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A study of the splash phenomenon of water drops on wood – Emitted droplet velocity and kinetic energy

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ABSTRACT

The dynamic prompt splash behavior of water drop impinging upon a natural wood surface (*Shorea* spp.) was studied in this work. The water drop images during the impacting process were taken sequentially to study the properties of the emitted droplets such as the critical Weber number, droplet number, shape, velocity, size, and kinetic energy. For prompt splashing on a *Shorea* spp. surface, the emitted droplets formed not only during their advancing wetting process but also during the drop receding process. The emitted droplets that formed at the early stage usually had greater velocity but significant deformation. The kinetic energy of the emitted droplets varied with great scattering at every impact height, but the average kinetic energy (KE_{avg}) of the droplets varied linearly with the impact height: KE_{avg} (erg) = 0.0017 (m_0gH), implying that every emitted droplet had approximately 0.17% of the initial potential energy of the impacting water drop. Furthermore, the number of emitted droplets depended linearly on the Weber number: N = 0.304 (*We*–77).

1. Introduction

The interaction between a liquid drop and a solid surface is of great interest to the fields of fluid mechanics, meteorology, agricultural engineering, and mechanical engineering. To enhance the wetting of a liquid drop on a solid surface or lower the chance of droplet splashing, the solid texture, surface roughness, hydrophobicity, substrate material, and porosity [1–14] have been widely studied.

When a liquid drop impacts a solid surface, three phases are generally observed: propagation of an internal shock wave, generation of a spreading lamella and drop deformation [15]. Moreover, the drop impact behavior (deposition, rebound, and splash) depends on both dynamic parameters (such as impact velocity, surface tension, and liquid viscosity) and substrate properties (surface roughness, hydrophobicity, and hardness). Among these actions, drop splashing may occur when the impacting drop has a significant inertial force relative to the sum of surface and viscous forces [6,10]. This is commonly observed when a low-viscous drop falls from far above a solid surface. Upon drop splashing, some tiny liquid droplets may detach from the outer-region fingers during the lamella spreading phase over the surface [11–14,16].

Prompt splashing often occurs at rough surfaces and is clearly influenced by the surface structure [15]. As the impact velocity increases to a certain level, on a rough surface the drop impact eventually leads to prompt splashing. According to the literature, the prompt splash phenomenon for liquid drop impacting is commonly observed on various defined micropatterns [6,17]. As the dimensionless length parameter (b^*/w, b^* is longest distance between two pillar and w is the width of the pillars) of the micropattern increases, the critical Weber number increases. In other words, a prompt splash is more likely to be observed with a low dimensionless length parameter [17]. Furthermore, Sivakumar et al. [6] studied the influence of the asperity height on the splash process for asperity heights on the millimeter scale, i.e., 1 mm and 3 mm. The water impact experiment featured an intense ejection of tiny liquid droplets for an asperity height of 1 mm. When the asperity height was changed to 3 mm, the droplet ejection was reduced drastically.

Moita and Moreira [18,19] studied the impact disintegration mechanism of fuel droplet on heated and non-heated surfaces. They reported that at non-heated surface, the surface roughness endorses droplet disintegration at smaller critical velocities and therefore promotes "prompt" splash.

Water impact on natural materials with roughness due to their own grooves has been rarely reported in the literature. To date, *Paulownia*, *Frazinus mandshurica, Betula costata* and *Jatoba* have been studied [7,20]. Chen and Wang [7] reported that the greater

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the wood density is, the lower the critical impact Weber number for droplet splashing will be. Instead of conducting the drop impact at room temperature, Lan and Wang [20] conducted a water impact experiment on a heated wood surface and found that an obvious deformation occurred. Because of the heat transfer between the solid and the liquid drop and/or the liquid evaporation, they observed that the dimensionless maximum drop height fluctuated with time.

Although the drop impact behavior has been extensively studied, only a few studies have focused on the dynamic aspect of splashes, particularly prompt splashing on natural woods, which is important for the fire extinguishing process of wood constructions and forests. In this study, *Shorea* spp. was used to study the impact dynamics, particularly on the emitted droplet during the prompt splash.

2. Experiment

2.1. Wood specimen

Shorea spp. is commonly used in general construction and flooring, therefore, it was chosen for studying the splash phenomenon in this study. The wood specimens were first polished using a polisher (Metkon Gripo 1V, Turkey) with sandpaper of grit number 240, which corresponded to an average particle diameter of 53 μm. The specimen was rotated throughout the 15-min polishing process to minimize the directional pattern. After polishing, the specimens were washed with DI water to remove any wood flour left and were then dried in an oven at 35 °C for 24 h.

A surface roughness tester (Taylor Hobson, Surtronic S-128, UK; ±3% measurement error) was used for the roughness measurement. The tester's tip was tilted at 45° while scanning the wood surface, and the average roughness of the surface was determined by scanning in two different directions, with ten locations in each direction. Fig. 1 illustrates the surface morphology of *Shorea* spp. after polishing.

The surface hydrophobicity was characterized by measuring the advancing and receding contact angles of water on *Shorea* spp. using the method reported in Lin et al. [21]. The advancing contact angle (θ_a) of *Shorea* spp. was found to be 130 ± 2°, and no receding contact angle (i.e., $\theta_r \sim 0°$) was observed.

2.2. Impact experiment

Water drops were generated using a stainless steel needle (gauge No. 28, internal diameter = 0.018 cm) with a zero downward velocity. Each water drop had an average diameter (D_0) of 0.239 cm, as measured by the drop weight of twenty falling drops. The falling distances (H, as shown in Fig. 2) varied from 8 to 43 cm. The value of H was obtain from the estimation of impact velocity, following the way reported in Ref. [22]. The position of the water drop was fitted to the equation of a free falling body to determine the contact time and the impact velocity (v_i = 125–290 cm/s in this work). The ratio of liquid inertia and surface tension is defined as the Weber number:

$$We = \frac{\rho v_i^2 D_0}{\gamma} \quad (1)$$

where D_0 represents the initial drop diameter and ρ and γ are the density and surface tension of the liquid, respectively. The Weber number ranged from 52 to 279 in this study.

The water drop impact experiments were carried out at 25 ± 0.5 °C. Sequences of digital images of the water drop were taken while the drop was falling and impinging upon the wood surface. As shown in Fig. 2, the apparatus of the imaging system used in this study contained a halogen light source, a plano-convex lens system for collimated beam generation, an objective lens, and two solid-state cameras, as described in detail by Wang et al. [23]. The video image system digitized the pictures into 400 lines × 400 pixels for both CCDs (CCD1: Optronis CR3000X2; CCD2: Mikrotron GmbH EoSens mini 2), and each was assigned a grey level value with eight-bit resolution.

The acquisition frame rate was 6770 images per second. The image forming system (CCD1) was calibrated using a stainless-steel ball of a known diameter (2.456 ± 0.003 mm) and 17.9 μm/pixel was obtained. CCD2 was then calibrated by digitizing the falling water drop before impact on substrate (t < 0) with a known initial drop volume, which was obtained from the average weight of twenty free falling drops. This calibration was performed before the impact experiment and a value around 38 μm/pixel yielded for CCD2. The uncertainty for CCD2 calibration was around 2%.

The size of emitted water droplets from splashing was calculated by fitting the droplet with the shape of an ellipsoid from pictures taken by the imaging system. Two illustration images showing the fitting between emitted droplet and ellipsoid curve was given later (upper part of Fig. 3). The volume and the average diameter ($V = 4\pi abc/3 = \pi D_{avg}^3/6$) of the emitted droplets were evaluated from the best fitting of the image of emitted droplet. In general, five sequential droplets were fitted to obtain an average droplet size.

2.3. Velocity calculation for the emitted droplets

The water drop initially deposited and spread on the wood surface. At the beginning of the spreading phase, the liquid front end of the lamella eventually formed the secondary droplets (emitted droplets) at the contact line. This is the so-called prompt splash phenomenon. The process was recorded sequentially and later

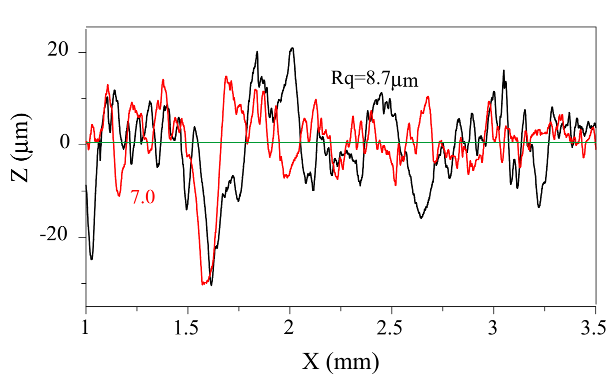

Fig. 1. Illustration of the surface morphology for polished *Shorea* spp. at two different locations with root-mean-square roughness (R_q) values of 7.0 and 8.7 μm.

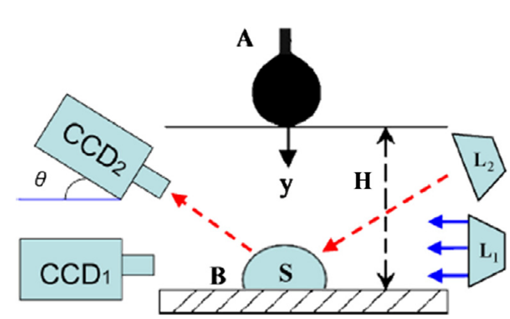

Fig. 2. Experimental setup for impingement of a free-falling water drop on a wood surface. A: needle; B: wood substrate; S: water drop; CCD: high-speed video camera; H: height of the drop before falling; L: parallel light source.