International Journal of Heat and Mass Transfer 98 (2016) 455–461

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Crown and drop rebound on thin curved liquid films

Gangtao Liang, Xingsen Mu, Yali Guo, Shengqiang Shen *

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Article history:
Received 29 December 2015
Received in revised form 19 February 2016
Accepted 11 March 2016

Keywords:
Crown
Rebound
Drop impact
Liquid film

ABSTRACT

Experimental and theoretical work was conducted to enrich the previous study concerning a single liquid drop impinging on curved liquid films. Two typical outcomes including crown sheet at high impact velocity and drop rebound at low impact velocity were mainly discussed. Different from the traditional crown on a flat film, the crown on curved films has larger upper size but smaller base size. Increasing Weber number produces a positive influence on crown diameter when sphere-drop curvature ratio is higher than 0.303. While this effect is minor for curvature ratio of less than 0.114. By reducing curvature ratio, crown diameter first increases then remains unchanged. An empirical formula was also provided to predict the crown scale. With respect to drop rebound, a physical model was established to assist theoretical derivations. Based on energy conservation, a theoretical formula for predicting the inferior limit of rebound thresholds was obtained to offset deficiency in experiments, which involves Froude number and a deformation factor. In this work, the inferior limit of the critical Weber number is 0.8, applied to drop bouncing off both a curved film and a flat film.

1. Introduction

Drop impinging on a thin liquid film is a common process in industry, during which a pre-existing film is mainly created by previous impact. Applications involving this process include spray coating and cooling [1], ink-jet printing [2], internal combustion technology [3], falling film evaporation [4], etc. In particular to the technique of horizontal-tube falling film evaporation in desalination, saline drops impinge on a very thin curved liquid film successively [5]. Our previous work [6–9] proved that curvature of the liquid film can produce great influences on outcomes after impact, including drop rebound [8], drop spreading [8,9], liquid sheet [6,7] and splashing [6,9], both qualitative and quantitative. However, current situation is that research about this aspect is still much lacking and most of work is focused on the impact onto a regular flat film. Before this work, some research in the public literature is reviewed, which however, inspires the present investigation.

Yarin and Weiss [10] conducted a detailed theoretical study on crown liquid sheet, and proposed that kinematic discontinuity is the main mechanism for crown formation and propagation. This theory was widely approved by researchers, which was also successfully verified from velocity fields in both numerical studies [11,12] and PIV experiments [13]. Later, Trujillo and Lee [14] modified this kinematic discontinuity theory and considered influences of film thickness. Solutions obtained from their modified model were compared against both experiments and computational results, showing a reasonably good agreement. Roisman and Tropea [15] generalized this theory further, taking into account inertial effects and neglecting surface tension and viscous forces in the crown. Based on their theoretical work, Yarin and Weiss [10] also noted a square-root dependence of non-dimensional time τ on crown diameter. Here τ is defined as

$$\tau = \frac{vt}{d_{\text{drop}}}, \tag{1}$$

where v is impact velocity, t is time and d_{drop} is drop diameter. Trujillo and Lee [14], Xie et al. [16] numerically obtained a same conclusion. But Coghe et al. [17] reported that such a rule is not supposed to hold for all crown evolution, and attempts to fit the whole experimental data with this were not successful. Cossali et al. [18] found that the exponent should be 0.43 ± 0.03 instead of 0.5 in Yarin and Weiss [10]. While in the previous work [7], it was 0.435 for the crown on a cylindrical film. Rieber and Frohn [19] used a three-dimensional volume of fluid method to investigate crown evolution, and results showed that the intact crown shape and its diameter at the bottom depend on time but not on *We*. Here *We* denotes Weber number, defined as

$$We = \frac{\rho v^2 d_{\text{drop}}}{\sigma}, \tag{2}$$

---

* Corresponding author. Tel.: +86 0411 84708464.
E-mail addresses: gtliang@dlut.edu.cn (G. Liang), zzbshen@dlut.edu.cn (S. Shen).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.046
0017-9310/

Nomenclature

b	diameter in the model
C	coefficient
D	crown diameter
D^*	non-dimensional crown diameter
d_{cylinder}	cylinder diameter
d_{drop}	liquid drop diameter
d_{sphere}	sphere diameter
E	energy
Fr	Froude number
g	gravitational acceleration
h	film thickness
h^*	non-dimensional film thickness
h_c	height in the model
m	mass
n	exponent
Oh	Ohnesorge number
Re	Reynolds number
t	time
v	impact velocity
We	Weber number
We_i	inferior limit of critical We

Greek symbols

γ	deformation factor
γ_a	average value of γ
μ	dynamic viscosity
ρ	density
σ	surface tension
τ	non-dimensional time
Γ	non-dimensional parameter
Λ	non-dimensional parameter
ϖ	sphere-drop curvature ratio
ω	cylinder-drop curvature ratio

Subscripts

1	impinging instant
2	bouncing off instant
g	gravity
k	kinetic
r	rim
s	surface
v	viscous

where ρ is liquid density and σ is the surface tension force. Liang et al. [3], Josserand and Zaleski [20], Agbaglah and Deegan [21] confirmed this result by varying impact velocity and physical properties separately. Rioboo et al. [22] and Lee et al. [23] pointed out that crown duration increases with film thickness. Liang et al. [24], Mukherjee and Abraham [25] investigated effects of gas properties on crown evolution. They all noted that an increase in gas density results in incurve of the crown and rise of gas viscosity can inhibit crown expansion. For the crown angle, Wang and Chen [26] noted that the crown wall is almost perpendicular to a horizontal liquid film when non-dimensional film thickness h^* equals to 0.5. Here h^* is defined as

$$h^* = \frac{h}{d_{\text{drop}}}, \tag{3}$$

where h is film thickness. Later, Fedorchenko and Wang [27] found that the crown angle is only determined by film thickness, independent of impact velocity and liquid properties. They also provided a theoretical formula to predict its value, which is simpler than that in Roisman and Tropea [15] of involving internal flows inside the film.

With regard to impact on curved films, it mainly includes the film on a cylindrical surface and a spherical surface. Curvature ratio ω and ϖ were usually used to express the relative scale between a drop and a curved impact target sustaining the film, defined as

$$\omega = \frac{d_{\text{drop}}}{d_{\text{cylinder}}}, \tag{4a}$$

and

$$\varpi = \frac{d_{\text{drop}}}{d_{\text{sphere}}}, \tag{4b}$$

where d_{cylinder} and d_{sphere} signify diameter of solid cylinders and spheres, respectively. For the impact on a spherical film, Liang et al. [9] noted that the drop spreading factor, defined as the ratio between spreading area and drop surface area, follows a linear law with dimensionless time. For splashing, with an increment of ϖ larger than 0.224, the critical We can be increased due to drop downward slippage, while the critical We almost keeps constant as ϖ is smaller than 0.224. Liang et al. [6] presented different outcomes after impact on a cylindrical film experimentally, with aid of a high-speed digital camera. They noted that outcomes for ω of less than 0.5 differ from that for ω of larger than 1. Later, they discussed liquid sheet features in Liang et al. [7]. With decreasing ω, liquid sheet approximates to the traditional crown gradually. Maximum liquid sheet height and its corresponding time increase with increasing impact We or decreasing ω. For drop rebound, Liang et al. [8] suggested that the critical We for rebound lies in a range and they found that the superior limit remains 9.2 as ω is less than 0.5, whereas it decreases a lot as ω is larger than 0.5. Interpretations for this trend was fully confirmed by discussions of a deformation factor, defined to measure deformation magnitude during a rebound period. However, the inferior limit was not discussed efficiently in the above work due to big measuring errors of very low velocity.

Based on our previous work above-mentioned, this study will provide more details during a single drop impinging onto curved liquid films. The present work contains two parts. In the first part, crown behavior resulted from impact on a spherical film with relatively high impact velocity is discussed, both qualitatively and quantitatively. Comparison among the crown on a spherical film, a cylindrical film and a horizontal flat film is also performed to reveal influences of target geometrical shapes. In the second part, the inferior limit of the critical We for drop rebound on a cylindrical film with low impact velocity is derived theoretically, in order to offset deficiency in experiments.

2. Experimental apparatus and procedures

Experimental apparatus and methods were described in [6,9] in detail, including film thickness at different curvature ratio. A single drop was produced by forcing liquid in a syringe at certain pressure through a stainless steel hypodermic needle. The needle was flat tipped, with inner diameter of 0.50 mm. The drop forms at the needle tip and detaches when gravity exceeds the surface tension force. Impact behavior was recorded by a Phantom V12.1 high