International Journal of Heat and Mass Transfer 100 (2016) 48–57

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Boiling from liquid drops impact on a heated wall

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ARTICLE INFO

Article history:
Received 9 March 2016
Accepted 21 April 2016
Available online 6 May 2016

Keywords:
Drop impact
Heated wall
Boiling
Rebound
Spread

ABSTRACT

With aid of high-speed imaging, boiling phenomena near the Leidenfrost point from a single liquid drop impact on a heated solid wall were identified, including reflection rebound, explosive rebound and explosive detachment. Wall temperature was ranging in 182–384 °C, and water, butanol, ethanol and 5.21% NaCl solution were adopted as the fluids due to their different properties. Transitions in the three boiling phenomena were determined concerning effects of Weber number and wall temperature, respectively. For the process of reflection rebound, the maximum spread factor and resident time of the drop are independent of wall temperature. With an increment in Weber number, the maximum spread factor rises, while its effect on the resident time is minor. Empirical correlations were acquired to predict the maximum spread factor and its corresponding dimensionless time as well as the dimensionless resident time. Moreover, formation of the central liquid jet was observed using the NaCl solution drop, which was interpreted by bubble entrainment with violent nucleating. Finally, preliminary discussions regarding drop detaching time in the explosive detachment process were undertaken. Results revealed that the drop detaching time decreases with Weber number, and wall temperature also can affect it.

1. Introduction

Liquid drop impinging on heated walls is witnessed in many industrial applications, such as spray cooling [1], plasma spray coating [2], metal quenching [3], oil drops impinging on walls in combustion chambers [4], etc. When liquid–solid contact temperature is higher than the liquid saturation point, the drop undergoes boiling processes. In general, according to lifetime of a sessile drop on the heated wall, boiling regimes of the drop are similar with that in pool boiling, including nucleate boiling, transition boiling and film boiling [5]. Nucleate boiling and transition boiling are distinguished by wall temperature corresponding to critical heat flux of the drop, but when wall temperature T_w is higher than the Leidenfrost point T_L, film boiling takes place and a very thin vapor film is generated between the drop and the heated solid wall.

Prevalently, the liquid drop has impinging momentum in industrial technology, which however, makes boiling of the drop even far more complicated. On account of vapor pressure under the drop and drop impact momentum in the film boiling regime, the drop experiences rebound after impact, schematic of which is shown in Fig. 1. To date, more attention has been given to film boiling, and both length scale of the drop maximum spread diameter $d_{s\text{-}max}$, and time scale of resident time t_r measured from the impact instant to the moment of bouncing off the heated wall were addressed.

Tran et al. [6], Ge and Fan [7], Ueda et al. [8], Makino and Michiyoshi [9] reported that the drop resident time t_r can be approximated as the period of a freely oscillating drop,

$$t_r = \frac{\pi}{4}\sqrt{\frac{\rho d_{drop}^3}{\sigma}}, \tag{1}$$

where d_{drop}, σ and ρ respectively signify drop diameter, surface tension and liquid density. Chatzikyriakou et al. [10] found that Eq. (1) much underestimates the residue time for a smaller impact angle of 5°. In Chen et al. [11] and Biance et al. [12], the constant items in front of the square root in Eq. (1) were 1.12 and 0.937, slightly higher than $\pi/4$ in Eq. (1). They also pointed out that the drop resident time is insensitive to wall temperature and impact velocity. Negeed et al. [13] concluded that for droplet fully evaporates during the spreading phase, the resident time increases with increasing wall temperature, increasing drop diameter and decreasing impact velocity. Follow-up work on drop spreading during interaction with heated walls was also performed by Negeed and his collaborators [14–16].

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.061
0017-9310/

Nomenclature

a	exponent
C	coefficient
d	drop diameter
d^*	dimensionless diameter
N	number of data points
R_a	surface roughness
Re	Reynolds number
T	temperature
t	time
v	velocity
We	Weber number

Greek symbols

μ	liquid viscosity
ρ	liquid density
σ	surface tension
τ	dimensionless time

Subscripts

drop	liquid drop
exp	experiment
L	Leidenfrost
pred	predicted
r	resident
s	spread
s-max	maximum spread
w	wall

When the drop rebounds on the heated wall after impact, normalizing diameter of the flattened area d_s (shown in Fig. 1), covered by the drop at the vapor–liquid interface during deformation, with initial drop diameter d_{drop} yields the so-called ‘spread factor’ d_s^* [17]

$$d_s^* = \frac{d_s}{d_{drop}}. \tag{2}$$

However, here it is clarified that this definition is not very proper in the film boiling regime due to existence of a thin vapor film between the drop and the heated wall, also the drop no longer wetting the surface. Yet, the term ‘spread factor’ is still used in this study like most publications. Hatta et al. [18] adopted the water drop with diameter 0.3–0.6 mm to investigate the maximum spread factor $d_{s\text{-}max}^*$. They noted that Reynolds number, Re, has no effects on it, which contradicts with the result in Chandra and Avedisian [19]. Here Re is defined as

$$Re = \frac{\rho v d_{drop}}{\mu}, \tag{3}$$

where v is impact velocity and μ is liquid viscosity. In Karl et al. [20], the maximum spread factor increases with impact velocity and decreases with surface tension, and in Negeed et al. [13], it increases with drop diameter. Akao et al. [21] combined above three factors together and used Eq. (4) to predict the maximum spread scale

$$d_{s\text{-}max}^* = 0.613We^{0.39}, \tag{4}$$

where We is Weber number, defined by

$$We = \frac{\rho v^2 d_{drop}}{\sigma}. \tag{5}$$

Tran et al. [22] showed that the maximum spread factor can be scaled by $We^{2/5}$, much larger than that for the impact on non-heated surfaces, $We^{1/4}$ [23]. They attributed this difference to an extra driving mechanism caused by the evaporating vapor radially shooting outwards and taking the liquid along. Also, Antonini et al. [24] noted that it was proportional to $We^{2/5}$. Moreover, in Chandra and Avedisian [19] it was in direct proportion to $We^{1/2}$, while in Biance et al. [12] and Chatzikyriakou et al. [25], the portions were $We^{1/4}$ and $We^{0.23}$, respectively. The above information points to a need for a more accurate predictive correlation of the maximum spread factor and more in-depth discussions.

Cossali et al. [26] performed experiments to study secondary atomization produced by the impact of a liquid drop on heated walls. In their work, the secondary atomization is only due to thermal (boiling) effects. They noted that a central jet forms for a water drop in the film boiling regime. However, this central jet disappears when viscosity increases, and the high viscous dissipation of kinetic energy may be responsible for this effect. Later, Cossali et al. [27] reported that the central jet appears at $T_w > 230\,°\mathrm{C}$. A possible explanation was provided that pressure wave generation at the impact point due to rapid formation of a central vapor bubble is the main inducement, but no experimental evidence supports this conjecture. They also stated that central jet characteristics depend slightly on surface roughness but more strongly on wall temperature and impact velocity. While in the later work by Tran et al. [6], the central jet was observed on structured surfaces but never emerged on smooth surfaces. They also gave a similar explanation as that in Cossali et al. [27]. All the work referred above suggests that surface features and liquid properties such as viscosity, play an important role in formation of the central jet, exactly in the film boiling regime. However, more experiments still need to be undertaken to further verify the central jet origin.

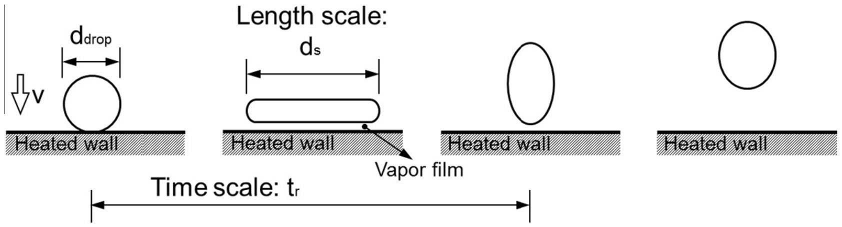

Fig. 1. Schematic of drop rebound after impact in the film boiling regime.