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DNS Study of Initial-Stage Shock-Particle Curtain Interaction

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Abstract. High speed particulate flow appears in many scientific and engineering problems. Current work focuses on the situation with volume fraction of particles between 0.001 and 0.5, in which both particle-fluid and particle-particle interactions are important. Based on the stratified multi-phase flow model (Chang & Liou, J. Comput. Phys. 225 (2007), 840-873) with Euler equations, by regarding one phase as solid, a numerical method is developed to conduct direct numerical simulations (DNS) to high speed particulate flows. It is then applied to simulate the problem with a planar shock wave impacting on a particle curtain, but focusing on the initial stage, in which the particles can be regarded as static. 2-D simulations are conducted by keeping the total volume fraction of particles and changing the number of particles. The convergence of shock wave locations and turbulent energy are observed. A 1-D volume-averaged model is also studied and compared with the DNS, which gives effective drag coefficients. A 3-D DNS is conducted to compare with the 2-D DNS and 1-D model, showing that more detailed 3-D DNS studies are needed. The convergent values obtained from current work can be applied to the study of very small particle cases and to the model development.

AMS subject classifications: 76L05, 76M12, 76T15

Key words: Stratified multi-phase flow model, shock wave, particulate flow, Riemann solver.

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1 Introduction

High speed particulate flows can be observed in supernova, natural disasters, medical injection, engine, etc. The total volume fraction of particles α_d is an important parameter [2]. In dilute regime $\alpha_d \ll 1$, the particle collision effects can be negligible [3], the influence of the attenuation coefficient, the Mach number of the initial shock wave, the diameter of

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the solid particles and the dust loading ratio were explored [4]. Additionally, experiments and simulations used to study these regimes often rely on an initial shock wave to hit particle cloud [5–7].

In the granular regime, when α_d is greater than 50%, particles are close to each other so that particle collision is the dominant mechanism to their motions and only small contributions are from the continuous phase [8]. In this regime, Baer [9] used a continuum mixture theory and applied mesoscale modeling to describe the behavior of shock-loaded heterogeneous media. Goetsch et al. [10] used a discrete element method to predict the particle curtain properties.

This work focuses on the dense non-granular regime ($0.001 < \alpha_d < 0.5$) [2]. In this regime, the fluid-particle interaction, the inter-particle interaction, the interactions between particles and the wakes of neighboring particles, and the interactions between particles and the reflected waves of neighboring particles become important [11,12]. Wagner et al. in 2012 did experimental studies on the planar shock wave impacting on a dense particle curtain in a multi-phase shock tube [13]. In these experiments, incident, transmitted and reflected shocks are observed, making the drag on the particles different at different locations in the curtain. Wagner et al. in 2015 improved their shock tube using the flash X-ray measurements to see the particle movement in a compressible, dense gas-solid flow with high optical opacity [14]. After shock impacting on the particle curtain, the curtain as a whole propagates downstream and its width increases with the peak volume fraction decreasing. Theofanous et al. in 2016 studied similar problems experimentally and obtained scaling laws for the expansion of the particle curtain width [15].

The numerical studies on this kind of problems are mainly conducted by applying point particle model [16], which lack detailed description of the particles and may lose some characters. Regele et al. used a stair-step approach to describe the cylinder walls and a modified version of NGA code to do 2-D DNS on the initial stage of shock-particle curtain problem [8]. In Regele et al., they only used 25 particles and lacked more detailed study on both DNS results and the 1-D volume-averaged model. Picano et al. [17] used an immersed boundary method (IBM) to do DNS study on buoyant spheres with volume fractions in the range of $\Phi \in [0,0.2]$. Recently, Theofanous et al. [18] showed that the ill-posedness of the mathematical problem in point-particle model and effective-field models makes them miss some key physics, and so DNS is needed to get those key physics.

In this paper, DNS studies are performed based on the stratified multi-phase flow model and regarding one phase as solid. Volume fraction is used to distinguish the continuous phase and the discrete phase. MPI parallelization is applied to perform high-performance calculations.

In Section 2, numerical methods in 3D situation are described and the computer code is validated with two test cases. In Section 3, the problem of a planar shock wave hitting the particle curtain are introduced and then simulated, firstly in 2D cylinder by shrinking z direction, then in 3D sphere for further discussion. Convergent study for 2D cylinder with different particle numbers is performed for the 2D cylinder situation. An 1-D