding Weber number is 100. The droplet diameter has a scatter within ±2 μm for each ejection, which is less than 3% the diameter of the droplet. The flying velocity of the droplet just before the collision, which has been measured using two flash lamps triggered with a different timing, has a scatter within ±0.01 m/s for each ejection, which produces the scatter within ±0.9 μs in the impact timing. The droplet ejected from the nozzle at an angle of 45° has a lateral fluctuation within ±10 μm in the flying path just before the collision, which causes a scatter within ± 0.9 μs for the time at which the droplet reaches the solid surface. A shutter is set in front of the print head, which prevents the nozzle from receiving the effects of the radiation and convection from the heated substrate, and removed just before each ejection of the droplet.

Photographs of the droplet collision are taken using a digital still camera (Nikon D3100) through a microscope with a magnification of 250 while being illuminated by a flash lamp with a flash duration of 180 ns (Sugawara NP-1A/NPL-5) (one image per ejec-