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A numerical study of the flow fields around falling hails

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ABSTRACT

The characteristics of the flow fields around falling hailstones of diameters 1 to 10 cm are studied. The flow fields are obtained by numerically solving the time-dependent Navier–Stokes equations for flow past hails which are assumed to be smooth spheres. The fall velocities of the hails are based on observational derived values. The Reynolds numbers of these flow fields range from 5780 to 206,000. The characteristics of these fields are discussed according to the streamtrace pattern, pressure deviation, *z*-velocity and vorticity fields. While the upstream flow remains quasi-steady, the wakes of these fields are increasingly turbulent and the maximum velocity region flanking the recirculation bubble exhibits a ring-shedding phenomenon as the Reynolds number increases. The eddy length and drag coefficient for each cases are also calculated and empirical relations are provided. Potential impacts of these characteristics to the cloud physical of hail are also discussed. An outlook of future works is also given.

1. Introduction

Each year large hails falling from thunderstorms cause multibillion dollars of damages on crops and properties worldwide and numerous substantial scientific research have been conducted hoping to find effective ways to mitigate such damages, but the results are still inconclusive (see, e.g.,Pruppacher and Klett, 1997; Wang, 2013). To really design effective hail suppression strategies, an important first step is to understand fully the physics of hail formation and their growth rates. Hail grows primarily by collecting supercooled water drops which freeze on the hail upon collision, a process called riming. How fast riming occurs depends on the size of the hail and drop. Different sized hails produce different flow fields when falling in air and drops of different sizes will react differently to these fields which, in turn, determine their different riming rates. Evidently, knowing the flow fields around falling hails is a crucial step toward the determination of accurate riming rates of hail.

Flow fields are not only necessary for calculating the riming rates, they are also necessary for determining the "ventilation coefficient" (see, e. g., Chapter 13 of Pruppacher and Klett, 1997; Chapter 9 of Wang, 2013) which is an enhancement factor for the heat and mass transfer rates to and from the hail. For example, a hailstone falling in a subsaturated air will evaporate by consuming latent heat from the surrounding air and causes the air to cool. Because of the high fall speed, the heat consumption and hence the cooling rate of air is many times higher than an evaporating hail that is stationary with respect to air. This is called the ventilation effect and the enhancement factor due to the motion is the ventilation coefficient. Such cooling is thought to be a key factor in causing the downburst phenomenon in a thunderstorm system (Fujita, 1985). Evidently, we will need to determine the flow fields around the falling hails first in order to determine the ventilation coefficients.

The flow fields around falling hails are previously unavailable because of the difficulty in solving the complete unsteady Navier–Stokes equations for such high Reynolds number cases. However, recently the speed of computers has

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improved significantly and high performance computational fluid dynamics (CFD) software packages become more widely available, it becomes practical to perform the numerical computations for such flow cases. This is what we have done in this study and the following sections will describe our computational results. This study is a sequel of similar studies by Kubicek and Wang (2012) and Wang and Kubicek (2013) who performed numerical computations of unsteady flow past conical graupel.

In the present study, we are treating hailstones as smooth spheres as a first approximation. Real hailstones have various degrees of roughness due to surface irregularities and they can be completely frozen or coated with liquid water. It is our plan to investigate the effect of the surface roughness and heterogeneity on the hail behavior in the future. Although the flow past a sphere has been a classical subject of fluid dynamical studies (see, e.g., summary in Chapter 10, Pruppacher and Klett, 1997, for laminar cases and papers such as Tomboulides and Orszag, 2000; Constantinescu and Squires, 2004, for turbulent cases), most focus on the numerical techniques. This paper focuses on the results that are relevant to falling hails.

2. Mathematics and physics of the flow field calculation

The governing equations of the flow fields for the present problem are the Navier–Stokes equation and the incompressible condition (see Pruppacher and Klett, 1997, Chapter 10):

$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \nabla\right) \vec{u} = -\frac{\nabla p}{\rho_a} + \nu \nabla^2 \vec{u} + \vec{g} \tag{1}$$

$$\nabla \cdot \vec{u} = 0 \tag{2}$$

where $\vec{u}$ is the air velocity, p the static pressure, ρ_a the air density, the kinematic viscosity of air and $\vec{g}$ the gravity. The boundary conditions are:

$$\vec{u} = 0 \quad \text{at the surface of the graupel,} \tag{3}$$

$$\vec{u} = u_\infty \cdot \hat{e}_z \quad \text{far away from the graupel} \tag{4}$$

where u_∞ is the fall speed of the hail (assumed to be its terminal fall velocity) and $\hat{e}_z$ is the unit vector in the z-direction. Eqs. (3) and (4) are the common boundary conditions for this type of problems.

We used the computational fluid dynamics package Fluent 13.1 of ANSYS, Inc. as the solver and selected the numerical scheme QUICK (Quadratic Upstream Interpolation for Convective Kinematics, see Freitas et al., 1985) to solve the Navier–Stokes equation, which was also the scheme used by Ji and Wang (1989, 1991) and Wang and Ji (1997). However, the gridding method of Fluent is finite volume instead of the Cartesian grid used by Ji and Wang. The finite volume allows closer matching of the inner boundary to the hail shape than the Cartesian mesh.

The procedure of the present computational study is different from that reported in Kubicek and Wang (2012) and Wang and Kubicek (2013) who computed the unsteady flow fields around falling conical graupel. There the calculation was first performed to obtain a steady axisymmetric flow field. Then an instantaneous velocity bias is added to cause the steady field to induce the eddy shedding. Without such an instantaneous bias, the flow fields remained steady (aside from the very short transient motions) even if the transient model of Fluent was used. In the present calculation we simply started the computation by using the transient model and the computed flow fields are readily unsteady. While the exact reason why this is so is unclear at the present, it is possible that the Reynolds numbers for hails falling in air are all very large (greater than several thousands) so that any reasonable numerical scheme can produce the unsteady features whereas the Reynolds numbers for falling graupel are smaller, being on the order of several hundred, which are on the borderline between steady and unsteady flow, and hence an adequate initial perturbation may be necessary to cause the numerical scheme to induce unsteady features such as eddy shedding.

3. Results and discussions

By definition in cloud physics, a hailstone should have a diameter or the largest dimension larger than 5 mm. Similar ice particles formed by riming but with diameters smaller than 5 mm are called graupel. Wang and Kubicek (2013) have reported the computed flow fields for falling graupel up to 5 mm in diameter. In the present study, we computed the flow fields for falling spherical hails of diameters 1, 2, 3, 4, 5, 7 and 10 cm. The present study assumes that the atmospheric environment is 1000 hPa and 10 °C and the hails fall at their respective terminal velocity u_∞.

Various investigators have performed measurements of the terminal velocities of falling hailstones and suggested empirical equations relating the terminal velocity and hail size (see Böhm, 1989). For example, Macklin and Ludlam (1961) measured fall speeds of hail in a laboratory experiment. Roos and Carte (1973) performed measurements of the fall speeds of various shaped hail models in a 1.5 km vertical mine shaft. Lozowski and Beattie (1979) and Matson and Huggins (1980) also performed direct measurements of hail fall speed near the ground. For the present study, the terminal velocities are determined based on the empirical equation given by Knight and Heymsfield (1983) for fresh hailstones in Colorado storms:

$$u_\infty = 8.445 d^{0.553} \tag{5}$$

where u_∞ should be in the unit of m s^{-1} and the diameter d in cm. The choice of using this empirical formula is arbitrary as equations based on other measurements are empirical also. In any event, the choice of formula may change the Reynolds number a little but will not affect the general features of the computed flow fields which are the focus of this paper.

The Reynolds number of the hail is defined as

$$N_{\mathrm{Re}} = \frac{d u_\infty}{\nu}. \tag{6}$$

Table 1 shows the diameter, terminal fall velocity, and Reynolds number of the hail investigated here.

While the present study assumes the atmospheric condition at the surface level, as we intend to study the general fall