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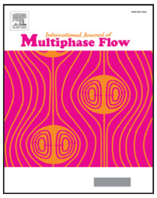

Droplet splashing on thin moving films at high Weber numbers

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ABSTRACT

The influence of a thin moving film on the splashing of droplets was investigated experimentally at high Weber numbers. This study was conducted using a flywheel experiment fitted with a new film generation system, which allows for the production of thin films with variable mean velocity for different liquids. The thickness was measured using a miniature confocal-chromatic sensor during the rotation of the flywheel. Using shadowgraph techniques, the splashing process was analyzed and the evolution of the crown height and diameter were described. It was also demonstrated that the film velocity and thickness influence the development of the crown geometry. The combination of a high-speed and a high-resolution camera allowed us to observe two different instabilities that accelerate the breakup process, leading to a complete atomization of the crown into secondary droplets. The instabilities observed were: spreading holes and a separation from the crown base. Using the formed holes, we calculated the lamella thickness using two different methods, yielding a constant value of 31 ± 3 µm for all the experiments. We estimated both the time at which the hole instabilities appeared and the time at which the breakup process began. Moreover, it was demonstrated that small bubbles in the lamella are responsible for the hole formation. We also showed that the entire breakup process is delayed by increasing the film flow velocity, regardless of the Weber number.

1. Introduction

Droplet impact on moving films is a fundamental process in a wide range of technical applications, such as aircraft icing (Liu et al., 2017) and vehicle soiling (Gaylard and Duncan, 2011). When an aircraft flies through a cloud of super-cooled droplets or when a vehicle moves through the rain, droplets impact the surface. A part of the droplet mass that impacts the surface while it is still dry forms a film which sticks to the surface. The other part of the mass atomizes into small secondary droplets. This phenomenon is called splashing. Thereafter, the subsequent droplets impact the thin film directly, and the impact with a dry surface is no longer relevant. The formed thin film then starts to move due to the shear stress on the surfaces caused by the airflow.

The impact dynamics are characterized using the Weber and Reynolds numbers (Josserand and Thoroddsen, 2016). The Weber number (We) is the ratio between the inertial and capillary forces, and the Reynolds number (Re) represents the ratio between the inertial and viscous forces. In the case of droplet impact on wetted surfaces, the film thickness also characterizes the impact dynamics. The film thickness is made dimensionless using the droplet diameter. These characteristic quantities are defined as follows:

$$We = \frac{\rho_l u_{\mathrm{imp}}^2 d_0}{\sigma_{l,g}}, \quad Re = \frac{u_{\mathrm{imp}} d_0}{\nu_l}, \quad \text{and} \quad \delta = \frac{h_f}{d_0}, \tag{1}$$

where ρ_l is the liquid density, d_0 is the droplet diameter, u_{imp} is the impact velocity, $\sigma_{l,\,g}$ is the liquid surface tension, ν_l is the kinematic viscosity of the liquid, h_f is the film thickness, and δ is the dimensionless film thickness.

Many investigations have been carried out over the last decades in order to better understand the splashing mechanism. Most of them were experimental investigations conducted at relatively low Weber numbers $We < 2,\,500$, for example Wang and Chen (2000), Rioboo et al. (2003), Hammond et al. (2005) and Deegan et al. (2008). Although these experiments are relevant for many applications — for example, vehicle soiling or aircraft icing where the impact velocities and the droplet diameters are high — the impact may differ in the outcome from the experiments performed at low Weber numbers (see Table 1). An experimental investigation on droplet impacting on a moving film was carried out by Alghoul et al. (2011) at $We < 460$ and $\delta > 1$. They observed that the shape of the jets were firstly asymmetric but became more symmetrical over time. However, the Weber numbers and film

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thicknesses do not correspond with vehicle soiling or aircraft icing problems. One of the few experimental investigations at $We > 3000$ and $\delta > 1$ was performed by Pan et al. (2008). They observed that different crown forms can be generated by changing the thickness of the film. However, the film was not moving in those experiments and higher Weber numbers were not achieved. This restriction on Weber number variation was due to a breakup process caused by aerodynamic drag on the droplets and oscillation during the cutting process. More recently, Faßmann (2015) managed to overcome the breakup process by accelerating the substrate instead of the droplets. He carried out a statistical investigation to quantify the diameter and velocities of the secondary droplets at $We = 700$ and $We = 3500$, with varying film thickness of $\delta > 0.1$. This experiment resulted in the conclusion that an increase in Weber number causes a reduction in diameter size of the secondary droplets, but increases the quantity of small droplets.

Table 1
Examples of Weber numbers presented in aircraft icing and vehicle soiling problems (see Bringi et al. (2003) and EASA CS-25 (2009)).

Example	d_0 (μm)	u_{imp} (m/s)	We
Vehicle soiling	100–4000	3–33	12.4–59,876
Aircraft icing	15–50	60–120	742–9897

The time evolution of splashing and the formation of the secondary droplets have also been studied by many authors. One of the most important works was performed by Cossali et al. (1997). They observed the droplet impact at low Weber numbers and categorized time evolution in four different phases: (1) the formation of the crown and possible prompt splash, (2) the instability of the rim and jet formation, (3) the breakup of jets and the formation of secondary droplets, and (4) the period of crown collapse. A later work presented by Thoroddsen (2002) showed that an axisymmetric ejecta sheet arises before the crown is formed at $\delta > 0.5$, i.e., during the first phase described by Cossali et al. (1997). This ejecta sheet disintegrates when $We > 500$ and generates secondary droplets, which should not be confused with the secondary droplets generated by the crown (Zhang et al., 2010). Afterwards, Zhang et al. (2012) demonstrated that the size of these secondary droplets is not necessarily much smaller than the size of the droplets generated by the crown, and that no correlation exists between the droplet origin and droplet size. The breakup mechanism that causes these secondary droplets has been studied by many authors, as shown in Dhiman and Chandra (2010). One interesting observation was made by Wang and Chen (2000), who found that the crown breakup starts from the lower part of the crown, when droplets impact very thin fluid films. However, those observations were made at very low Reynolds numbers ($Re = 1168$), and are not provided as a detailed time-resolved visualization. In the aircraft icing and vehicle soiling problems, the Reynolds number is one order of magnitude higher.

More recently, Roisman et al. (2006) performed a linear stability analysis showing that the main source of secondary droplets is the creation and breakup of the crown. This phenomenon is similar to the bag breakup process caused by the aerodynamic drop deformation, as shown in Opfer et al. (2014). A different breakup mechanism was observed by Thoroddsen et al. (2006) using a film of lower surface tension than the primary droplet. This kind of splashing produces small droplets from the film, which impact with the inner side of the lamella, subsequently generating holes. However, when the primary droplet and the film have the same surface tension, the lamella does not breakup by hole formation. Studies on the rupture of thin soap films have been carried out for the last decades showing a similar behavior regarding the hole formations in the lamella (Taylor, 1959; Culick, 1960; Prévost and Gallez, 1986; Thete et al., 2015). The rupture characteristics and the thickness evolution of such films is described by a nonlinear theory, characterizing the surface waves, as shown in Prévost and Gallez (1986).

In contrast to the large number of experiments on droplet impacts performed to date, only a few theoretical investigations have been carried out (Josserand and Thoroddsen, 2016). One notable theory was presented by Yarin and Weiss (1995). They developed a mathematical model for the description of the splashing phenomena which is based on a kinematic discontinuity in the velocity. This model is in agreement with the experiments at low Weber numbers. Later, Roisman and Tropea (2002) generalized this theory for the impact on liquid fluids and inclined surfaces. As with the theory of Yarin and Weiss (1995), the generalization performed by Roisman and Tropea (2002) is also in agreement with the experiments. However, this model has not been validated at high Weber numbers due to missing experimental data. A review of the recent theoretical, numerical, and experimental investigations of droplets impacting with a solid and wetted surface can be found in Yarin (2006), Thoroddsen et al. (2008), and Josserand and Thoroddsen (2016).

In this study, we aim to describe the splashing of monodispersed droplets on thin moving films ($\delta < 0.15$) at high Weber numbers ($We > 2000$). Specifically, we seek to observe the splashing and describe the formed crown and lamella thickness, and compare it with the four phases of splashing at low Weber numbers presented by Cossali et al. (1997). We also intend to describe the influence of the film velocity on the crown geometry and on the breakup process. This work aims to give us further insight into the splashing phenomenon on moving films at high Weber numbers by providing a detailed description of various crown geometries and the breakup process, which is relevant for a host of technical applications.

2. Experimental methods

We redesigned the flywheel experiment introduced in Faßmann et al. (2013) to achieve high Weber numbers and reproduce the impact of monodisperse droplets normal to thin moving films. Moreover, we developed a new film generation system which allowed for the investigation of moving films of different fluids — such as water or alcohols — to be conducted (see Fig. 1(a)).

The mode of operation of the flywheel experiment can be described as follows: Each droplet is formed and released by a droplet generator. These droplets fall freely due to gravity through a shielding tube. Meanwhile, the flywheel, on which the substrate is mounted, rotates under the droplet generator at a constant angular velocity (ω).

The droplet generator consists of a syringe pump, a needle, a polyurethane hose, and a cage with a solenoid (see Fig. 1(b)). The syringe pump KDS200 from KD Scientific was used to regulate the volume rate. The syringe is connected to the needle under the cage through the polyurethane hose. After a specific amount of water is pumped into the needle, the droplet forms and hangs until the cage is hit by the solenoid. Subsequently, the droplet separates itself from the needle and falls under the influence of gravity. The flywheel and the droplet generator are synchronized so that droplets impact on the substrate surface after some milliseconds of free fall. A Standford DG535 delay generator was used to synchronize the droplet generator and cameras to the flywheel. To investigate the impact of droplets on wetted surfaces, a thin moving film is generated on the substrate during the rotation of the flywheel. This is done using a recirculation system that pumps fluid into the flywheel.