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Technical Note

The influence of liquid pool temperature on the critical impact Weber number for surface bubble formation

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ABSTRACT

A series of experiments were conducted concerning the influence of liquid pool temperature on the formation of surface bubble. Single water droplet impacted on an ethanol pool 56 mm in depth, and the droplet diameter is about 2 mm. The impaction processes were recorded using a high-speed photography camera with 2000 fps. All the experiments were performed at 20 °C and the ethanol pool was heated by a hot plate. The result reveals that the critical Weber number for forming surface bubble is affected by the pool temperature, decreasing with the increase of impacted liquid temperature.

1. Introduction

Single droplet impacting on a solid or liquid surface has been focused for more than one hundred years, some typical phenomena were observed, including floating [1], bouncing [2], coalescing [3], jetting, splashing [4–7] and surface bubble [8]. In this work, we focused on the critical Weber number for surface bubble formation.

Zou et al. [9] experimentally studied the impacting behaviors, and reported that when the droplet impact energy is not enough to break the air film between the droplet and liquid surface, the floating or bouncing occur. Increasing the Weber number leads to coalescence. With the further increase of Weber number, the splashing appears, which can be subdivided into crown splashing, jetting splashing and surface bubble splashing that crown closes above the crater, as shown in Fig. 1 [7]. Very little work has been devoted to the formation mechanism of surface bubble due to the practical difficulties of imaging a drop that is falling from approximately 10 m above the pool to obtain the terminal impact velocity [10].

The surface bubble was first discovered by Worthington [11], who explained the constriction of the upper rim of the bubble-thin cylindrical envelope in terms of surface tension. He denoted that the crown can close above the crater at high impact energy. By evaluating the Weber number, it can be found that a surface bubble was formed under the condition of the Weber number > 1000.

Franz [12] delineated that the crown upper part can close to form a bubble floating on the impacted liquid surface when the droplet velocity approaches the terminal velocity. In addition, Mutchler et al. [13] reported that the surface bubble cannot be observed at any low limit cases. A lower limit was given by Hallett et al. [14], who pointed out that they never obtained closure of the crown if $We < 370$. Medwin et al. [15] described the formation process of surface bubble for single water droplet with terminal velocity impacting on the water surface.

Engel [16] also found the surface bubble and made a theoretical analysis of cavity depth for a water droplet impinging onto the water surface and developed an equation that describes the cavity development. He reported that the maximum crater depth can be approximated as equation $U_1 + U_2 + U_3 = \pi\rho_d D^3 u^2/24$.

Xu et al. [8] investigated the impact behaviors for single water droplet impingement onto a burning ethanol surface from fire suppression perspective. It was reported that there is a critical Weber number for the transition between surface bubble and jetting, and the surface bubble can be observed when the weber number is equal to 310.

To the authors' best knowledge, all of the investigations on surface bubble behavior were performed at room temperature. In order to understand water droplet behavior on the burning surface from fire suppression perspective, some experiments were carried out to visualize the surface bubble behavior for single water droplet impinging on a heated ethanol surface. The result indicates

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Nomenclature

We	droplet Weber number ($We = \rho_d u^2 D/\sigma_d$)
D	droplet diameter
u	droplet impact velocity
U_1	gravity potential energy of cavity
U_2	gravity potential energy of wave above the surface
U_3	potential energy due to generated surface.
d	thickness of crown wall
V	contract velocity
Δd	thickness difference between upper rim and lower part of crown wall ($\Delta d = d_l - d_u$)
H	maximum crown height
G	gravity
g	gravitational acceleration
E	energy
W	work
R	maximum crater depth
y	height
r	thickness
h	depth of the pool
ΔT	temperature difference between the bottom and top surface
υ	target liquid kinematic viscosity
R_a	non-dimensional Rayleigh number

Greek symbols

δ	average thickness of crown sheet
θ	angle
ρ	density
σ	surface tension
β	volume expansion coefficient
α	target liquid thermal diffusivity

Subscripts

d	droplet liquid
u	upper rim of crown wall
l	lower part of crown wall
total	total impact energy
dissipated	dissipated energy during impact
crater	energy used to form crater structure
crown	energy used to form crown structure
t	target liquid
g-crown	crown gravitational potential energy
s-crown	crown surface energy

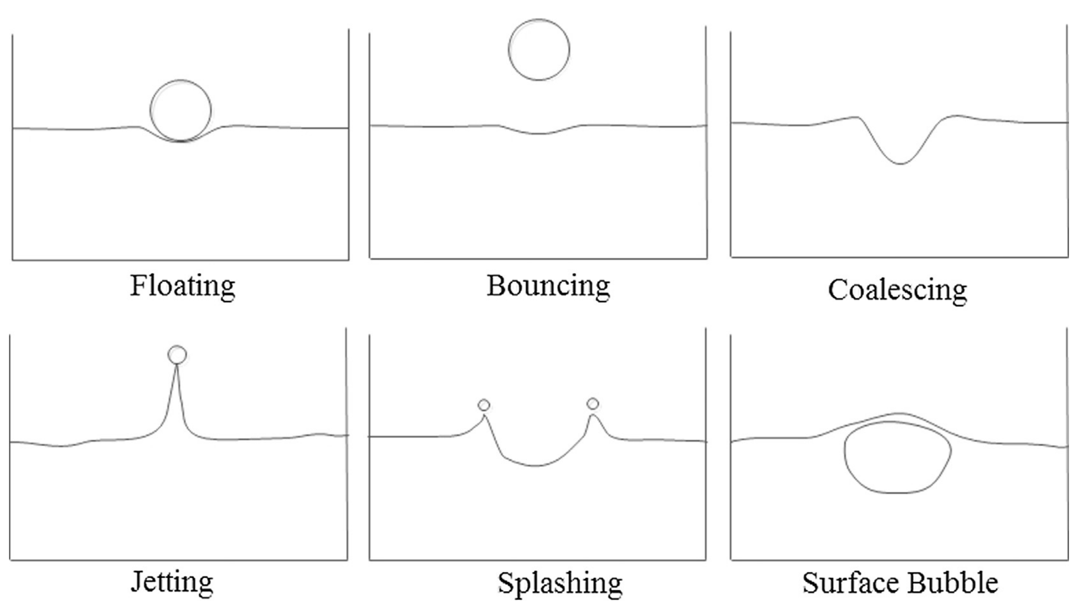

Fig. 1. Phenomena of drop impact on liquid surface.

that surface bubble can occur at low Weber number for single water droplet impingement onto the hot liquid surface.

2. Experimental apparatus

Experimental setup displayed in Fig. 2 is used to investigate the water droplet impinging onto the hot ethanol surface, which is similar to apparatus of previous studies [8,17,18]. The main components include a droplet generator, a strong illuminant with a light diffuser, a heating device, and a high-speed photography camera. The single water droplet is generated using a syringe pump and forms at the tip of the injection syringe and then falls down under the gravity effect. The falling height is changed to obtain varied impact velocity, which is calculated by tracking the location of droplet in two images with 0.5 ms time spacing prior to impact, with a measuring accuracy ±0.05 m/s. The droplet size is about 2 mm, which is obtained by pixel analyzing, the measuring error is 1 pixel with size of 0.025 mm, for all the experiments and each experiment is conducted at ambient temperature. Temperature variations of droplet due to evaporation are ignored. Ethanol is chosen as target liquid which is contained in a quartz glass container, and heated by a hot plate with an accuracy ±0.5 °C. The temperature distributions of the ethanol pool are measured by five K-type thermocouples with an accuracy ±1 °C, which are located at 1 mm, 3 mm, 6 mm, 20 mm and 54 mm beneath the