International Journal of Multiphase Flow 101 (2018) 186–201

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Investigation and quantification of flow unsteadiness in shock-particle cloud interaction

Zahra Hosseinzadeh-Nik[a,b], Shankar Subramaniam[b], Jonathan D. Regele[a,*]

[a] Department of Aerospace Engineering, Iowa State University, Ames, IA 50010, USA
[b] Department of Mechanical Engineering, Center for Multiphase Flow Research & Education (CoMFRE), Iowa State University, Ames, IA 50010, USA

ARTICLE INFO

Article history:
Received 7 August 2017
Revised 28 December 2017
Accepted 12 January 2018
Available online 16 January 2018

Keywords:
Shock-particle interaction
Unsteadiness
Vorticity equation
Velocity fluctuations

ABSTRACT

This work aims to study the interaction of a shock wave with a cloud of particles to quantify flow unsteadiness and velocity fluctuations using particle-resolved direct numerical simulation (PR-DNS). Three cases are studied, with each case revealing one aspect of the intricate flow phenomena involved in this interaction. The unsteady interaction of a shock wave with a transverse array of particles reveals the origin of unsteadiness under the effect of mutual wave-wave and wave-wake interactions between the particles. In the second case, the interaction of a shock with a particle cloud is studied, with a focus on the interaction of the complex wave system with the vortical structure. A budget analysis of the vorticity equation reveals the sources of strong unsteadiness in the particle cloud. A detailed analysis of the velocity fluctuation and kinetic energy in the fluctuating motion is performed to ascertain the importance of the velocity fluctuations that arise from the strong unsteadiness. An analogous analysis is presented, in the third case, for a gradually-induced flow on the same particle cloud along with a comparison to the shock induced case to assess the impulsive effect of shock on intensity of the fluctuating field statistics.

1. Introduction

The interaction between shock waves and particles is an important phenomenon in compressible particle-laden flows (Forney et al., 1987a, 1987b; Ling et al., 2011a, 2011b; Parmar et al., 2010; Tedeschi et al., 1999). When a shock wave propagates around a particle a complex wave system including regular and irregular shock-wave reflection and diffraction is established (Bryson and Gross, 1960; Chung, 2007; Ling et al., 2012; Tanno et al., 2003; Whitham, 1959).

Shock interaction with a single isolated particle has been studied extensively (Parmar et al., 2009; Sun et al., 2005; Tanno et al., 2003; Whitham, 1959). In many typical applications, shock waves interact with a cloud or dispersion of particles (Nourgaliev and Theofanous, 2007; Theofanous et al., 2016; Theofanous and Chang, 2017). In these processes, depending on the solid phase volume fraction, α_s, the flow topology ranges from a very dense gas-solid flow ($\alpha_s \geq 0.5$) during the propagation of the shock wave within the particle cloud to a dilute gas-solid flow ($\alpha_s < 0.01$), at distances far from the source. Between these two extremes ($0.01 < \alpha_s < 0.5$), there exists a dense gas-solid flow regime during early interaction times. A detailed discussion of these three regimes is given by Zhang et al. (2001).

The modeling techniques developed for an isolated particle are suitable for dilute particle-laden flows (i.e., with negligible particle volume fraction), but cannot be applied directly in dense particle-laden flows (i.e., with finite particle volume fraction) (Ling et al., 2012; Tanno et al., 2003). With increasing particle volume fraction, the existence of neighboring particles further complicates the interaction between shock waves and particles. In these situations, inter-particle interactions, interactions between particles and reflected or diffracted waves from neighboring particles, and interactions between particles and the wakes of neighboring particles become important.

Much experimental work in the dilute regime has been conducted (Geng and Groenig, 2000; Rudinger, 1980; Sommerfeld, 1985). Simulations and theoretical analysis have been applied to predict shock attenuation in this regime (Miura and Glass, 1983; Wang et al., 2001). Computational modeling has also shown the capability to capture the gas–solid flow physics in the very dense regime. For instance, Baer and Nunziato (1986) use continuum mixture theory to accurately model the normal shock impingement. However, there is a substantial knowledge gap in gas–solid flows with intermediate particle volume fractions. Thus, detailed knowledge of the interactions that occur in dense gas–solid flow is required (Ling et al., 2012, 2011b; Wagner et al., 2015, 2012).

* Corresponding author.
E-mail address: jregele@lanl.gov (J.D. Regele).

https://doi.org/10.1016/j.ijmultiphaseflow.2018.01.011

Shock–particle interaction is strongly time-dependent (Parmar et al., 2010, 2008; Sun et al., 2005). The particle is subjected to strong gas acceleration as the shock wave passes over it (Gonor et al., 2004; Wagner et al., 2012). Sun et al. (2005) and Bredin and Skews (2007) presented time-resolved measurements of the force on a stationary particle subjected to a shock wave. The instantaneous force on the particle under such highly unsteady conditions was shown to be much larger than the corresponding quasi-steady force that would have resulted if the change from the quiescent pre-shock state to the uniform post-shock state were to happen very slowly (Ling et al., 2012; Parmar et al., 2010). In particular, the instantaneous force during the passage of the shock wave is reported to be an order of magnitude larger than the steady drag force resulting from the post-shock gas velocity (Ling et al., 2011b). This clearly highlights the importance of unsteady effects in shock–particle interactions.

The unsteady effects are usually neglected even if strong interactions between compressible flow features and particles are to be expected (Lanovets et al., 1993; Najjar et al., 2006; Zhang et al., 2001). However, in some applications, such as in detonations, the large unsteady forces exerted on the particle can cause deformation and breakage. Similarly, intense unsteady heating can cause melting or initiate chemical reactions. There are a limited number of papers that address the influence of unsteady forces on the motion of particles interacting with a shock wave, such as Parmar et al. (2009) and Forney et al. (1987b). Ling et al. (2012, 2011b) also proposed a model that includes unsteady contributions to particle-fluid interaction force and heat transfer.

Wagner et al. (2012) pioneered an experiment to isolate the flow behavior involved in a multiphase shock tube to investigate the unsteady interaction of a shock with a Mach number of 1.67 with a dense particle cloud. Ling et al. (2012) developed a one-dimensional phase-averaged point-particle model, including the unsteady momentum coupling forces, to reproduce the experimental results of Wagner et al. (2012). The results highlight the importance of unsteadiness in the shock-particle interaction in the dense gas-solid regime. Although this model appears promising, it is appropriate to question whether all aspects of the experimental flow can be captured using a one-dimensional model that only includes the unsteady momentum coupling forces. Regele et al. (2014) took a step forward in revealing the complex phenomena in this interaction and showed that high flow unsteadiness is present in the flow field. They compared the phase averaged results with a 1D model and indicated that the 1D model can characterize the overall steady-state flow behavior but fails to capture unsteady behavior due to the neglect of unsteady terms such as the Reynolds stress. There is also evidence that the Reynolds stress can be important in simple homogeneous incompressible flow in the dense particle-laden regime (Mehrabadi et al., 2015; Sun et al., 2016). In these results, the inter-particle interactions, the interactions between particles and the wakes of neighboring particles play a role. However, the interactions between particles and the reflected or diffracted waves from neighboring particles is absent. Even in the absence of shocks, Mehrabadi et al. (2015) showed that the Reynolds stress term is non-negligible and fluctuations in the gas-phase velocity can contribute significantly to the total gas-phase kinetic energy. Furthermore, the authors denote local particle-scale gas-phase velocity fluctuations generated by the presence of particles, larger than the Kolmogorov length scale, as pseudo-turbulent velocity fluctuations. They refer to the kinetic energy associated with these fluctuations as the pseudo-turbulent kinetic energy (PTKE) because these fluctuations can be generated even in laminar gas-solid flow. They show that the PTKE in the fluctuating motion can be as high as the kinetic energy in the mean flow, especially for systems with higher solid volume fractions. The ratio of PTKE to mean kinetic energy increases with the solid volume fraction and decreases with the mean slip Reynolds number. This provides evidence that the pseudo-turbulent effects play an important role in the dense gas-solid regime. Sun et al. (2016) provided evidence that the velocity fluctuations can also result in temperature fluctuations.

Regele et al. (2014) showed that velocity fluctuations from shock-particle interactions are more significant and can be on the same order as the mean velocity. However, since the calculations were performed with the Euler equations, additional studies including viscous and thermal diffusion are required to more accurately quantify the magnitude of the velocity fluctuations. These observations along with the experimental results of Wagner et al. (2012) indicate that quantification of the unsteadiness and gas-phase velocity fluctuation in the shock-particle cloud interaction is necessary to better understand the flow interaction.

The overarching goal of this paper is to quantify the flow unsteadiness and velocity fluctuations induced by shock waves interacting with particle-clouds and determine their sources. The approach is to perform 2-D simulations of shock waves impacting an array or cloud of particles, where the same Mach number and particle configuration used in Regele et al. (2014) is used for consistency. The fully compressible Navier–Stokes equations are solved with a characteristic based volume penalization method (Brown–Dymkoski et al., 2014), which provides a more accurate estimate of the magnitude of these terms than the previous Euler simulations (Regele et al., 2014). A transverse array of particles is used to obtain deeper insight into the wave dynamics and unsteady vortex generation on each particle under the mutual wave-wave and wave-wake interaction between the particles. Quantification of the shock-particle cloud interaction highlights the impact of the complex shock dynamics that arise from the effect of neighboring particles on the mean and fluctuating flow field evolution. Finally, in addition to the flow unsteadiness induced by fluid flowing through the particle cloud, the initial interaction of the shock wave with the particle cloud is likely to produce flow unsteadiness itself. It then becomes unclear how to differentiate between unsteadiness that originates from the initial shock wave and vortical motion. In order to distinguish between these two sources, additional simulations of gradually-induced flow over the same particle cloud are performed to remove the impulsive effect of the shock and understand how the impulsive shock dynamics contribute to the unsteadiness and the fluctuating field statistics.

The paper is organized as follows. The mathematical approach and the numerical methods are presented in Sections 2 and 3 respectively. The results for a shock wave impacting a transverse array of particles are contained in Section 4 and the results describing the particle cloud behavior are in Section 5. Finally, conclusions are drawn in Section 6.

2. Mathematical approach

2.1. Governing equations for PR-DNS

In this work the interaction of shock and compression waves with particles are studied where the particles are frozen in place because of the large density ratio between the two phases (Regele et al., 2014). In these interactions the smallest scale flow feature, other than the shock thickness, is the boundary layer present near the surface of each particle. The appropriate method to accurately capture these flow features is the Particle-Resolved Direct Numerical Simulation (PR-DNS) methodology in which the flow scales, introduced by the presence of large particles, are resolved (Mehrabadi et al., 2015; Sun et al., 2016). To this end, the fully compressible Navier-Stokes equations are solved to ensure the accuracy of the captured features in the cloud and the wake structure behind the cloud. The non-dimensionalized continuity, mo-