

ANALYSIS OF PLANAR WAVES WITHIN A PARTICLE-LADEN GAS INDUCED BY PISTON IMPACT

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ABSTRACT

Models based on continuum mixture theory are frequently used to predict transient engineering-scale phenomena occurring within multiphase systems. These models are also used in a wide range of applications, including the simulation of deflagration-to-detonation (DDT) transition in granular explosives, flows in fluidized and packed beds of particles in chemical reactors, and dusty gas flows in porous media. In the present work the structures of compaction waves generated by piston impact are examined. In addition, structural dependence on system and model parameters are also analyzed. These problems are commonly used to simulate accidental impact scenarios, as well as the propagation of shocks in dusty gases and detonation waves in explosive systems. Here, a piston moving at a constant speed generates compaction waves propagating through a mixture of air and the granular high explosive HMX ($C_4H_8N_8O_8$). Initially, the mixture contains a spatially uniform distribution of HMX particles having a single grain size, with both phases in mechanical and thermal equilibrium at ambient conditions. Important parameters characterizing these simulations are grain diameter D , piston speed u_p , and initial solid volume fraction ϕ_s^o .

Generally, multiple flow regimes evolve, which are separated by solid volume fraction, as shown in Figure 1; the locations and relative sizes of these regions depend on D and ϕ_s^o . As ϕ_s increases the probability of intergranular collisions increases and the gas is locally accelerated, resembling flow through a converging nozzle. As ϕ_s approaches the no-load value at which the grains settle under gravity, called the free-pour volume fraction ϕ^* , the solid grains experience sustained contact called lockup, and resist further compaction. This material-dependent resistance is called the intergranular stress β_s . Gas permeability is significantly reduced; consequently, gas and solid velocities rapidly equilibrate. At high piston speeds, a solid plug may also form, where porosity is very low and solid stress substantially increases. Although wave structures have been analyzed for dilute and initially packed systems [1, 2], the transition region has not been examined in detail. The present work predicts wave structures for a wide range of initial volume fractions ($0.01 \leq \phi_s^o \leq \phi^*$) and compares results to available predictions in the literature.

The governing equations used here are modifications of the well-studied Baer-Nunziato model [3]. Evolution equations for the phase mass, momentum and energy, as well as solid volume fraction, are specified. Interphase transport processes are described by source terms; these are fully described by two quantities: relaxation coefficients and energy partitioning functions. Relaxation coefficients specify the rate at which phase velocities, stresses, and temperatures equilibrate. It should be noted that stress equilibration involves changes in ϕ_s governed by the compaction equation. Partitioning functions are used to apportion dissipative heating associated with interphase transport to each phase. Whereas the relaxation coefficients are specified by empirical correlations, the

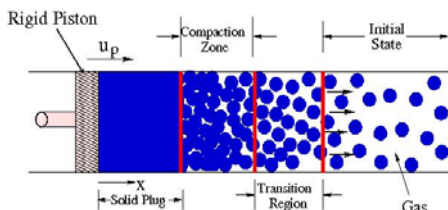


Figure 1: Piston impact problem with general flow regimes.

partitioning functions allow for substantial modeling flexibility. However, accurate forms for these functions are difficult to obtain due to a lack of experimental data. Partitioning functions have been typically suggested in an *ad hoc* manner [4], such as using the phase mass fraction. However, the choice of function can have a significant effect on the phase temperature profiles, and this sensitivity is poorly characterized. In this work simulations are presented for different forms of the partitioning functions to illustrate this dependence and suggest appropriate forms for future modeling.

Figures 2 and 3 show predictions for velocity and pressure profiles in a laboratory frame at fixed time for $\phi_s^o = 0.3$, $u_p = 100$ m/s and $D = 150$ μm , where x represents distance from the piston surface. A two-wave structure is predicted here; a precursor compression wave in the gas phase is followed by a slower compaction wave in the solid. High gas permeation is evident from the gas-phase acceleration behind the precursor wave. From a mesoscale perspective solid pressure increases with ϕ_s due to increasing particle collisions. Velocities and pressures begin to equilibrate behind the compression wave, but relaxation accelerates following grain lockup.

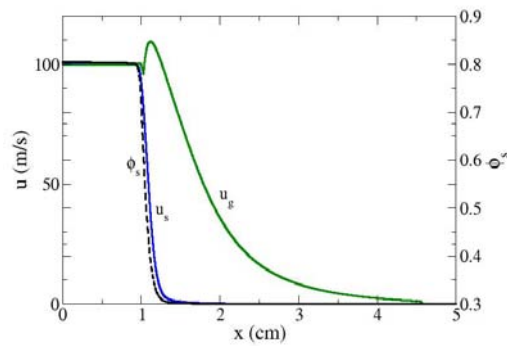


Figure 2: Velocity and volume fraction fields at $t = 178$ μs .

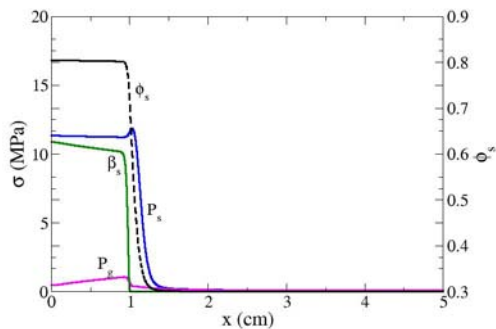


Figure 3: Stress and volume fraction fields at $t = 178$ μs .

Figure 4 plots gas temperature and the contributions of several heating mechanisms. Near the piston surface, compaction heating becomes more significant due to higher solid pressures, while drag and compression work dominate the energetics away from the surface, suggesting that the influences of different heating mechanisms depend on solid volume fraction.

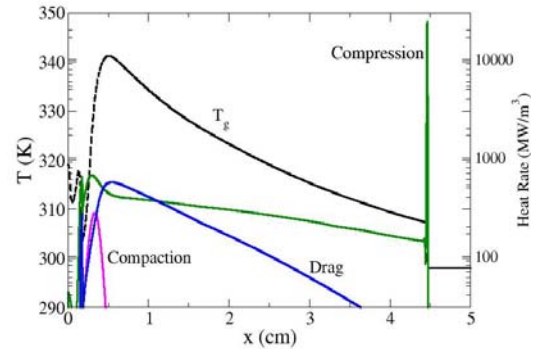


Figure 4: Temperature profiles with multiple heating processes.

Similar qualitative trends are also observed at higher piston speeds and initial volume fractions, and relaxation zone lengths for pressure, velocity and temperature decrease. Furthermore, grain size also has a significant effect on the lengths of the equilibration zones. Since the relaxation coefficients vary as D^{-2} , these structures become very difficult to numerically resolve. A subject of future work is the use of asymptotic methods to derive a reduced model in pressure and velocity for mixtures containing both micron and nanometer-sized solid grains. The current model will also be modified to account for these bimodal distributions [5], and can be used to verify the asymptotics.

ACKNOWLEDGMENTS

NSF-IGERT, LSU High-Performance Computing (HPC), Louisiana Optical Network Initiative (LONI).

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