Experimental Thermal and Fluid Science 55 (2014) 150–157

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental investigation of a drop impacting on wetted spheres

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

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

A R T I C L E   I N F O

Article history:
Received 26 December 2013
Received in revised form 15 March 2014
Accepted 16 March 2014
Available online 24 March 2014

Keywords:
Drop impact
Wetted sphere
Spreading
Splashing

A B S T R A C T

Numerous experiments were performed to investigate a heptane drop impact dynamics on wetted spheres using a high speed camera. Outcomes after impact include spreading at a low impact Weber number and splashing at a high value. Limits between the two outcomes can be greatly affected by the sphere-drop curvature ratio ranging in 0.090–0.448. Additionally, the spreading process on wetted spherical surfaces is discussed in detail. The spreading factor defined as the ratio between the spreading area and the drop surface area can be increased by increasing the curvature ratio or by reducing liquid viscosity, while the effect of the increment in the Weber number is minor. It is found that the spreading factor follows a linear law with dimensionless time, which is confirmed by the butanol drop spreading as well. Finally, concerning different curvature ratios and fluids, many coefficients with respect to the linear law are obtained to predict the spreading scale by regressing the experimental data.

1. Introduction

The drop impact phenomenon is common in industry, such as drops impact on surfaces of heat transfer tubes in horizontal-tube falling film evaporators [1], spraying cooling [2], ink jet printing [3], plasma spraying technique [4] as well as various fire safety situations [5], etc. Rein [6] summarized the main studies focused on the liquid drop impact phenomenon and made comprehensive reviews about this subject. Some research in the public literature precisely inspires the present investigation.

For the drop impact on dry solid surfaces, Fukai et al. [7] presented a theoretical study on the spreading process accounting for the surface tension, and obtained the recoiling occurrence and mass accumulation around the spreading film periphery. Their results also show that the dependence of the maximum spreading radius on time is non-monotonic. Later, Fukai et al. [8] proposed another theoretical model, considered the presence of inertia, viscosity, gravitation, surface tension and wetting effects. Their theoretical model predicts well the deformation of the impacting drop, not only in the spreading phase, but also during recoiling and oscillation. Rioboo et al. [9,10] conducted many experiments and provided qualitative and quantitative analysis. The results show that outcomes after impact include splashing, rebound, partial rebound and deposition. The time evolution of the spreading factor is divided into four distinct phases: the kinematic phase, the spreading phase, the relaxation phase and the wetting/equilibrium phase. Xu et al. [11] investigated the influence of the surrounding gas pressure on splashing limits and found a striking phenomenon: splashing can be suppressed by decreasing the surrounding gas pressure. Afterwards, Xu et al. [12,13] reported the interplay between substrate roughness and the surrounding gas pressure. They associated two distinct types of splashing with each parameter: prompt splashing is due to surface roughness, while corona splashing is resulted from instabilities produced by the surrounding gas. Bi et al. [14] experimentally found that liquid viscosity plays a decisive role in the spreading process, and surface tension has a leading influence on the recoiling process. Both the two properties jointly determine the oscillation characteristics. For a single drop impact on hot surfaces, Negeed et al. [15] discussed thermal properties of the hot surface and drop characteristics on the drop evaporation. Later, Negeed et al. [16,17] presented solid–liquid contact time and the maximum drop spreading diameter, concerning effects of the surface roughness amplitude, the oxide layer thickness, the *We*, and surface superheat.

In some industrial equipments, the impact target surfaces are not always planar. For example, in horizontal-tube falling film evaporators, liquid drops impact on heat transfer tubes. The target surfaces are curved instead of planar. Concerning a drop impact on curved dry surfaces, Pasandideh-Fard et al. [18] simulated a 2 mm water drop impact on tubes with the diameter in 0.5–6.35 mm and low velocity of 1 m/s. They found that drops landing on the largest tube cling to the solid surface, but for smaller tubes, there are not enough surface areas for the liquid to remain attached, and drops fall off after impact, disintegrating into several smaller drops. Hung and Yao [19] studied experimentally water drops with a diameter

---

[*] Corresponding author. Tel.: +86 0411 84708464.
E-mail addresses: gtliang@126.com (G. Liang), zzbshen@dlut.edu.cn (S. Shen).

http://dx.doi.org/10.1016/j.expthermflusci.2014.03.008
0894-1777/© 2014 Elsevier Inc. All rights reserved.

Nomenclature

A	area, mm^2
d	diameter, mm
h	film thickness, mm
k	coefficient
Oh	Ohnesorge number, $\mu/(\rho\sigma d_{\mathrm{drop}})^{1/2}$
R_a	surface roughness, μm
Re	Reynolds number, $\rho v d_{\mathrm{drop}}/\mu$
t	time, ms
v	impact velocity, m/s
We	Weber number, $\rho v^2 d_{\mathrm{drop}}/\sigma$

Greek symbols

δ	dimensionless film thickness, h/d_{drop}
μ	liquid viscosity, Pa s
ρ	liquid density, kg/m^3
σ	surface tension, N/m
τ	dimensionless time, vt/d_{drop}
Φ	spreading factor, $A_{\mathrm{s}}/A_{\mathrm{drop}}$
ϖ	sphere-drop curvature ratio, $d_{\mathrm{drop}}/d_{\mathrm{sphere}}$

Subscripts

c	critical
drop	liquid drop
h	horizontal
s	spreading
sphere	solid sphere
v	vertical

of 110–680 μm impacting on isothermal cylindrical wires. Their results show that outcomes after impact include disintegration and dripping. Smaller drops are disintegrated if the incoming drops have high velocity or the wire diameter is small. Larger dripping drops are formed when the velocity is low or the wire diameter is large. Shen et al. [20] studied influences of several dimensionless parameters on the drop deformation after impact on a two-dimensional round surface using lattice Boltzmann implementation of the pseudo-potential model. Four typical deformation processes can be found in their research: moving, spreading, nucleating and falling. In Chow and Attinger [21], the drop diameter was 80 μm and the target sphere diameter was in the range of 0.06–10 mm. Their visualization experiments show that the sphere curvature has no significant influences on the maximum spreading factor for a substrate-drop curvature ratio below 0.3. Hardalupas et al. [22] reported experiments on liquid drops with the diameter 160–230 μm impacting on small solid spheres with the diameter 0.8–1.3 mm at impact velocity 6–13 m/s. They observed a retraction of the liquid crown at low drop impact velocity and disintegration from cusps located on the crown rim at high impact velocity. They also pointed out that the increase in the sphere curvature promotes the splashing onset. Bakshi et al. [23] reported experimental investigations of drops with the diameter 2.4–2.6 mm impacting onto a spherical target of 3.2 mm in diameter. Spatial and temporal variations of the film thickness on the target surface were measured. Three distinct temporal phases of the film dynamics are clearly visible from their experimental results: initial drop deformation, inertia dominating and viscosity dominating.

However, the research above mentioned is limited to a drop impact on dry surfaces. For the impact on wetted surfaces, i.e., solid surfaces covered by thin liquid films, a lot of work was also completed. Cossali et al. [24] and Motzkus et al. [25] defined the impact target as a thin liquid film when the dimensionless film thickness δ varies in the range of 0–1. Rioboo et al. [26] found experimentally three outcomes including deposition, crown formation without splashing and splashing by varying impact velocity (0.44–3.14 m/s), the drop diameter (1.42–3.81 mm) and the dimensionless film thickness (0.004–0.189). Particularly for a dimensionless film thickness less than 0.02, crowns without splashing could almost no longer be observed. Okawa et al. [27] and Shi et al. [28] gained the same results by experiments and three-dimensional simulations. Cossali et al. [24] and Vander Wal et al. [29] associated splashing with the production of satellite drops separating from the crown liquid sheet after the impact, which were named as secondary drops. Cossali et al. [24] firstly distinguished two kinds of splashing: prompt splashing and delayed splashing. The prompt splashing is associated with ejected drops from the crown edge when it is still advancing, while the delayed splashing occurs near or after the crown maximum expansion and is associated with the crown wall breakup. Motzkus et al. [30] also demonstrated outcomes of coalescence, prompt splashing and delayed splashing in their work.

From the above reviews on a single drop impact phenomenon, we note that most impact targets are dry planar or curved surfaces, and studies focused on the impact on wetted surfaces are limited to planar wetted surfaces. Inspired by the above research, it is found that there are few studies especially focused on the impact dynamics for a single drop impinging on wetted curved surfaces. In the previous study [31], the outcomes after a single drop impact on wetted cylinders were presented. Later, the rebound and spreading processes were discussed in detail in [32]. However, the drop impact on cylinders is a three-dimensional problem. For a drop impact on wetted spheres with a two-dimensional geometry, the impact behavior is still unclear. Thus, in the present research, outcomes after a single heptane drop impact on wetted spheres are presented through experimental observations using a high speed camera. In addition, the spreading factor is analyzed, with respect to influences of the We and the sphere-drop curvature ratio ϖ.

2. Experimental apparatus and procedures

The experimental apparatus is similar with that in [31], and shown in Fig. 1. The main components include a syringe, a hypodermic needle connected with the syringe by a latex tube to generate drops, a high speed camera, a wetted sphere, a xenon lamp used to provide illumination for photography, a light diffuser, and a data acquisition computer.

A single drop can be formed by forcing the liquid in the syringe at a certain pressure through the stainless steel hypodermic needle. The needle is flat tipped, with an inner diameter of 0.50 mm. The drop is formed at the tip of the needle and detaches when the gravity exceeds the surface tension force. The impact behavior is recorded by a Phantom V12.1 high speed camera with capacity of 10^6 frames per second, equipped with a 100 mm, f-2.8 Tokina macro lens. The camera is aligned horizontally. In order to obtain photographs with sufficient image resolution, the shooting speed is set as 10,000 frames per second, with 1024 × 512 pixels in each image. The back light method is employed in the experiments to expose the impact images and the cold light source is provided by a xenon lamp XD-300 with a power of 350 W. A light diffuser is used between the sphere and the xenon lamp to make the light