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Modeling the evolution of droplet size distribution in two-phase flows

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Abstract

A theoretical model is developed in the present study to simulate droplet motion and the evolution of droplet size distribution (DSD) in two-phase air/dispersed water spray flows. The model takes into account several processes which influence DSD and droplet trajectory: droplet collision and coalescence, evaporation and cooling, gravitational settling, and turbulent dispersion of dispersed phase. The DSDs determined by the model at different locations in a two-phase flow are evaluated by comparing them to experimental observations obtained in an icing wind tunnel. The satisfactory coincidence between simulation and experimental results proves that the model is reliable when modeling two-phase flows under icing conditions. The model is applied for two particular examples in which the modification of DSD is calculated in two-phase flows under conditions describing in-cloud icing and freezing drizzle.

Keywords: Droplet collision; Droplet size distribution; Evaporation; Turbulent dispersion; Two-phase flow

1. Introduction

One of the most important factors influencing atmospheric icing processes is the droplet size distribution (DSD) of the aerosol cloud. A typical way to model atmospheric icing and the modification of the droplet cloud preceding ice formation is to produce an air/dispersed water two-phase flow in an icing wind tunnel, and exposing an icing object to this flow. The aerosol cloud undergoes significant changes before reaching the icing object; and the DSD of the dispersed phase appears to be an important characteristic which is modified, among others. Several factors are responsible for this modification, including interactions between the dispersed and carrying phases resulting in evaporation, mutual interactions within the dispersed phase known as binary droplet collisions, and the effect of external forces leading to gravitational settling of droplets and

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vertical variation of the DSD. The extent to which these processes affect the characteristics of the aerosol cloud depends on the level of turbulence in the air flow. The turbulence also plays a key-role in the formation of aerosol clouds in wind-tunnel experiments. High levels of turbulence cause unrealistic thermodynamic processes in the tunnel and unnatural ice accretion. A certain level of turbulence, however, is essential to assure mixing and homogeneity in the cloud.

Models of two-phase flows have been presented in a vast number of publications. Crowe et al. (1977) developed a computational model which solved gas flow equations and droplet equations, and also considered the decrease of droplet mass and temperature due to evaporation and cooling; they ignored, however, the effects of turbulence on droplet dispersion and collisions between droplets. Dukowicz (1980) proposed a stochastic approach to consider turbulence dispersion of droplets, which was elaborated for thick sprays by O'Rourke and Bracco (1980), and modified in Gosman and Ioannides (1981) and in Marek and Olsen (1986). O'Rourke and Bracco (1980) also considered droplet collisions and coalescence in their model by a stochastic approach, which was subsequently applied in Gavaises et al. (1996). The different outcomes of binary droplet collisions were included in the composite collision outcome model of Post and Abraham (2002). The developments of Ko and Ryou (2005) took into account the formation of satellite droplets, which are the results of high-kinetic-energy collisions between droplets (Orme, 1997). The relative velocity of colliding droplets is usually low in flows modeling atmospheric icing processes; therefore the formation of satellite droplets was neglected in a preceding study by the present authors (Kollár et al., 2005a), and the composite collision outcome model was improved in the range of low relative velocities of colliding droplets. An improved model (Kollár et al., 2005b) includes the effects of both the droplet collision and the evaporation and cooling; it ignores, however, the turbulent dispersion of droplets. The importance of this latter process was already emphasized by Kollár et al. (2005a), who predicted that the main reason for the discrepancy between their theoretical and experimental results was the consequence of neglecting turbulence droplet dispersion. The present developments overcome this deficiency of the previous model.

The main goal of this paper is to construct an improved model of two-phase flows, which applies our previously developed model for droplet collisions, calculates the modifications in droplet mass and temperature due to evaporation and cooling, takes into account the effects of turbulence on droplet dispersion, and thus, is capable of simulating the evolution of DSD in the flow. This model also considers the deflection of droplet trajectories due to gravity, and thereby, it is applicable to determine the vertical separation of droplets of different sizes in a horizontal flow. A further achievement of this research is the validation of the results provided by the model by means of DSD measurements in the test section of a wind tunnel. Finally, the model is applied to simulate the evolution of DSD and the vertical separation of droplets under in-cloud icing and freezing drizzle conditions as modeled in an icing wind tunnel.

2. Processes influencing DSD

This section discusses four processes which have great influence on droplet size and trajectory, and whose effects are considered in the model: (i) droplet collision and coalescence, (ii) evaporation and cooling, (iii) gravitational settling, and (iv) turbulent dispersion of droplets.

2.1. Droplet collision and coalescence

The binary droplet collision phenomenon is discussed in detail and a composite collision outcome model is constructed in Kollár et al. (2005a); a brief summary follows. When two droplets interact during flight, five distinct regimes of outcomes may be distinguished: (i) coalescence after minor deformation (or slow coalescence), (ii) bouncing, (iii) coalescence after substantial deformation, (iv) reflexive separation, and (v) stretching separation. The phenomenon of droplet collision is controlled by several physical parameters, but the outcome of collisions is usually described by three non-dimensional parameters: (i) Weber number, We, which is the ratio of the inertial force to the surface force, (ii) impact parameter, B, which is the distance from the center of one droplet to the relative velocity vector placed on the center of the other droplet, divided by the sum of radii of colliding droplets, and (iii) droplet size ratio, Δ, which is the ratio of diameter of the smaller droplet to that of the larger one. Boundary curves between the regions of possible outcomes are proposed in terms of