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A wind tunnel study of the effects of collision processes on the shape and oscillation for moderate-size raindrops

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ABSTRACT

Drop–drop collision experiments were carried out at the Mainz vertical wind tunnel. Water drops of 2.5 mm diameter were freely floated at their terminal velocities in a vertical air stream and collided with 0.5 mm diameter droplets. The collisions were recorded with a high speed digital video camera at a frame rate of 1000 per second. Altogether 116 collision events were observed, 75 of which ended with coalescence, and the rest with filament type breakup. The coalescence efficiency and its dependence on the Weber number and on the eccentricity of the colliding drops showed good agreement with earlier numerical studies. Thirty-six recorded collisions were further analyzed in order to characterize the oscillation behavior of large drops after a collisional excitation. Besides the introduction of the experimental method for studying the raindrop collisions, the study primarily focused on the characterization of the average value and the amplitude of the axis ratio variation, the active oscillation modes and their frequencies, and the decay of the oscillations excited by the collision. In spite of the fact that the amplitude of the axis ratio variation increased up to 4 to 6 times of its value before collision – depending on whether the collision ended with coalescence or breakup –, the average axis ratios increased by less than 1%. Since the sizes of largest drops after collision remained practically unchanged during the collision process, the frequencies of the active fundamental ($n = 2$) oscillation modes of the drops did not change significantly either. Instantaneously after collision the transverse oscillation mode and the whole body rotation dominated, while at a later instant the oblate–prolate mode determined again the drop shape alteration. It was further found that the damping of the oscillation after collision can be adequately described by the viscous decay of a liquid spherical drop.

1. Introduction

In warm clouds, collision followed by coalescence of cloud drops is the primary process for rain initiation. In cold clouds, mm-size raindrops are the results of melting ice particles, such as graupels or hailstones. Large raindrops collide with drizzle sized droplets while falling from the cloud. During moderate to heavy rainfall 1 to 10 collisions take place per second in one cubic meter air (Beard et al., 1983). After collision the drops can i) remain permanently united and form a large drop conserving the volume; they can ii) break up and produce lots of smaller droplets with different sizes; or they can iii) bounce off and apparently retain their initial sizes. In rain formation the first two cases are of importance as they directly influence the size distribution of the drops. The size distribution, in turn, is a key input parameter of modeling cloud and precipitation evolution (e.g., Seifert et al., 2005), for instance, or calculating the rainfall rate using weather radar (Bringi and Chandrasekar, 2004).

In spite of its crucial importance only a very few experimental studies focus on collisions of mm-size raindrops. The pioneering laboratory works of McTaggart-Cowan and List (1975), as well

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as Low and List (1982a,b) resulted in a parameterization of coalescence efficiencies and fragment size distribution after collision induced breakup. The later studies of Ochs et al. (1986), Czys and Ochs (1988), as well as the very recent investigations of Barros et al. (2008), Emersic and Connolly (2011) and Testik et al. (2011) were primarily focused on the extension and the correction of the parameterization of fragment size distributions and/or collision outcome regimes. However, these very few experimental data while delivering important results and widening scientific understanding also suffer from uncertainties such as unreliable determination of drop sizes, incorrect fall speeds, or very little fragment droplets. Recently, numerical experiments were performed and compared to laboratory data (Beheng et al., 2006; Schlottke et al., 2010; Straub et al., 2010). Their advantage is that the input parameters such as drop sizes and eccentricities of colliding drops are easily variable. Furthermore, earlier experimental studies of the collision process focused on the fragment size distribution and the coalescence efficiencies but they did not deal with the shape changes of the raindrops during collision in detail. Nevertheless, the transient shape change after collision result in significant deviations in the backscatter ratio and linear depolarization ratios when compared to static raindrop shapes (Jameson and Durden, 1996; Beard and Johnson, 1984). Indeed, an appreciable fraction of large raindrops in heavy rain showers are oscillating with high amplitudes (Beard et al., 1983) and undergo significant shape variations.

The present study on drop–drop collision is a continuation of our earlier laboratory experiments on raindrop microphysics mainly focusing on the axis ratio variation and the oscillation modes of freely floating drops. The goal of this paper is to introduce the experimental setup, the measurement procedure and the analysis method for the characterization of the axis ratio variation, the oscillation modes, and the decay of the oscillation after drop–drop collisions. A first data set is presented where the sizes of the colliding drops were selected to be 0.5 mm in diameter for the smaller ones and 2.5 mm for the larger ones. Based on theoretical considerations, Beard et al. (1983), Beard and Johnson (1984) and Johnson and Beard (1984) concluded that the oscillation energy is a maximum for collisions between drops of diameters from 2 to 5 mm, and droplets of diameters around 500 μm (see Pruppacher and Klett, 1997, p. 408). Backscatter ratio calculations of raindrops implied that the lowest drop diameter where the effect of oscillation rises for different rainfall rates is about 2 mm (Beard and Johnson, 1984). On the other hand, the number concentration of mm-size raindrops decreases exponentially with size. Therefore, moderate-size drops with diameters of around 2.5 mm can be considered as representative in studies involving drop–drop collisions. Furthermore, collisions between drops of diameters close to the chosen two sizes (0.5 and 2.5 mm) were investigated in the numerical study of Schlottke et al. (2010), allowing a direct comparison between their numerical and the present laboratory experiments.

This paper is organized as follows. In Section 2, the parameters used for characterizing the collision process and the oscillation of raindrops are summarized in Section 2. In Section 3, the experimental apparatus is described, and the image processing and the data analysis methods, including the identification of different oscillation modes are introduced. The experimental results with discussion are given in Section 4.

2. Parameters used for characterizing raindrop collisions

2.1. Characterization of the collision process

Some parameters of the collision process are thought to be well understood or at least properly characterized. One of them is the above mentioned size distribution of fragment drops. The other one is the coalescence efficiency which increases with decreasing Weber number. The coalescence efficiency is defined as the ratio of the number of collisions resulting in coalescence to the total number of collisions. The Weber number is the ratio of the collision kinetic energy (CKE) and the surface energy of the coalesced drops. (Note that this definition of the Weber number is somewhat different from that used in some other studies, e.g., in Testik et al., 2011. The relation between both Weber number definitions is given, e.g., in Schlottke et al., 2010.) The collision kinetic energy is defined as

$$CKE = \frac{\pi}{12}\rho_w \frac{d_L^3 \cdot d_S^3}{d_L^3 + d_S^3} \cdot \Delta v^2 \tag{1}$$

where ρ_w is the density of the water, d_L and d_S are diameters of the larger and the smaller colliding drops, respectively (Low and List, 1982a). The impact velocity, i.e. the velocity difference of the two colliding drops is denoted by Δv. The surface energy of the coalesced drops can be calculated as

$$S_c = \pi\sigma\left(\mathrm{d}_\mathrm{L}^3 + \mathrm{d}_\mathrm{S}^3\right)^{2/3} \tag{2}$$

where σ is the surface tension of water (Low and List, 1982a). Roughly speaking, if the collision kinetic energy exceeds the energy that could keep the surface together, the drop breaks up. Indeed, at high Weber numbers – so that if *CKE* exceeds significantly S_c –, no collision ends up with permanent coalescence of both drops, but breakup takes place under all circumstances (Schlottke et al., 2010). Whether the collision outcome is breakup or coalescence, depends on the eccentricity of the colliding drops too. Following Schlottke et al. (2010), the eccentricity is given as

$$\varepsilon = \frac{2\gamma}{d_L + d_S} \tag{3}$$

where γ is the distance of the drops' centers. Another geometric impact parameter is the impact angle θ (see, e.g., Testik et al., 2011) which relates to the eccentricity as

$$\sin\theta = \varepsilon. \tag{4}$$

Schlottke et al. (2010) gave a formula for the critical eccentricity for breakup depending on the ratio of the diameters of the colliding drops. In general, the probability for breakup after collisions is higher for larger eccentricities. Depending on the colliding drop sizes and the eccentricities, four different breakup types were distinguished by McTaggart-Cowan and List (1975): filament (or neck), disk, sheet and bag breakup. Based on its distinctive morphology Testik et al. (2011) introduced a subtype of disk breakup for low *CKE*s, which they called crown breakup.

As mentioned earlier, the third collision outcome scenario beside coalescence and breakup is if the colliding drops