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Shape and oscillations of the water drops freely suspended in a horizontal electric field: A wind tunnel study

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ABSTRACT

The time-averaged axis ratios, frequency and amplitude of oscillations of water drops of 2.67–6.6 mm diameter were determined by suspending them in a vertical wind tunnel in the absence and presence of horizontal electric fields using a high speed camera at 1000 frames per second. A systematic decrease in the drop's axis-ratio is observed with increase in its diameter and/or horizontal electric field. The results revealed with high speed photography are in good agreement with earlier results. The drop distortion due to horizontal electric field is more pronounced for the drops in the size-range of 3.36–6 mm diameter showing that the electrical forces progressively enhance the horizontal elongation of the drop resulting in its instability at 6.6 mm. The drop oscillation frequency computed from temporal variation of axis ratio, decreases with increase in drop size but shows no significant change in oscillation frequency in the horizontal electric field of ≤ 500 kV m^{-1}. However, the oscillation amplitude increases with increase in drop size up to a threshold value and then flatten-off in the electric field of ≤ 300 kV m^{-1} demonstrating the nonlinear effect of net forces acting on such large drops. In higher electric field of 500 kV m^{-1}, gradual increase in the amplitude of oscillation with an increase in drop diameter has been observed. Moreover, for a particular drop size, the amplitude of oscillation decreases with increase in the electric field upto 500 kV m^{-1}. The oscillation frequency of the waterdrops experiences multimode oscillations. The dominant fundamental mode of oscillations (2,0) always exists for all drops in our experiments along with the coexistence of higher modes of oscillations i.e. (2,1) and (2,2) mode. Possible effects of electrical forces on shape parameters and their implications on cloud microphysics and in radar meteorology are discussed.

1. Introduction

The importance of the shape of raindrops to the field of cloud microphysics has been recognized since extensive wind tunnel studies of Lenard (1904) who observed drop deformation and speculated that drop's internal circulation and surface tension forces were the key factors to control it. Following these initial experiments, several experimental studies, notably by Blanchard (1950); Jones (1959); Pruppacher and Beard (1970); Richards and Dawson (1971); Rasmussen et al. (1985); Kamra and Ahire (1989); Beard and Kubesh (1991); Coquillat and Chauzy (1993); Bhalwankar and Kamra (2007) and Szakáll et al. (2009). provided comprehensive information about the forces acting on the raindrop which determine the shape and stability of the falling drops.

Several theoretical models have been developed to describe the equilibrium shape of oblate spheroidal raindrops, specifically considering the response to gravity (Green, 1975; Beard, 1984), the perturbation response to aerodynamic pressure (Savic, 1953; Pruppacher and Pitter, 1971) and the large amplitude response to both hydrostatic and aerodynamic pressures modified for distortion (Beard and Chuang, 1987). These models calculate the shape of non-oscillating raindrops. In the atmosphere, however, raindrops continuously oscillate in an oblate–prolate mode. The cause of the oscillations has mostly been attributed to turbulence or to the drop's vortex shedding or collision characteristics of these drops with other tiny drops (Blanchard, 1950; Beard, 1984; Beard and Tokay, 1991). The frequency and amplitude are the key parameters of oscillations of the drop. The frequency of the oscillating water drop was first theoretically calculated by Rayleigh (1879). as $f_2=(2\sigma/\pi^2 a_0{}^3\rho_w)^{1/2}$ where σ is the surface tension, a_0 is the equivalent spherical radius of the drop and ρ_w is the density of water. These computations show that the oscillation frequency decreases with increase in drop size. Using orthogonal cameras in his field measurements, Jones (1959) found a large scatter in the axis ratio of raindrops of 2–6 mm diameter, which revealed that

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raindrops can attain non-equilibrium shapes as a result of large amplitude of oscillations.

The raindrops of diameter larger than 1 mm diameter falling in the air at their terminal velocity progressively become oblate spheroidal in shape and continuously oscillate. These drops may oscillate simultaneously in more than one mode. The most significant oscillation modes associated with the fundamental mode are the axisymmetric (2,0) mode, the transverse (2,1) mode and the horizontal (2,2) mode. The modes of an oscillating spherical drop degenerate, so that their frequencies are same as calculated from Rayleigh's formula. All the three oscillation modes can exist with characteristic spatial orientation of the drop. However, for larger oblate–spheroidal drops with flattened base, the oscillation frequencies do not degenerate, but different oscillation modes i.e. (2,1) and/or (2,2) modes possess different frequencies lower than that predicted by the Rayleigh frequency along with fundamental frequency (Feng and Beard, 1991). Thus the amplitude of oscillation resulting from all simultaneously existing modes depends on the drop diameter (Szakáll et al., 2009).

Accurate determination of raindrop shape and oscillation is an important factor in radar meteorology and provides information to better understand the drop collision–coalescence and breakup processes in clouds. Aircraft measurements of Chandrasekar et al. (1988) showed that drop oscillations must be the primary cause of the shift in its axis ratio from the equilibrium value. Recent comparisons of mean drop shape and the axis ratio distribution between the measurements made using 2D video disdrometer and wind tunnel experiments by Thurai et al. (2009) show an increase in oscillation amplitude with increasing drop diameter. All these studies are conclusive that the drops do oscillate and account for the upward shift in the mean axis ratio relative to their equilibrium shapes. Such shift in axis ratio can significantly alter the differential radar reflectivity (Z_{DR}) signals used to estimate the drop size distribution and rainfall rate (Seliga and Bringi, 1976), especially in heavy rain showers.

It is well known that the shape of raindrops is determined by the balance of surface tension, aerodynamic and hydrodynamic forces and forces due to drop's internal circulations (Pruppacher and Klett, 2010). In thunderclouds, however, raindrops carry electric charge and are located in strong electric fields. The ambient electric field in thunderclouds is generally considered to be vertical in direction with typical values observed in the range of 100–200 kV m^{-1} on a large scale (Fitzerald and Byers, 1962; Marshall and Rust, 1991). However, some observations show that electric fields may be greatly inclined from the vertical and have a strong horizontal component of electric field (Winn et al. 1974; Byrne et al., 1974). Winn et al. (1974) in their rocket-borne measurements of electric field inside active thunderclouds show that very intense fields of the order of 400 kV m^{-1} do exist although they may confine to small areas of intense electrification. Moreover, the highest electric field of 430 kV m^{-1} observed by them is reported to be horizontal in direction. So, the values of horizontal electric field considered in our experiment are comparable with the observed electric field values in thunderstorms. Moreover, the drop sizes in our experiment cover the size range of the majority of drops in clouds.

The drop charges and electric fields produce an electrostatic force which opposes the surface tension force and affect**s** the balance of other forces acting on drop and thus affect its shape (Pruppacher and Klett, 2010). Influence of direction of electric field, vertical or horizontal, on the distortion of the drop has been studied by several investigators. The electrical force in the vertical electric field acts along its minor axis and counteracts the aerodynamic forces making them first spherical and then prolate in shape with the increase in electric field (Richards and Dawson, 1971; Rassmussen et al., 1985; Kamra and Ahire, 1989). On the contrary, the horizontal electrical forces tend to distort the drop along its major axis increasing the oblateness of the drop (Bhalwankar and Kamra, 2007). The fact that, both aerodynamic and electrostatic forces act together in the same direction in the horizontal electric field and during their oscillation, the magnitude of the drop distortion and the electrical forces acting on its surface feedback each other to further increase the oblateness of a drop (Kamra et al., 1993). The numerical model of Coquillat et al. (2003) estimated such elongation of drops along the direction of electric field and the consecutive change in their axis ratios.

In this paper, we study the time-averaged axis ratios, frequency, amplitude and mode of oscillations of drops of 2.67–6.6 mm diameter suspended in a vertical wind tunnel in the absence and presence of a horizontal electric field. A high speed camera was used to acquire a large number of images by continuous recording of the oscillating drops for the relatively long time interval. We compare our present results with the earlier theoretical and experimental results. We also discuss some of the implications of our results to the cloud microphysical processes and radar meteorology.

2. Experimental set-up and methodology

2.1. Vertical wind tunnel and experimental procedure

A small, low-turbulence open-ended vertical wind tunnel, described earlier by Kamra et al. (1986, 1993) was used to suspend water drops of equivalent diameter of 2.67–6.6 mm at their terminal velocity. A centrifugal blower sucks the air from an air-conditioned room and maintains the continuous airflow in the wind tunnel. In a minor modification of this wind tunnel a wire mesh screen of size 8 meshes per centimeter was fixed between the blower and divergent section to streamline the incoming air. Vertical velocity and the intensity of turbulence in the airflow in the cross section of the modified wind tunnel were measured with a pre-calibrated VelociCalc-Multi-function Ventilation meter (TSI, model 9565-P). It can measure the average velocity with a resolution of 0.01 m s^{-1} and calculates the intensity of turbulence from a 3-minute sample of the velocity readings in a particular position. The level of turbulence with the crossed-wire screen, back-pressure plate and the electrodes fixed in their positions, and the newly added screen was found to be less than 0.65% in the center of the observation section where the drops were suspended. The depth of velocity well, i.e. the difference in the center of well and the free stream velocity, in the modified wind tunnel is reduced to ~12% as compared to that of ~30% in our earlier measurements (Kamra et al., 1991).

Two flat, suitably rounded and smoothened circular aluminum electrodes were mounted vertically above the test section to generate the horizontal electric field (Kamra et al., 1993). The horizontal electric field values of 100, 300 and 500 kV m^{-1} were used in our experiments.

Distilled water drops of 2.67, 3.36, 4.05, 5.11, 6.0 and 6.6 mm equivalent diameters were suspended in the wind tunnel at their terminal velocities using a calibrated pipette (Single channel Finnpipette-F2, Thermo Fisher Scientific Inc., USA) with 0.2 μl volume accuracy. The values of electric field and the drop diameters used in the present experiment were similar to those in our earlier experiments (Bhalwankar and Kamra, 2007). The detailed description of wind tunnel and other experimental arrangements are given in Kamra et al. (1993).

2.2. Details of photographic technique

Various photographic techniques have been used in earlier