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Ethanol drop impact on an inclined moving surface☆

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ABSTRACT

This experiment investigates the impact outcomes of ethanol drop on a moving inclined surface at the various inclined angles and moving velocities. The gravity not only can promote the instability of the expanding film at downward flow but also can stabilize the film at upward flow during the drop impact onto a stationary inclined surface. Considering the horizontal moving surface, the surface velocity excites the occurrence of splashing that is toward the opposite direction of surface movement, whereas it suppresses the splashing in the same direction of surface movement. When the inclined surface moves downward at a proper surface velocity, the impact outcomes can be changed from downward splashing to deposition, and furthermore, the direction of splashing also can be changed to upward by increasing the surface velocity. The regime of deposition will be enlarged by an appropriate surface velocity, and this tendency is more obvious with a larger inclined angle.

1. Introduction

Drop impacting is a common natural phenomenon and is popularly utilized in a variety of industrial applications such as rain falling, ink-printing, fuel injecting, spray cooling and spray coating. The outcomes of liquid impacting onto a dry surface can be characterized into three regimes — spreading, splashing and bouncing [1]. Besides liquid properties and droplet kinematics, characteristics of the target surface such as wettability, roughness, temperature and inclination are the important factors to influence the impact outcome significantly [2–4]. In some applications such as spray painting and metal sprays, only the deposited film is of interest. In other cases such as inhalators and engine combustion, the distribution of secondary droplet size after impacting is taken into consideration. In our investigations, we focus on the drops impacting onto an inclined and moving surface to observe the variation of impacting outcomes.

Some studies of drop impacting onto an oblique surface were published previously. Stow and Hadfield [5] investigated the drop impacting onto a smooth and inclined surface and the asymmetry of the expanding film was observed. Šikalo et al. [6] focused on the distinction between rebound and deposition. It was mentioned that splashing usually occurred in all directions, however, the splashing in the downward direction could solely be produced by the proper impacting energy. Lavergne and Platet [7] studied various outcomes of ethanol drop impacting onto an inclined wetted surface, and a K number ($K = Oh \cdot Re^{1.25}$) was defined to determine the threshold of splashing. Kang and Lee [8] observed the evolution of water drop impinging on inclined surfaces with various slopes and surface temperature. The liquid drops slipped on the inclined surface were analyzed numerically by both Bussmann et al. [9], Reznik and Yarin [10] and Lunkad et al. [11] and the effects of gravity and surface tension were also discussed in their researches.

Regarding the investigation of drop impacting on a moving surface, Mundo et al. [12] observed the occurrence of asymmetric splashing after impacting. In their experiment the drop was ejected from an orifice and impacted onto the surface of rolling cylinder. Povarov et al. [13] reported that there were three types of outcomes from the water droplet impact onto a rotating disk. Their experiment focused on the interaction between droplet and air boundary layer which was formed by the disk rotation. Yao and Cai [14] aimed at the effect of temperature of a rotating disk. As the disk's rotating speed increases, the critical Weber number for the occurrence of splashing decreases appreciably. Chen and Wang [15] studied the low speed impacting of water droplet onto a moving hydrophobic surface. The phenomena of partial rebound, deposition and split deposition were observed. Courbin et al. [16] focused on the effects of centrifugal force when milk drop impacted on the center of rotating superhydrophobic disk.

In the condition of low impacting energy or high surface tension, the evolution of spreading film's geometry becomes asymmetric regardless of drop impacting onto an inclined or a moving surface (Fig. 1). When the spreading film flows down on an inclined surface, the liquid accumulates at the lower edge and retracts at the upper edge due to the gravity effect [9]. The asymmetric outline of the film on a moving surface is caused by the bottom of the liquid drop that is adhered and dragged by the moving surface. The remainder of the drop, governed by the force of inertia, will stay and expand above the impacting point. In this situation the velocity of front edge depends on

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Nomenclature

a	vertical diameter of elliptical drop
b	horizontal diameter of elliptical drop
D_0	diameter of droplet
D_{eq}	equivalent diameter of droplet
K	splashing threshold
g	gravity
Oh	Ohnesorge number
r	radius from the wafer center
Re	Reynolds number
V_i	initial velocity of droplet
V_t	tangential velocity of moving surface
We	Weber number
We_n	normal Weber number

Greek symbols

θ	surface inclination angle
ρ	density
σ	surface tension
ω	angular velocity of wafer

the surface velocity, and the velocity of rear edge is affected by the impacting energy.

The objective of this paper is to investigate the combined effect of moving surface velocity and its inclination angle on impacting outcomes. Silicon wafer disk which roughness is under 50 nm is used as an impacting target throughout the study. The effect of surface roughness on the drop impacting can be ignored owing to its smooth surface feature. Ethanol liquid is used in the experiment because it is easy to produce splashing due to its low surface tension which is approximately 0.022 N/m. Ethanol is capable of wetting wafer surface completely, therefore, the static contact angle is nearly zero. The effect of centrifugal force applied to film expansion after impacting can be neglected because the distance between the impacting point and the rotating center is relatively larger than the diameter of drop expanding film.

In order to quantify the threshold of splashing for ethanol drop impact on the inclined surface, a normal Weber number (We_n) is adopted in this paper [3] and is deduced from $We=\rho D_0 V_i^2/\sigma$, where ρ is the liquid density, D_0 is the diameter of the droplet, V_i is the impacting velocity of the droplet, and σ is the surface tension of liquid. We number represents the competition between kinetic energy and surface energy of the droplet. The kinetic energy intends to deform the shape of the droplet, whereas the surface energy tries to keep the droplet geometry compact. The difference between We and We_n is V_i replaced by $V_i\cos\theta$, where θ is the inclined angle between wafer surface and the ground.

2. Experimental techniques and apparatus

A schematic of the experimental system is shown in Fig. 2. A hypodermic needle connected with a syringe is used to generate a single droplet at a time. The pendant drop falls down from the needle and impacts onto a 6 in. silicone wafer disk. The target disk is rotated and driven by a servomotor which is equipped with a programmable-logic-controller. The drop impacting velocity can be varied by changing the distance between the needle and the impact surface. A high speed CCD camera with 256×240 pixels (Photron FASTCAM-Super 10K) is used to record the image at the rate of 1000 frames/s, and the camera is set horizontally towards the pivot of the tilted wafer disk to shoot the side view images. The spatial resolution is about 0.045–0.071 mm/pixel due to the different distance between the cameras and the impacting point. A lamp is set in an appropriate position for illumination purpose. All the images in the recording system are then transferred to a computer for the further process.

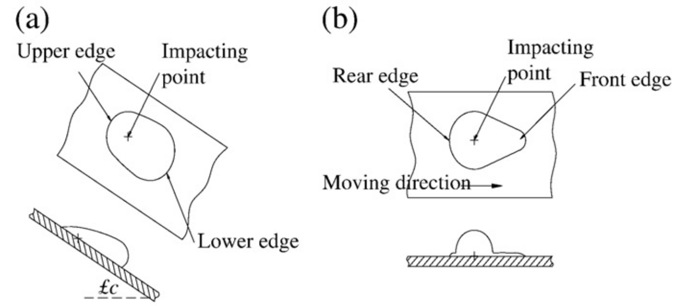

Fig. 1. Sketch of the geometry of drop spreading film (a) on an inclined surface (b) on a moving surface.

The droplet diameter and velocity are measured from the recorded image. A probe with 1.25 mm diameter placed next to the impacting point is used as a reference for calibration. The actual droplet diameter can be calculated to the scale of probe in the picture. Velocity of the droplet is then calculated by the droplet's travel distance in terms of two consecutive pictures. Liquid density, surface tension and the size of hypodermic needle affect the actual droplet size. During the drop fall the geometry of ethanol drop is slightly elliptical. In order to calculate the precise size of drop, an equivalent drop diameter is defined and calculated by the equation of $D_{eq}=(ab^2)^{1/3}$, where a is the vertical diameter and b is the horizontal diameter of the elliptical drop. Normally the equivalent diameter of ethanol droplets is measured between 2.32 and 2.58 mm. The error of measurement mainly comes from the resolution of image and the deviations of drop diameter and drop velocity, which are 2.2% and 6.5% respectively. The disk's inclination angle is adjusted between 0 and 50° and the deviation of angle is 0.1° due to the accuracy of the instrument. The uncertainty of the calculated Weber number is about 9%.

The rotating disk is used to simulate a moving surface and the impacting point is positioned on the horizontal line which passes through the disk center. The distance between the impacting point

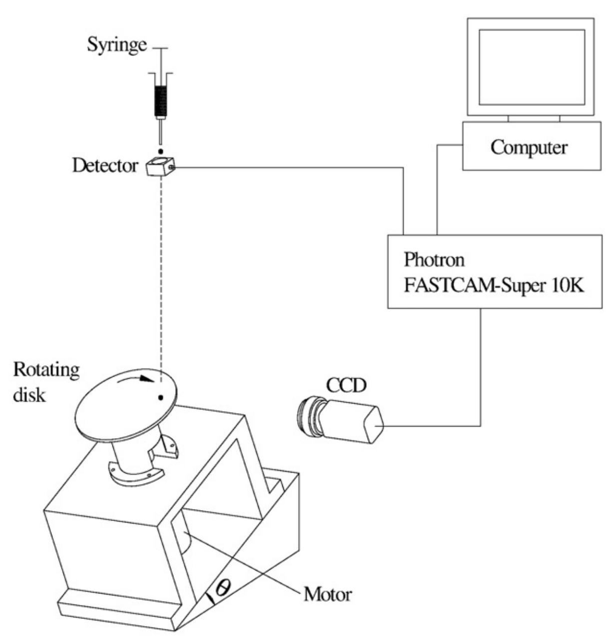

Fig. 2. Schematic of the experimental set-up.