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Characterization of secondary droplets during thermal atomization regime

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ABSTRACT

When a single drop impacts onto a very hot substrate with a high impact velocity the collision leads to a generation of a fast vertical spray of fine secondary droplets. These small drops are generated during disintegration of a thin drop lamella by a vapor, formed by the liquid vaporization. They are formed near the moving, disordered dewetting front. Finally, the remaining liquid of the drop breaks up into several larger fragments. The present study is focused on the characterization of such secondary droplets generated during drop impact in the thermal atomization regime. The drop impact has been observed and characterized using two high-speed video systems observing from the side and top. The characterization of secondary droplets has been performed using a dual-mode phase Doppler measurement system. The characteristic number, size and velocity of secondary droplets are measured for various parameters. It has been shown that the velocity of the secondary drops is scaled with the characteristic vapor velocity.

1. Introduction

In many industrial processes, for example spray cooling of high power electric or electronic parts, aircraft gas turbines and internal combustion engines, the interaction of a spray and a hot wall can be observed [1–3]. For an isothermal drop impact without phase change the outcome (rebound, deposition or splash) is mainly determined by the impact parameters, liquid properties, substrate morphology and wettability [4–8] and for the properties of the surrounding gas [9–11]. Drop impact onto a hot surface can be additionally accompanied by Marangoni effects, nucleate boiling, film boiling, phase change phenomena and other thermodynamic effects [12]. By varying the surface temperature, the drop impact outcome can change significantly and additional thermodynamic influences can be observed. At high surface temperatures significantly above the saturation temperature, the drop does not remain in contact with the surface, since a vapor layer arises between the drop and the surface. The minimum film boiling temperature at which this occurs is known as the Leidenfrost point [13] and it is influenced by various parameters, e.g. surface material, liquid properties, and impact parameters [14–16]. Comprehensive reviews of the phenomena for drop and spray impact can be found in Liang and Mudawar [17–19] and Breitenbach et al. [20].

For an impinging drop onto a hot surface various outcome regimes at different wall temperatures and impact parameters have been observed in the literature, e.g. drop deposition, explosive detachment, dry and explosive rebound or film splash [21–24]. Numerous of these outcomes lead to drop breakup and to the generation of multiple secondary droplets. The splashing angle, size and velocity of secondary droplets has been recently investigated for a continuous drop chain impacting onto a hot surface [25].

The number, size and velocity of the secondary droplets are rather important in numerous applications, for example in internal combustion engines, where they affect mixture formation and residues. It is also known that the surface properties and the impact conditions significantly influence the characteristic size of secondary droplets and the conditions determining when drop breakup occurs [26–28]. A comprehensive overview of further studies related to the characterization of secondary atomization during drop impact onto a hot surface can be found in Moreira et al. [29] and Liang and Mudawar [17].

The present study is focused on the characterization of secondary droplets generated after drop impact in the thermal atomization regime. The main breakup mechanisms following drop impact in the thermal atomization regime have been recently analyzed in Roisman et al. [28]. Thermal atomization has been observed and characterized using a high-speed video system. Since the fine secondary droplets are of the order of some tens of microns; hence, not resolvable with simple imaging optics, a dual-mode phase Doppler system is used to measure the velocity and size of the secondary droplets for various impact parameters and surface temperatures.

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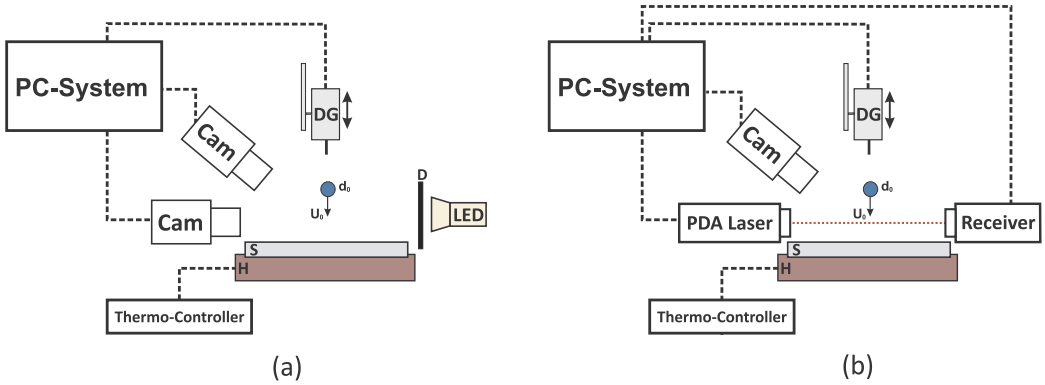

Fig. 1. Experimental setup with (a) two high speed video cameras [Cam] and an illumination system [LED] to observe the drop impact phenomena and with (b) a phase Doppler system [PDA] consisting of a laser and a receiver to characterize secondary droplets. The heating system [H and S] is controlled by a thermo-controller and the drop is produced in the drop generation unit [DG].

2. Experimental method

The experimental setup, shown in Fig. 1, consists of a drop-on-demand generator, a heated target, the heating and thermal control system, a data acquisition system, the phase Doppler instrument for spray characterization and a high-speed video system to observe the drop impact phenomena. Two CMOS high-speed cameras are mounted to record side-view and top-view images with a maximum resolution of 1280 × 800 pixels at 6200 fps. In order to perform high-speed shadowgraph imaging, a 120 W LED spotlight with a 3 mm optical diffusor plate [D] is used as an illumination system to achieve a homogeneous background. The heating system consists of an impact surface [S] embedded in a copper cylinder [H] heated with a 250 W cartridge heater. A ceramic material of low thermal conductivity is used to insulate the sidewalls of the copper cylinder. The surface temperature is measured with a type-K thermocouple within the impact substrate, mounted just below the impact surface (0.5 mm) and controlled with a PID thermo-controller (three term controller). To achieve an average surface roughness of $R_a \approx 0.06\ \mu m$ the aluminum impact surface (EN AW 7075) is processed with abrasive paper and finally polished with a mirror polishing paste. The final surface roughness has been measured by an atomic force microscopy.

The drop impacts normal to the hot substrate. It is produced by static drop generation in the drop generator unit [DG] with a blunt hypodermic needle. A piezoelectric micropump delivers the fluid through the needle until a drop falls down due to gravity. By changing the height of the drop generator the impact velocity can be adjusted, since it is the free-fall velocity. The initial temperature of the drop $T_l \approx 25\,°C$ is controlled with a thermocouple type-K in the liquid system close to the needle. The fluid used in the experiments is highly purified laboratory water (double-distilled). Finally, drops with a diameter of $D_0 = 2.2 \pm 0.05$ mm and an impact velocity between $U_0 = 0.5–2.5 \pm 0.05$ m/s have been obtained. The initial surface temperature can be varied in the range $T_{w0} = 50–400\,°C$ with an uncertainty of $\pm$ 1.5 °C according to class I thermocouples.

To characterize the fine secondary droplets generated during the thermal atomization regime a DANTEC dual-mode phase Doppler analyzer [PDA] is used. This system, based on interferometry [30], provides data of the diameter, components of the velocity vector and concentration of transparent spherical droplets. In the present experiments the system has been equipped with a DANTEC Flow Explorer with two 300mW DPSS lasers at wavelengths of $\lambda_1 = 532$ nm and $\lambda_2 = 561$ nm to measure two velocity components (axial z and radial r) of the secondary droplets simultaneously. As receiving optics a 112 mm Dual-PDA receiver is used. The focal lengths of the receiver and the transmitter are both $f = 500$ mm, the scattering angle was chosen $\phi = 29°$ and the spatial slit in the receiving optics is 100 μm. With the given optical parameters of the laser system a maximum drop diameter of $d_{max} \approx 120\ \mu m$ is measured. The data acquisition of the dual-mode phase Doppler measurement system operates in cyclic mode. It is repeatedly triggered by a laser light barrier which detects the falling drop. The phase Doppler measurements are accompanied by the simultaneous observations of splash by the high-speed video system. This method allows to associate the PDA data with the observed phenomena.

Since the phase Doppler system is a pointwise measurement technique three different radial positions r, all with an axial position $z_0 = 4$ mm above the impact surface, have been measured to describe various regions: center of the lamella $r_1 = 0$ mm, rim region $r_3 = 6$ mm, and between the center and the rim $r_2 = 2$ mm. The positions are fixed for all measurements due to the highly dynamic motion of the spreading drop. Fig. 2 shows a sketch of the different measurement positions.

3. Observations of drop impact phenomena

The observations of the impact phenomena lead to a classification into different impact outcomes. In Fig. 3 various impact regimes have been shown: (a) drop deposition, (b) drop dancing, (c) drop rebound, and (d) thermal atomization. A corresponding regime map for various impact velocities U_0 and initial surface temperatures T_{w0} is shown in Fig. 4. Most of the impact regimes are commonly known and have been identified in various previous studies [21,24,31]. Recent investigations also described the thermal atomization regime, shown in Fig. 3(d) for initial surface temperature $T_{w0} = 260\,°C$, impact velocity $U_0 = 1.7$ m/s, and drop diameter $D_0 = 2.2$ mm.

The thermal atomization regime [28] is described by thermally induced dewetting of the substrate, which is characterized by intensive lamella evaporation, initiation of lamella levitation, and finally drop disintegration. The intensive vapor flow leads to a generation of the fast vertical spray of fine droplets induced by the lamella evaporation and a number of larger drops formed as a result of the drop disintegration and rim breakup. The larger drop fragments may have a splashing angle to the wall [25]. Nonetheless, both processes take place in a very short time period, mainly within the first few milliseconds after initial contact of the impinging drop with the hot impact substrate.

As seen in Fig. 4, thermal atomization occurs only for higher surface temperatures and impact velocities. This leads to the assumption that

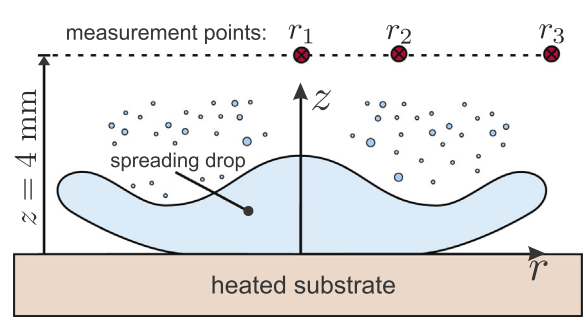

Fig. 2. Sketch of phase Doppler measurement positions.

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