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Wind tunnel study on the size distribution of droplets after collision induced breakup of levitating water drops

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ABSTRACT

Wind tunnel experiments on collisions between drop pairs of 2.5 and 0.5 mm diameter have been performed and the coalescence and breakup events have been recorded by a high-speed digital camera. From the comprehensive analysis of the captured images, the most important parameters utilized in numerical models, such as coalescence efficiency, breakup type, number of fragments and fragment size distribution after breakup were determined. The experimentally obtained parameters have been compared to parameterizations based on earlier laboratory studies of Low and List, and on direct numerical simulations. A very good agreement between experimental results and parameterizations has been found. However, the parameterization based on direct numerical simulation fails to forecast the number of fragments of small sizes. Ultimately, a piece of puzzle is provided to the very important but still incomplete experimental data set of drop-drop collision outcome.

1. Introduction

Drop-drop collision is one of the most important processes influencing the raindrop size distribution (RSD) and, therefore, the precipitation formation in warm clouds. The rate at which raindrops of given sizes d_L and d_S collide is commonly estimated using the collision kernel, K, (Czys and Chyun Tang, 1995; Pruppacher and Klett, 1997; Rogers, 1989).

$$K(d_L, d_S) = \frac{\pi}{4} E_{collision} (d_L + d_S)^2 \Delta v_{rel} \tag{1}$$

where Δv_{rel} is the relative velocity of the colliding drops. The collision kernel gives the number of drops of diameter d_S in the volume swept by a drop of diameter d_L per unit time. In general, larger drops are capturing smaller ones, because their fall speeds are higher. However, if a drop gets into the wake of another drop, rear side capture of the larger size drop can also occur due to the reduced velocity in the wake (Emersic and Connolly, 2011). In Eq. (1) $E_{collision}$ is the collision efficiency which can be assumed to be unity for precipitation size drops (Testik and Barros, 2007). Multiplying the collision kernel with the number concentration $N(d_L)$ and $N(d_S)$ of the drops with sizes d_L and d_S, respectively, the rate of collision, CR, between drop pair (d_L, d_S) is obtained (Beard et al., 1983):

$$CR(d_L, d_S) = N(d_L) \cdot N(d_S) \cdot K(d_L, d_S) \tag{2}$$

Eq. 2 reveals that the collision rate depends on the number concentration and, hence, the drop size distribution. The RSD is known to be very variable; might change from one precipitation event to another, and depends strongly on the geographical location and on the type of precipitation. In Fig. 1, the normalized collision rates calculated using Eq. 2 for drop pairs in case of stratiform precipitation of 5 mm hr^{-1} rain rate utilizing gamma RSD with parameters (m = 2 and λ = 2.8) from the disdrometer study of Tokay and Bashor (2010) are shown as a contour plot. The terminal speeds of the colliding drops were calculated from the parameterization of Beard (1976). As can be seen from Fig. 1, the highest collision rates, i.e. the largest possibility of collision can be presumed between drops of 0.6 and 1.6 mm diameters in the simulated event. In collisions with relatively large CR, smaller colliding drops of diameters (d_s) between 200 µm and 1.2 mm, and large drops of diameters (d_L) between 1 mm and 3 mm are involved. In very light precipitation events, the sizes of the colliding pairs corresponding to significant CR are shifted somewhat to smaller sizes, while for very high or extreme precipitation, the sizes are shifted to larger drop sizes in comparison to Fig. 1. Therefore, collisions between drop pairs with respective diameters of d_S = [0.2 mm to 3 mm] and d_L = [0.5 to 3 mm] are of importance when studying the microphysics of drop-drop collisions for precipitation prediction.

The collision between two drops may yield three different scenarios: the drops can *i)* bounce apart retaining their initial sizes; they can *ii)* remain permanently united and form a large drop conserving the

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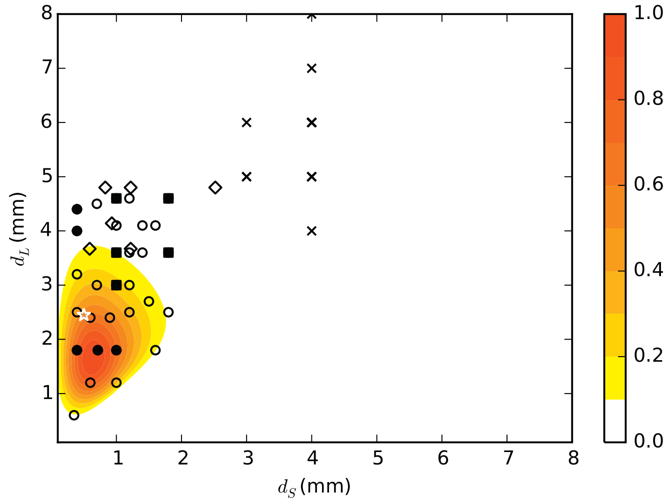

Fig. 1. Normalized collision rate of different precipitation size water drop pairs. Symbols: experimentally and/or numerically studied drop pairs: crosses: EC11, diamonds: BA07, rectangles: ML75, solid circles: LL82a, open circles: SCH10, asterisk: SZ14 and present work.

volume (coalescence); or they can *iii)* break up and produce lots of fragments of tiny droplets. The outcome of the collision depends on the relative sizes of the drops, i.e. the diameter ratio $p = d_S/d_L$ (Testik, 2009).

On the temporal evolution of the RSD, the collision induced breakup has probably the largest effect. After breakup, several satellite droplets (fragments) of different sizes are generated. Five different types of breakups are generally distinguished: filament (also called neck), sheet, disc, bag, and crown breakup (Testik et al., 2011). The size distribution and the total number of fragments, which in the end determine the RSD, depend on the breakup type, and need to be characterized for numerical cloud and precipitation forecast models (e.g., Seifert et al., 2005), and for retrieval algorithms of weather radar (Bringi and Chandrasekar, 2004).

In literature, the number of experimental studies on the fragment size distribution (FDS) of collision induced breakup is still very limited, since the proper realization and accurate measurement of atmospherically relevant parameters of colliding drops – drop and fragment sizes, terminal fall velocities and relative speeds, impact angle, etc. – are very difficult. The drop pairs investigated in earlier laboratory studies of different authors are plotted in Fig. 1 with symbols. In the pioneering laboratory works of McTaggart-Cowan and List (1975) – hereinafter ML75, indicated by solid rectangles in Fig. 1 – and Low and List (1982a) – hereinafter LL82a –, an accelerator system designed for drop-drop collisions was utilized. The FSDs measured by LL82a for 10 different drop pairs (solid circles in Fig. 1) are the most frequently used experimental data for generalized parameterization for numerical models (e.g., Low and List, 1982b; McFarquhar, 2004). Later, Barros et al. (2008) – hereinafter BA08 – conducted drop breakup experiments using a 14 m-height fall shaft to encourage the interaction of two vertically falling drops of moderate sizes (shown by open diamonds in Fig. 1). Recently, Emersic and Connolly (2011) – hereinafter EC11 – utilized an open wind tunnel to study collision induced breakup. In their experiments one of the drops were levitated in a velocity dip at the center of the vertical air stream of an open wind tunnel, and another drop was injected from above – i.e. from downstream -, and collided with the stagnant drop. The measurements of EC11 were carried out with very large raindrops (crosses in Fig. 1).

Direct numerical simulations were performed by Schlottke et al. (2010) –hereafter SCH10 – and compared to laboratory data of LL82a. The advantage of the DNS is that the key parameters of collision, such as drop sizes and eccentricities of colliding drops are easily variable. SCH10 investigated 32 drop pairs (indicated by open circles in Fig. 1) among others the 10 drop pairs of LL82a.

For the last three decades, the initial observation of LL82a and ML75 has remained the major source for FSD after collision induced breakup parameterization involved in numerical models for rainfall microphysics. Low and List (1982b) – hereafter LL82b – were the first to provide parameterization for different breakup types. McFarquhar (2004) – hereinafter M04 –presented an improved parameterization of the LL82a data set based on a more physical basis by taking mass conservation into account, and providing a complete uncertainty analysis. Straub et al. (2010) – hereinafter SA10 – formed a parameterization which was based on the DNS experiments of SCH10. Their parameterization resulted in similar FSD as the LL82b parameterization for most drop pair sizes.

From Fig. 1 it is apparent that there is still a lack in laboratory experiments in the drop pair range where the most collisions occur in the simulated case. Nevertheless, the total number of laboratory data in the literature corresponding to different drop pair sizes is 23, and only 4 when considering moderate size drops (smaller than 3 mm), thus the collision database needs to be extended.

In a recent study, experiments on collisions between drops of approximately 2.5 and 0.5 mm diameters were carried out in the Mainz vertical wind tunnel (Szakáll et al., 2014 – hereafter SZ14). The collision rate of drop pairs in the SZ14 experiments are marked by a white asterisk in Fig. 1. The data point corresponding to the investigated drop pairs falls in the range of high collision rate therefore might have an important contribution to the parameterization of FDS in collision induced breakup events. Nevertheless, the study of SZ14 focused primarily on the shape change of raindrops during and after collision, which is an important issue in, e.g., radar based precipitation nowcasting. We present in this paper a reanalysis of the collision experiments of SZ14, paying special attention on the coalescence efficiency and the FDS fragment size distribution after drop-drop collision. Hence, we provide here one more data point into the still very incomplete database of collision efficiency and FSD of collision of moderate size raindrops.

This paper is organized as follows: in Section 2 the experimental apparatus is described, and the microphysical parameters relevant for describing the collision events are summarized, while the results are introduced and discussed in Section 3, where a comparison of the experimentally obtained FSD to the parameterization of SA10 and M04 is given, too.

2. Methodology

2.1. Experimental setup

The drop-drop collision experiments were carried out at the vertical wind tunnel of the Johannes Gutenberg University of Mainz, Germany (Szakáll et al., 2010; Diehl et al., 2011). The experimental setup used in the experiments is depicted in Fig. 2a, and described in details in SZ14. Briefly, individual water drops of 2.5 mm diameter were freely floated in the observation section (OS) of the wind tunnel and collided with tiny droplets of approximately 0.5 mm diameter introduced upstream of them. The continuous air flow through the tunnel is maintained by two vacuum pumps. The air speed of the wind tunnel can be set precisely and quickly to the terminal velocity of the water drop under investigation (7.1 m/s in the present case) maintaining the continuous free floating of the large colliding drops in a stable fashion in the OS. Before entering the OS the tunnel air flow is conditioned by a laminarization and contraction section (LCS), so the air speed in the OS is constant and the air flow is laminar with a residual turbulence level below 0.5%.

The collisions were recorded by a high speed digital video camera (Motion ProX, Redlake, Inc.; CAM in Fig. 2a) mounted to the OS. The camera captured images of the colliding drops at 2000 fps (frames per