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Special phenomena from a single liquid drop impact on wetted cylindrical surfaces

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ABSTRACT

Experimental observations concerning various outcomes during a single butanol drop impact on wetted cylindrical surfaces are performed using a high speed digital camera at 10,000 frames per second. It is found that outcomes after impact differ a lot when the cylinder-drop curvature ratio alters from 0.091 to 2.395. For the impact on the wetted cylinder with the curvature ratio smaller than 0.5, rebound, spreading, cymbiform liquid sheet and splashing emerge in succession with impact velocity increase. However, for the wetted cylinder with the curvature ratio much larger than 1, rebound, coalescence, dripping and disintegration are observed. Several three-dimensional simulations are also conducted to investigate the spreading process in the cylinder directrix direction. It is found that the spreading length can be increased by increasing impact velocity. The curvature ratio cannot influence the spreading factor when the curvature ratio is less than 0.5.

1. Introduction

Drop impact on a solid surface covered by a thin liquid film which can be deemed as a wetted surface is an interesting phenomenon, especially for liquid sheet formation and secondary drops detached from the rim of the liquid sheet, the behavior of which has fascinated many investigators to make great efforts on it either experimentally or theoretically for a long time. This phenomenon also widely exists in many industrial aspects, such as oil drop impact on walls in combustion chambers, spray ink printing, plasma spraying and so on. Generally, different application aspects involve different shapes of the liquid film and the film shape mainly depends on the substrate that the liquid adheres, so the film shape can be varied by changing the substrate shape.

For drop impact on a horizontal liquid film, Cossali et al. [1] and Motzkus et al. [2] distinguished the impact target as the thin liquid film when the dimensionless film thickness (h/d_{drop}) varies in the range of 0–1, where h is the film thickness and d_{drop} is the drop diameter. Due to different focus points, researchers obtained various outcomes from drop impact on a horizontal thin liquid film. Rioboo et al. [3] presented three experimental 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). Especially for the dimensionless film thickness less than 0.02, crowns without splashing were almost no longer observed. Okawa et al. [4] and Shi et al. [5] gained the same results by experiments and three-dimensional simulations. Cossali et al. [1], Vander Wal et al. [6] and Yarin [7] associated splashing with production of satellite drops separating from the crown liquid sheet after impact, which were named as secondary drops. Cossali et al. [1] are also the first to distinguish 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 is that occurring near or after the stage of the maximum expansion and is associated with breakup of the fluid sheet forming the crown. Motzkus et al. [8] demonstrated outcomes of coalescence, prompt splashing and delayed splashing in their study. In experiments of Wang and Chen [9], a new splashing phenomenon was observed for drop impact onto a very thin film with the 0.05 dimensionless film thickness. In their experiments, not only the upper rim of the crown but also the whole crown wall expands significantly outwards as the shape of a bowl, then the crown cracks from the lower part of the crown wall and breaks up totally into many tiny drops shortly after impact. They also found that the critical splashing is insensitive to the film thickness for a given solid surface if the film is sufficiently thin and the critical splashing level increases with liquid viscosity. Guo et al. [10] undertook experiments about a single drop impact on a liquid film and found that a kind of campaniform liquid sheet can be formed with the dimensionless film thickness 0.3 and impact velocity 3.65 m/s. The campaniform liquid sheet is similar to the well known crown liquid sheet but the rim will close up under high impact velocity and the thick film. Weiss and Yarin [11] noticed that a disk like jet forms in the neck region between

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the drop and the pre-existing liquid film in their simulations. If impact velocity is high enough, this jet can pinch off a torus-shaped liquid volume at its tip or reconnects with the pre-existing liquid film. Josserand and Zaleski [12], Davidson [13] and Nikolopoulos et al. [14] also found this kind of jet by numerical investigations. However, this phenomenon was first experimentally observed by Thoroddsen [15] using fluorescent dye and the visualizations showed that the jet sheet originates from the underlying liquid layer, not the drop liquid. Liang et al. [16] found that generation of the jet is due to higher pressure difference in the neck region. Liang et al. [17] also pointed out that the crown diameter can be increased by increasing impact velocity or by reducing the film thickness in their research.

In many other industrial situations, geometry shapes of the impact target surfaces are not always planar. For example, in horizontal-tube falling film evaporators, liquid drops impinge on surfaces of heat transfer tubes continuously. The impact surface is curved instead of planar. Concerning drop impact on curved dry surfaces, Hung and Yao [18] performed water drops with the diameter 110–680 μm impact on isothermal cylindrical wires experimentally. Results showed that outcomes after impact include disintegration and dripping. Smaller drops are disintegrated if the incoming drop has high velocity or the wire diameter is small. Larger dripping drops are formed when the velocity is low or the wire diameter is large. Pasandideh-Fard et al. [19] simulated the impact of a 2 mm diameter water drop on tubes ranging in the comparable diameter from 0.5 mm to 6.35 mm with low velocity 1 m/s. They found that the drop landing on the largest tube clings to the solid surface, but for smaller tubes, there is not enough surface area for the liquid to remain attached, and the drop falls off after impact, disintegrating into several smaller drops. Hardalupas et al. [20] reported experiments on liquid drops with the diameter 160–230 μm impacting on the surface of small solid spheres with the diameter 0.8–1.3 mm at impact velocity 6–13 m/s. They observed 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 sphere curvature promotes onset of splashing. Bakshi et al. [21] reported experimental investigation of drops with the diameter 2.4–2.6 mm impact onto a spherical target of 3.2 mm in diameter. Spatial and temporal variation 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: the initial drop deformation phase, the inertia dominated phase, and the viscosity dominated phase. In experiments of Chow and Attinger [22], the drop diameter is 80 μm and the target sphere diameter is in the range of 0.06 mm to 10 mm. Their experiments show that the sphere curvature has no significant influence on the maximum spread factor for a substrate-drop curvature ratio below 0.3.

However, according to Harlow and Shannon [23], Manzello and Yang [24], different impact targets can greatly influence the dynamic behavior. When impact velocity is high, the target surfaces wetted or dry can largely affect the crown liquid sheet formation [25]. Through the literature reviews, it is found that most wetted impact targets are horizontal and the non-planar surfaces are always dry absolutely. Besides, as far as the authors' knowledge, there is almost no studies specially focused on drop impact on wetted cylindrical surfaces. Inspired by these, in the present research, some outcomes from a single drop impact on wetted cylinders through experimental observations using a high speed camera are mainly demonstrated. It is conjectured that the cylinder diameter can affect the impact outcomes, so cylinders with different diameters are selected. In addition, in order to study the spreading process in the cylinder directrix direction, three-dimensional simulations are also performed.

2. The experimental apparatus and procedures

Fig. 1 is the schematic diagram of the experimental apparatus used in the study. 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 cylinder, a xenon lamp which is 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 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, which is equipped with a 100 mm, f-2.8 Tokina macro lens. The camera is aligned horizontally, normal to the generatrix of the cylinder. 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 cylinder and the xenon lamp to make the light be distributed uniformly on the wetted cylindrical surface. Because the whole impact process occurs in a very short time, the trigger mode is selected as post trigger. Namely, after drop impact on the wetted cylinder, the trigger is launched, then the signal is delivered to the data acquisition computer and the impact process is recorded.

Before each experiment, several drops are cleared away to ensure that the liquid remains free of any air bubbles. Eight cylinders are adopted and the diameter d ranges from 0.76 mm to 19.94 mm. The cylinders are polished by the Cw 1500 silicon carbide electro coated abrasive paper to assure that the average roughness of the cylinder surfaces R_a is less than 0.05 μm. The drop diameter can be acquired by pixel analyzing and calibration is performed by using a reference substance. The software MATLAB 7.1 is used to fulfill the pixel analyzing process. The drop is similar to an ellipse and the diameter is measured in both the horizontal and vertical directions. In research of Stow and Hadfield [26], Rioboo et al. [27], the equivalent diameter of the ellipse is defined as

$$d_{drop} = (d_h^2 d_v)^{\frac{1}{3}}, \tag{1}$$

where d_h denotes the diameter in the horizontal direction and d_v in the vertical direction. The equivalent diameter of the butanol drop is 1.82 mm. The uncertainty is 1 pixel, and the error is 0.025 mm, which corresponds to 1.37% relative error of the real diameter. In this research, the cylinder-drop curvature ratio β is used to denote the relative size of the drop to the cylinder diameter, defined as

$$\beta = \frac{d_{drop}}{d}. \tag{2}$$

Hence, the curvature ratio is ranging from 0.091 to 2.395. The distance between the needle tip and the cylinder is adjusted to vary drop impact velocity. The impact velocity v is derived by tracking the location of the drop centroid in two images with 0.5 ms time spacing before impact, which ranges from 0.19 m/s to 2.79 m/s with an accuracy of ±0.05 m/s.

In the experiments, a thin liquid film is spread on the surface of cylinders uniformly by using a high-quality painting brush. Both the drop and the film are butanol in the experiments, viscosity μ of which is 2.95×10^{-3} Pa.s and surface tension σ is 2.01×10^{-2} N/m. When the liquid film becomes stable and has a relatively uniform thickness, the experiment can be started. The thickness of the liquid film is measured directly by comparing an image of the film surface to a reference image of the dry cylinder.

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