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Laboratory simulation of spontaneous breakup of polluted water drops in the horizontal electric field

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ABSTRACT

A laboratory simulation experiment to study the spontaneous breakup of distilled and polluted water drops suspended in horizontal electric field of 0, 100, 300, 500 kV m^{-1} has been performed in a small vertical wind tunnel. Water drops are formed from distilled water and from 100 ppm solution of ammonium sulfate and potassium nitrate. Results show that the life time of the both distilled and polluted water drops decreases with the increase in electric field. The water drops formed from both distilled and polluted water become more oblate as the electric field is increased. The results have been interpreted in terms of enhanced instability of water drops due to the changes in surface tension, viscosity, conductivity and hydro-dynamics of the water drop. Significance of the results is discussed in view of the possible modification of the drop size distribution and consequent growth of raindrops and lightning activity due to the combined effect of pollutants and electrical forces in clouds formed over big cities.

1. Introduction

Various microphysical processes such as collision, coalescence, breakup and evaporation of the drops contribute to the evolution of raindrop size distributions (RSDs) in clouds. The RSDs determine the development of precipitation in clouds, and influence radar reflectivity–rain rate (Z–R) relations. Further, these are needed for retrieving the satellite signals and for the development of cloud models. Hence, there is a need to understand the processes that affect the evolution of RSDs. Breakup of raindrops is one such important process in the evolution of RSD in convective clouds. Langmuir (1948) first proposed the formation of rain in warm clouds by the chain reaction process in which fragmentation of large drops due to aerodynamic breakup and subsequent growth of smaller drops by collision–coalescence process leads to the eventual RSDs in convective clouds. Since then many experimental and theoretical studies showed the importance of the raindrop breakup in the evolution of their size distribution in clouds. The drop breakup may result from (i) hydrodynamic instability of a large single drop i.e. spontaneous breakup, or (ii) a collision between two drops which results in collision-induced breakup. Several previous studies emphasize that the overwhelming cause of drop breakup is due to the collision-induced breakup process (McTaggart-Cowan and List, 1975; Low and List, 1982a,b; Feingold et al., 1988; McFarquhar, 2004; Emersic and Connolly, 2011). However, discussing the relative importance of spontaneous breakup of raindrops, Blanchard (1949), Komabayasi et al. (1964), Beard and Pruppacher (1969), Reisin et al. (1998) expressed that collision-induced breakup restricts the formation of giant drops with diameter >4 mm. Recently, Villermaux and Bossa (2009) supported the importance of spontaneous breakup as compared to that of collision-induced breakup on the basis of their laboratory experimental results showed that the time scale for distortion and spontaneous breakup for a single drop is much shorter than the typical collision time between the drops.

In addition to spontaneous breakup and collisional breakup, the third conceivable cause proposed for the drop breakup is the strong electrical force acting on drop's surface in thunderclouds. The raindrops located in the high ambient electric field region of thunderclouds or if these are highly charged, get deformed to the extent that their surfaces with high curvatures become hydrodynamically unstable and the drop disrupt and/or produce corona discharge (Latham, 1965; Richards and Dawson, 1971; Levine, 1971; Kamra et al., 1991, 1993; Coquillat and Chauzy, 2003; Bhalwankar and Kamra, 2007).

In most of the previous theoretical and experimental studies, drops have been considered to be formed from the pure water. In recent decades, however, impact of anthropogenic pollutants on cloud microphysical processes have become increasingly

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important as these pollutants pollute the cloud drops by the nucleation and scavenging processes. Moreover, in a model study Wurzler et al. (1995) found significant difference between the scavenging behavior of nitrate and sulfate aerosol particles by the cloud drops. Incidences of acid rain in big cities show a great impact of pollutants on cloud and raindrops. Further, analysis of rain water and cloud water samples show that there is a variety of chemical compounds in the rain water and their concentrations at different locations vary over many orders of magnitude (Huff and Changnon, 1973; Pruppacher and Klett, 2000).

The polluted water drops and strong electric fields coexist in the thunderstorms which develop over big cities. The change in surface tension, viscosity, density and electrical conductivity of polluted drops is likely to significantly affect the collision–coalescence and breakup mechanisms which in turn influence the formation of rain in thunderclouds (Boussaton et al., 2005; Bhalwankar and Kamra, 2009). In recent wind tunnel observations, Müller et al. (2013) investigated the shape and oscillations of raindrops with reduced surface tension. Their analysis of the photographic images of polluted drops shows that, oscillation modes and frequencies of these drops are affected due to change in surface tension. Moreover, the surfactant film on the surface of a polluted drop can suppress the friction between the drop and the surrounding air, and can reduce the internal circulation. Also, the increase in fluid viscosity of a drop reduces the oscillation amplitudes. Further, several studies suggest that presence of the polluted drops in thunderclouds not only modify the size distribution of raindrops but also influence the occurrence and nature of the lightning activities over cities (Westcott, 1995; Steiger et al., 2002). Possible role of drop distortion and disruption under electrical forces in the polluted and unpolluted thunderclouds in affecting lightning activity has recently been discussed in detail by Bhalwankar and Kamra (2013).

Objective of this article is to report preliminary results of a laboratory simulation experiment to study the effect of pollutants on breakup characteristics of the water drops freely suspended in presence of strong horizontal electric fields. Our earlier experiment to study the spontaneous breakup of the charged and uncharged drops (Kamra et al., 1991) and distortion of polluted drops in electric fields (Bhalwankar and Kamra, 2009) have been extended to observe the combined effect of pollutants and horizontal electric field on the probability of breakup of large drops. In the present study, we are considering only nitrate and sulfate contaminants as these pollutants are commonly observed with significant impact on the atmosphere (Hegg et al., 1984; Sanusi et al., 1996). Although, the results may not be applicable directly to all the clouds as the concentrations used here are higher than normally found in the rainwater and the electric field considered is in horizontal direction but they are indicative of the influence of pollutants or electrical forces on shape and breakup of raindrops. Significance of these results in modifying the drop size distribution and lightning activity in thunderclouds has been discussed.

2. Experimental procedure

Experiments were conducted in a small, low turbulence, open-ended vertical wind tunnel by freely suspending the uncharged water drops of known volume. It consists of a blower, diffuser section, reservoir, straight section fitted with a honeycomb and screens to minimize the turbulence, test section and a back pressure plate (Kamra et al., 1991, 1993). Fig. 1 shows the schematic diagram of vertical wind tunnel along with a cross-wire screen to create a velocity well in the airflow and electrodes installed above the test section. Water drops are freely suspended

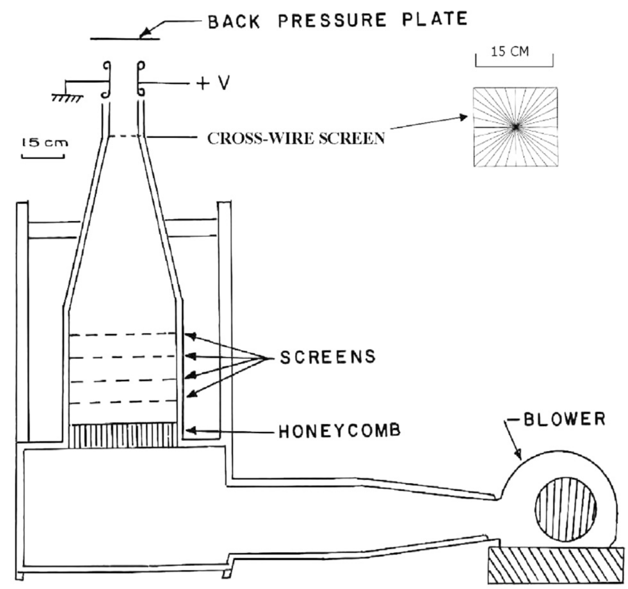

Fig. 1. A schematic diagram of vertical wind tunnel along with a cross-wire screen to create a velocity well in the airflow and horizontal electric field arrangement.

at their terminal velocities in a velocity well created in the airflow. Vertical velocity and the intensity of turbulence in the air-flow were measured with a hot wire anemometer (TSI-1054). The details of the measurements along with the profiles of the vertical velocity and intensity of turbulence in the tunnel are reported earlier by Kamra et al. (1991). These measurements show that even in presence of electrodes and back pressure plate the turbulence level in the center of test section where drops are suspended is less than 0.8%.

Water drops of 6.6 mm equivalent diameter corresponding to a volume of 150 μl measured with a pipette of 3 μl accuracy were formed from distilled water or from 100 ppm solutions of ammonium sulfate and potassium nitrate. A marked glass pipette with turned edge at one side and Teflon piston fitted in the other end to push a measured volume of distilled water or aqueous solution was used to suspend a drop of known size in the wind tunnel in presence and absence of electric fields. The pipette, while releasing the drop in wind tunnel, was grounded to ensure that the drops were uncharged and was also calibrated by weighting method. Drops were formed from three types of water: pure distilled water and 100 ppm solution of ammonium sulfate and 100 ppm solution of potassium nitrate which contain higher ion concentration. The electrical conductivity of the distilled water, ammonium sulfate and potassium nitrate solutions measured with a conductivity meter (Eutech Instruments) with an accuracy 0.01 $\mu S\ cm^{-1}$ was 1.10, 149 and 110.6 $\mu S\ cm^{-1}$ respectively. The electrical conductivity of polluted drops is about 2 orders of magnitude higher than the distilled water. The values of surface tension, viscosity and density of the sulfate and nitrate solutions at 20 °C, interpolated from tables (Lange and Forker, 1967) also show increasing tendency with respect to distilled water.

To generate horizontal electric field, two flat, circular, aluminum electrodes of 15 cm diameter with suitably rounded edges are mounted vertically above the test section and separated by a distance of 12 cm. So, by applying a potential of 60 kV to one of the electrodes, an electric field of up to 500 $kV\ m^{-1}$ was generated without any measurable corona from the electrodes. Drops were suspended between the two electrodes and then the electric field was quickly raised to a desired value within 2–3 s. The time interval after raising the desired value of electric field to the