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A preliminary numerical study on the time-varying fall attitudes and aerodynamics of freely falling conical graupel particles

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ABSTRACT

The flow fields and dynamic motions of conical graupel of diameters 0.5–5 mm falling in air of 800 h Pa and −8 °C are studied by solving the transient Navier-Stokes equations numerically for flow past the conical graupel and the body dynamics equations representing the 6-degrees-of-freedom motion that determines the position and orientation of the graupel in response to the hydrodynamic force of the flow fields. The shape of conical graupel made through a simple but practical existing mathematical equation allows us to have an uneven mass distribution, which is generally believed to have great influence on ice particles' orientations while falling when inertial force becomes increasingly dominant over other effects. The simulated motions include vertical fall, lateral translation, sailing, rotation and pendulum swing. The computed flow fields are characterized in terms of streamtrace patterns as well as the vorticity magnitude fields, and the corresponding motions of the conical graupel is physically featured by looking upon the graupel surface distributions of pressure coefficient, torques contributed by both pressure as well as viscous effects. Tumbling doesn't occur when an initial orientation of the graupel is either 20° or 160° about Y axis, and the torque contributed by the pressure effect is dominant over that contributed by the viscous effect.

1. Introduction

The riming process is a collision-coalescence process where ice particles have mutual collisions with supercooled water droplets and the liquid later become frozen on the ice surface (Pruppacher and Klett, 1997; Wang, 2013). The graupel particles are products of the riming process typically found in a variety of convective clouds and become hailstones in vigorous thunderstorms with sufficient updraft to hold them.

Because of its importance in thunderstorm development, the present generation cloud resolving models usually include some form of parameterizations about graupel microphysics (e.g., Chen and Xiao, 2010; Kovačević and Ćurić, 2013, 2015; Noppel et al., 2010; Straka and Mansell, 2005). Due to our limited understanding of graupel behavior in clouds at current stage, however, there are rooms for improvement on these parameterizations.

One of the first tasks to make improvement is to understand correctly the hydrodynamic behavior of graupel when they are falling in the cloud. Graupel particles do not always fall straight downwards, like other falling objects (Field et al., 1997; Willmarth et al., 1964; Zikmunda and Vali, 1972); instead, they will likely flutter down to the ground and occasionally tumble as their orientation changes dramatically with time. The fluttering may be mainly caused by the coupling of upward or downward motions to lateral oscillations by the surrounding air fluid through eddy shedding (Belmonte et al., 1998). This inevitably leads to the complicated orientation-varying motions and their underlying physics, thus making the surrounding air fluid patterns even more complicated than when the flow is going past the stationary ice particles. Understanding of the motion and flow field is crucial to better understanding of the riming growth and developing the hailstone suppression technologies to curtail prodigious damage caused by the falling hailstones. To this end, we investigate the dynamic conical-shaped graupel particles.

A number of recent publications have addressed some of the modeling challenges associated with the analysis of flow fields around the ice particles. These include the further flow field studies for spherical hailstones (Cheng and Wang, 2013; Cheng et al., 2014), snowflakes (Cheng et al., 2015; Ji and Wang, 1990), cylindrical ice crystals (Hashino et al., 2014, 2016; Ji and Wang, 1991; Wang and Ji, 1997), conical graupel (Kubicek and Wang, 2012; Wang and Kubicek, 2013), as well as lobed hailstones (Wang et al., 2015). In addition to the mentioned numerical simulations, from an actual experimental perspective, Jayaweera and Mason (1965) first described the behavior of freely

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falling cylinders and cones in a viscous fluid with their stability discussion, and, about fifteen years later, Pflaum et al. in Pruppacher's group in UCLA (Pflaum, 1978, 1980; Pflaum et al., 1978; Pflaum and Pruppacher, 1979) used a vertical wind tunnel to describe some essentially observed motions of the ice graupel particles. More recently, some laboratory experiments on graupel riming with collection kernels were carried out by Blohn et al. (2009) in Borrmann's group at Mainz Germany. While these efforts are helpful to better understand the growth of ice particles, the hydrodynamic effects on free-falling graupel particles still remain hazy.

Modern numerical methods play an important role not just in retaining the computational accuracy, but also in accelerating the computations, especially for many 3D complex fluid flow transport processes (like our complicated motions of the conical graupel and its surrounding fluid fields), by at least two orders of magnitude compared to traditional techniques (Chueh, 2011; Chueh et al., 2013). These methods, which a high performance simulator needs to acquire to improve computational speed for a given level of accuracy, provide the coverage of at least most of the following five areas: (1) higher order spatial discretizations that can yield the same accuracy at smaller computational cost, but need to incorporate nontrivial stabilization mechanisms for hyperbolic problems to benefit from the higher accuracy (Kröner, 1997; van Leer, 2006); (2) adaptive mesh refinement that can vastly reduce the number of cells required to resolve the flow field (Ainsworth and Oden, 2000; Bangerth and Rannacher, 2003; Carey, 1997; Chueh et al., 2010; Verfũrth, 1996); (3) adaptive time stepping methods that allow the use of large time steps limited solely by the physical time scale rather than numerical stability (Chueh et al., 2010, 2013); (4) operator splitting methods for coupled problems to transform a complex, coupled problem into a sequence of simpler problems for which more efficient solver techniques are available (Chueh et al., 2013); (5) efficient solver and preconditioning methods that can accelerate the solution of the linear problems (Golub and Van Loan, 1996). Nowadays, it is already becoming more widely available for many open source softwares (e.g. OpenFOAM– http://www.openfoam.com/; deal.II–http://www.dealii.org/) as well as commercial softwares (e.g. ANSYS Fluent and COMSOL) to be practically equipped with such state-of-the-art numerical methods. And, most importantly, ones from academic fields other than computational or numerical science can directly apply the methods in numerical simulations as a black box to their engineering and scientific purposes for the understanding of their engineering frontier and fundamental physics, respectively, without knowing the details of these complicated methods.

Numerical solutions of the flow fields around the falling graupel or hailstones were previously unavailable, chiefly because of difficulty in meshing the complex graupel and hailstone shapes created through some mathematical formulation (Wang, 1982; Wang et al., 2015). Without tackling this thorny problem, many tiny localized flow behaviors accompanied by complex graupel and hailstone shapes may not have been revealed and hence not elucidated through the numerical simulations, thus compromising the reliability of the simulations. However, recent numerical packages (e.g. Gmsh–http://geuz.org/gmsh/, OpenFOAM and ANSYS Fluent) already make it available and practical for us to generate such complex shapes for the simulations in various different particular file formats through CAD (computer-aided design). One of them, called STL(standard tessellation language or STereoLithography), which was already used in our previous work for lobed hailstones and is supported by many softwares (Wang et al., 2015), can allow us effectively to represent the complex geometrical shapes of the graupel and hailstones. By employing this capability with the above-mentioned high speed computers, it has become practical to perform the numerical computations for such flow cases.

In this study the Navier-Stokes equations are solved numerically while considering the dynamic motion of the graupel. We present and discuss the results of a 3D numerical study on the dynamic conical graupel falling in air in terms of the flow fields and the hydrodynamic motion of the graupel. This study is a sequel of the dynamic snowflake (Cheng et al., 2015) and ice crystal (Hashino et al., 2016). The present paper is organized as follows. In Section 2, the mathematical and physical background for the dynamic graupel falling in air, the governing equations, and the mathematical expressions used to generate the graupel are presented, followed by the results and their discussions in Section 3 and the summary and future outlook in the final Section.

2. Physics and mathematics of the flow field calculation

Many hydrometeors have complicated shapes, such as hexagonal columns, plates, and dendrites for ice crystals, cones, and spheroids for graupel and hailstones, and near-oblate-spheroids for large raindrops (Wang, 1982). These shapes often make the analysis of physical properties difficult. One often has to approximate these shapes by other simpler shapes, for example, large raindrops by oblate spheroids, ice columns by circular cylinders and ice plates by thin oblate spheroids. The approximations are made so that simple mathematical formulas can be used to describe the shapes of these particles. In the present study, we use a mathematical equation given by Wang (1982) to describe essentially the size and shape of the conical graupel used in our calculation. This equation is shown in the following:

$$x = \pm a\sqrt{1-\left(\frac{z}{c}\right)^2}\cos^{-1}\left(\frac{z}{\lambda c}\right), \tag{1}$$

where x and z are the horizontal and vertical coordinates, and a and c are the horizontal and vertical semi-axis lengths, respectively, of an ellipse, as shown in Fig. 1. The parameter λ, whose value is ought to vary between 1 and ∞, serves to control the sharpness of the peak of the conical graupel: small λ produces sharp apex whereas large λ produces smoothly-curved peak. It is important to note that all the graupel particles considered herein are assumed to have the value of $\lambda = 1$ so that all of them have a sharp apex on the top and a nearly flat on its bottom, representing that the mass is unevenly distributed in space between its top and bottom ends. This special quality can also be typically found in natural graupel. So, although it is possible to generate more protrusions on the surface like those shown in Wang et al. (2015), we feel that the present method already gives a typical approximation for the shape of graupel for us to unravel the preliminary underlying physics.

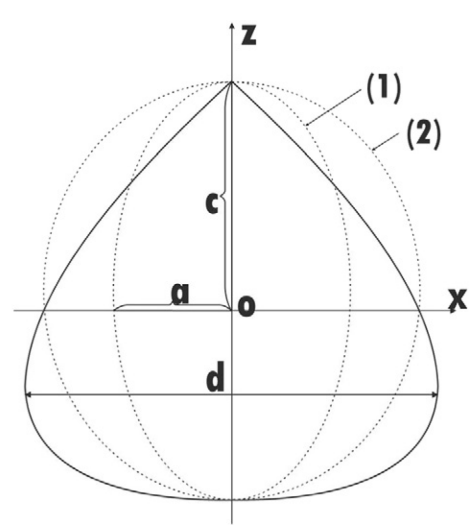

Fig. 1. Definition of the coordinate system and various quantities. Solid curve is an axial cross-section of a conical body generated by Eq. (1) proposed by Wang (1982). Dashed curves (1) and (2) are the generated ellipse and limiting ellipse, respectively. The origin O shown here represents the position (0,0,0) in relation to Eq. (1).