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Study of droplets distribution on canopy of ringsail parachute in light rain

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ABSTRACT

As a basal part of the entire study of reliability performance of ringsail parachute and re-entry capsule descending in rain environment, droplets distribution characteristics on canopy surface are investigated firstly via two-phase flow approach in the paper. The model of ringsail parachute and capsule is built on the basis of the sizes of Chinese Shenzhou series spacecraft components. The simulation of droplet trajectories is implemented numerically using the Discrete Phase Model. The numerical simulations considering various rainfall rates and velocities of a ringsail parachute and capsule descending in light rain conditions are conducted. The results show that for one specific rainfall rate, there is a homologous critical value of descending speed of parachute and capsule, which is the dividing line between raindrops being trapped and not being trapped by the canopy; if the descending velocity is less than the critical value, no raindrops will be captured; in raindrops-trapped cases the raindrops are distributed on the bottom skirt zones of the canopy surface and not evenly distributed. The work in the paper will be helpful and significant for the further study of the effects of rain environment on the spacecraft recovery.

1. Introduction

Rainfall is a common natural phenomenon. However, when rainfall occurs, the manned space mission which includes rocket launch and spacecraft recovery will be delayed or canceled generally. Especially in the spacecraft recovery, the bad weather is more likely to bring unknown danger because the parachute, which is widely used to supply aerodynamic resistance to the spacecraft recovery, is quite sensitive to the weather conditions. Up to now almost all of the spacecraft recovery activities are carried out in good weather conditions. So it is of great significance to research the effects of rain condition on the performance of parachute for achieving the all-weather implementation of manned space mission. Chinese spacecraft landing area is located in a place where the rainfall is scarce most of the time. Light rainfall has a higher probability of occurrence compared with moderate and heavy rainfall. According to the local rainfall characteristics over the past years, light rain environment is considered in the paper. The research background of the paper can be introduced from the two aspects of ringsail parachute and rain.

Ringsail parachute has been widely applied in the aerospace area with its excellent performance. According to existent literatures, ringsail parachute has a better stability than some other types. It is because the gaps between the rings and sails are much more than others while the improved porosity can enhance stability of parachute. Also the ringsail parachute is more popular in the aerospace field due to its rather higher drag coefficient. It can provide enough resistance for the deceleration of re-entry capsule. So far a lot of research on the ringsail parachute has been carried out. Gao and Yu [1] researched the influence of reefing ratio on inflation performance of ringsail parachute and found that the reefing ratio was in linear relationship with the maximum opening load. Yang et al. [2] investigated the influence of permeability of fabric on aerodynamic performance of a ringsail parachute by establishing a new governing equation of flow considering the permeability of fabric. After comparing the numerical results with the traditional results they concluded that the new model was significant to improve the accuracy of flow field simulation. Stein and Tezduyar have achieved great success on the aspect of parachute fluid–structure interaction (FSI) in the past years [3–5]. The FSI modeling of a ringsail parachute for Orion space vehicle was studied in detail by Tezduyar et al. [6] and the results of a special case in which the influence of side winds was included were presented. In fact FSI has always been a focus of researching various types of parachute. Tutt and Taylor [7] used LS-DYNA to numerically simulate the inflation of parachute which was based on the Arbitrary Lagrangian Eulerian (ALE) Method. Kim et al. [8] modeled the evolution of parachute canopy and risers via using the

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front tracking method on a spring system. In addition there is also some FSI research of parachute and suspension line simulation via the immersed boundary (IB) method [9,10]. Most published literatures on the aspect of any types of parachute are generally aimed at studying the flow field, geometry, material characteristics or FSI problems. Until now, no directly relational literatures on the subject of descent of parachute in light rainfall environment are available.

Systematic research of rainfall has begun since more than half a century ago. In 1948 Marshall and Palmer [11] investigated the distribution of raindrops with size and gave its expression which was widely approved and adopted in the subsequent study of rain. Afterwards in 1976 an expression for the ground level and atmospheric raindrop size distribution was derived by Markowitz [12]. The later research concerning effects of rain is mainly concentrated in several fields, which include flight safety of aircraft, erosion of building surface and running safety of high speed train [13–15]. Particularly previous study on flight safety of aircraft is of great reference value to the subject in this paper. The research on flight safety of aircraft in rain environment began as early as in 1941 [13]. Then in 1983 Haincs and Luers [16] investigated the effects of heavy rain on aerodynamic penalties of landing aircrafts, and found the raindrop cratering and water film, which could produce drag increase of 5% to 10% for a 100 mm/h rain, were the causes of airfoil roughness. Afterwards Wan and Pan [17] carried out numerical simulation of aerodynamic efficiency of 2-D airfoil NACA64-210 under the influence of heavy rain via two-phase flow approach. In their study the raindrop trajectories were simulated by applying the discrete phase model (DPM) and the k–ε model was chosen as major turbulence model. The simulation results via two-phase flow approach were in good agreement with the experiment results obtained by Bezos and Campbell [18]. It is shown that in heavy rain environment the degradation of lift to drag ratio in average value was rather accurate compared with the experiment results. In recent years Ismail et al. [19] investigated the effects of heavy rain on the aerodynamic efficiency of 2D NACA 0012 airfoil and 3D NACA 0012 rectangular wing and the results showed significant increase in drag and decrease in lift in heavy rain condition. Also, in their study DPM was used to model the rain particles. These research papers indicate DPM of two-phase flow approach has been an approved and efficacious model to simulate the raindrop trajectories.

It is found from the foregoing statements that the influence of rain condition on performance of ringsail parachute has been rarely investigated up to now. The two-phase flow approach including DPM can be employed to deal with the involved problem. According to the principle of priority the raindrops distribution on canopy surface should be studied firstly before studying the effects of rain condition on the performance of parachute.

The ringsail parachute and capsule at high altitude has a higher descending velocity than the raindrops in the air according to the existing data. For example, when the average diameter of raindrops is 4 mm, which belongs to an uncommon heavy rainfall level, the descending velocity is about 9.550 m/s at the altitude of 2000 m. Meanwhile the descending velocity range of ringsail parachute and capsule is from 10 m/s to 30 m/s. One imaginary scene is that the ringsail parachute and capsule is chasing after the raindrops in the air. This means the research of descent of ringsail parachute and capsule in the rainfall is a little different from the study of aircraft flight. The relevant airdrop experiment is impracticable to conduct in the natural rain condition or in the indoor environment because of the difficulties of precise measurement of droplet parameters. So with progress in numerical modeling techniques, the numerical simulation, which is a comparatively reasonable way at present, is carried out in the paper. FSI is not considered because the shape of inflated canopy has been stable relatively when parachute and capsule entered the rainfall region at an altitude of no more than 5000 meters. In the simulation both the velocity conditions whether the raindrops can be trapped by the ringsail parachute canopy and the raindrops distribution on the canopy surface are studied.

The outline of the paper is as follows. Firstly the adopted mathematical and physical models are introduced. Then considering different rainfall rates and velocity conditions the two-phase flow approach is employed to simulate the descent of ringsail parachute and re-entry capsule in rain environment. Afterwards the results of distribution of raindrops are analyzed adequately. A summary of results analysis is provided in the last section.

2. Mathematical and physical model

2.1. Continuous phase model

In the two-phase flow approach the fluid is treated as a continuum. The descent of ringsail parachute is at a low speed of no more than 30 m/s in the paper. The incompressible Reynolds-averaged Navier–Stokes equations are solved for the continuous phase. The pressure-based segregated SIMPLE algorithm is employed to calculate the pressure-correlation equation. The second-order accurate scheme is implemented in the spatial discretization of pressure, momentum, energy and turbulence terms. The governing equations of flow field are written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

where ρ represents the density of fluid, u_i and u_j are the velocity components, p is pressure, $-\rho\overline{u_i' u_j'}$ represents the Reynolds stress term.

The Reynolds number of the flow field near the ringsail parachute is about $Re = 3.0 \times 10^7$ which indicates the turbulence model is needed. Owing to its reasonable accuracy for a wide range of turbulent flows, the k–ε model, which has been widely accepted in engineering applications, is adopted to model the turbulence. The k–ε model is commonly used to solve the turbulence in the past study of flow filed of parachute or raindrop trajectories [14,15, 17,19,20]. It is a model on the basis of model transport equations for the turbulence kinetic energy k and its dissipation rate ε. The model transport equation for k is derived from the exact equation while the model transport equation for ε is obtained using some physical reasoning. The turbulence kinetic energy k and its dissipation rate ε can be obtained from the following transport equations [21]

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{4}$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$