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Importance of unsteady contributions to force and heating for particles in compressible flows. Part 2: Application to particle dispersal by blast waves ☆

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ABSTRACT

Particle dispersal by blast waves is an interesting phenomenon. A model problem, i.e., a sudden release of a compressed gas–particle mixture contained in a spherical container, is employed to investigate the fundamental physics of particle dispersal. The problem is simulated by the multiphase flow models proposed in Part 1 of this article that include unsteady contributions in momentum and energy exchange between gas and particles. At early times, when particles are accelerated in the expansion fan, unsteady force and heating contributions are much larger than the corresponding quasi-steady contributions. Consequently, neglecting unsteady contributions leads to significant errors in particle front location (the boundary of the particle cloud). The complex wave interactions in the flow have strong influence on the particle motion. As a result, the particle motion is a non-monotonic function of particle density or diameter and the evolution of particle concentration is non-uniform and unsteady.

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1. Introduction

Particle dispersal by blast waves is an interesting phenomenon that can be observed in nature, such as in volcanic eruptions, see Chojnicki et al. (2006), and in the application of multiphase explosives, see Zhang et al. (2001) and Tanguay et al. (2007). As a simple model of these problems, we can consider the sudden release of a highly compressed spherical gas–particle mixture. When the mixture is exposed to an environment with lower pressure, a blast wave is generated and the particles are dispersed outward at high speed. The rapid time evolution of the gas–particle mixture makes measurements through experimental techniques very difficult. Therefore, the modeling and simulation approach becomes an important tool in investigating this problem.

To focus on the fundamental physics of particle dispersal by blast waves, in this work we employ a specific problem of simple geometry. A schematic of the problem considered here is shown in Fig. 1. The gas–particle mixture is initially stored in a spherical container of radius $\widetilde{R}_{sc}$ and surrounded by air at standard atmospheric conditions. Tilde denotes dimensional quantities. At $\tilde{t}=0$, the container is removed instantaneously and the mixture is exposed to the surroundings, leading to a blast wave and the outward dispersal of the particles.

The blast wave generated by a sphere of pressurized gas without particles is a classical problem. The blast-wave theory developed by Taylor (1950), von Neumann (1941) and Sedov (1959) gives an analytical solution for a spherical blast wave generated by a point source of energy. Brode (1955) extended the investigation to a finite-size source of the kind shown in Fig. 1 using numerical simulations and found that the blast wave generated by a finite-size-source is more complicated. Other studies of the spherical blast-wave problem include the experiments of Boyer (1960) and Baker (1973), simulations by Brode (1959) and Liu et al. (1999), and the (approximate) analytical investigations by Friedman (1961) and McFadden (1952). A good summary of the evolution of blast-wave studies is given by Sachdev (2004).

A spherical blast wave generated by a finite-size-source was called the "spherical shock-tube blast" by Brode (1957), as the problem setting and the flow at early stages are similar to the planar shock-tube problem. However, the radial effect has a strong influence and eventually makes the spherical blast wave substantially different. Assuming spherical symmetry, a simple description of the flow is as follows. It can be seen from Fig. 1 that, when the compressed gas is released, a shock wave (the so-called main shock), an expansion fan, and a contact discontinuity are generated, similar to the planar shock-tube problem. The shock wave and the contact discontinuity travel outward, but in contrast to the planar case, their speeds decrease with time. Here, we denote the inner and outer boundaries of the expansion fan as the head and tail, respectively. Due to the over-expansion arising from the radial effect, the pressure to the left of the tail of the expansion fan is lower than on the right, resulting in the formation of a secondary shock wave. As the pressure gradient across it is positive,

☆ Unsteady force and heating in shock–particle interaction.

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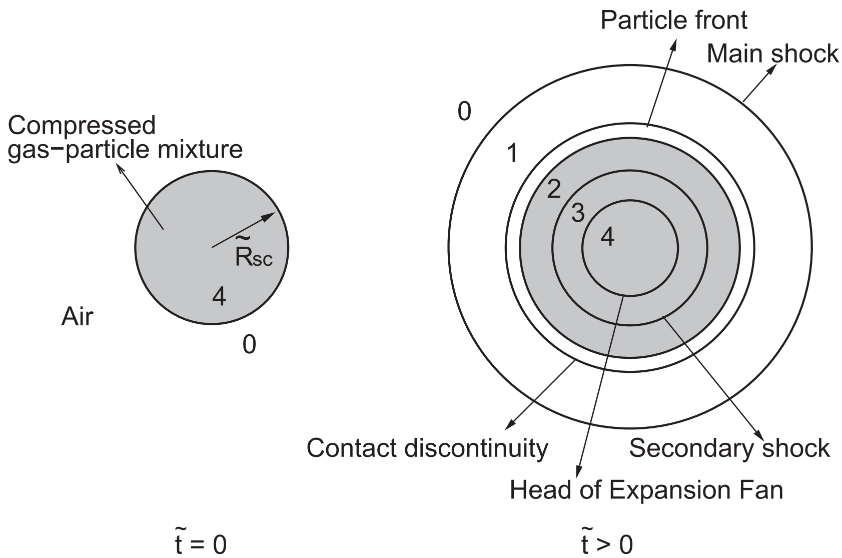

Fig. 1. Schematic illustration of particle dispersal in a spherical blast generated from a compressed gas–particle mixture. The shaded area indicates the existence of the particles.

the secondary shock is an imploding shock. But due to the large initial gas velocity, the secondary shock is initially swept outward, before eventually turning inward. Similarly, the contact discontinuity also reaches a maximum radial position and turns inward.

Here we consider the extension of the finite-source spherical blast problem to multiphase flow. Thus, as shown in Fig. 1 the finite-sized spherical container is initially filled with a compressed gas–particle mixture. The problem becomes more complex through the addition of particles. Once the compressed gas–particle mixture is released, the particles are driven by the gas flow and move outward. Due to inertia, the particle front (the boundary of the particle cloud) initially lags behind the contact discontinuity. In the planar shock-tube problem, the particle front will never catch up with the contact discontinuity, see Ling et al. (2009). But in the spherical case, as the contact discontinuity decelerates and reverses direction, the particle front may cross the contact discontinuity and move into the shock-compressed ambient cooler air. In fact, it has been observed that under some conditions, the particle front can even cross the main shock, see Lanovets et al. (1993) and Zhang et al. (2001).

In many applications, the dispersal of particles resulting from the spherical blast is of interest. In particular, we want to answer questions such as: when will particles move ahead of the main shock? What fraction of particles will move ahead of the main shock? Similarly, under what condition will particles move ahead of the contact discontinuity and what fraction of particles will get ahead of the contact discontinuity? These questions are important for several reasons. In the case of dispersal of reactive metal particles in a multiphase explosion, particles that remain between the origin and the contact discontinuity can burn only anaerobically, while particles beyond the contact discontinuity can burn aerobically. Similarly, particles ahead of the shock are subjected to ambient air, while those just behind the shock are subjected to shock heated ambient air.

To reliably compute particle dispersal resulting from a multiphase blast using point–particle approach, it is essential to accurately account for the momentum and energy exchange between an individual particle and the surrounding gas. Similarly, to capture the thermal evolution of the particle distribution, it is important to accurately account for the energy exchange. In the present application, particles interact with the main and secondary shock waves, the contact discontinuity, the expansion fan, and the non-uniform flow regions between these waves as they disperse outward. The particle force and heating models must be able to capture the interactions between particles and unsteady compressible flow features to yield accurate prediction of particle dispersal.

In Part 1 of this article (Ling et al. (submitted for publication), hereafter referred to as LHB1), we established force and heating models that include unsteady mechanisms. The models were first applied to the problem of a particle interacting with a planar shock wave. Analytical results established the significance of the unsteady force and heating contributions to shock–particle interaction over a wide range of shock Mach number, particle Reynolds number, and particle density ratio. The models were also applied to the problem of particles interacting with a spherical blast wave generated by a point source. The results showed clearly that neglecting unsteady force and heating contributions can introduce significant errors that are long-lasting and magnified in the non-uniform and unsteady flow behind the spherical shock wave. These results confirmed the importance of unsteady force and heating contributions and the ability of the model of LHB1 in capturing interactions between particles and compressible flow features. This is significant because the majority of simulations of compressible multiphase flows only take into account quasi-steady contributions. Here, the multiphase flow model of LHB1 is applied to the problem of particle dispersal by a spherical blast wave pictured in Fig. 1. The results will be compared with those computed by the conventional quasi-steady drag and heat transfer correlations. The difference between the results can be treated as the error of neglecting unsteady contributions.

Key parameters in this problem include particle–gas density ratio, ratios of the particle diameter and particle initial location to the container radius, ratios of the initial pressure and density of the compressed gas to those of the ambient air. As the focus of this work is on the particle behavior, we keep the initial gas pressure ratio and gas density ratio fixed, and carry out a systematic study of the influence of the parameters associated with particles.

2. Problem formulation and numerical methods

In the present problem, the particles are assumed to be spherical and inert. The particles are initially uniformly distributed inside the spherical container and are in thermal equilibrium with the