A New Facility for Studying Shock-Wave Passage Over Dust Layers

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1 Introduction

To predict dust layer entrainment into the post shock gas flow, it is important to understand the initial motion of the particles. Previous work has been performed to enrich the dust dispersion knowledge. In spite of all the efforts, it is still difficult to completely describe the dust entrainment mechanism. A conclusive model to accurately simulate the exact entrainment process has yet to be developed. Therefore, to ensure safety regarding dust explosion hazards, it is important to study the dust lifting process experimentally and identify important parameters that will be valuable for development and validation of numerical predictions of this phenomenon.

Former experimental works have studied the interaction of unsteady dust layers with different elements of gas-dynamic flows (shock, compression, and expansion waves). Earlier shock and dust particle interaction experiments focused on understanding the phenomenon of dust lifting [1]-[8]. Flethcher's [2] explanation on the mechanism of dust lifting was based on experiments as well as and theoretical analysis. He criticized Gerrard's [1] conclusion that dust entrainment is under the action of a shock wave passing through the dust layer. Instead, he concluded that the dust is lifted by the rapid flow behind the propagating shock. Bracht and Merzkirch [3] identified the governing force in dust lifting is the Saffman force and supported their experimental work with a numerical model. The behavior of a coal-dust layer with a weak shock wave passing above it was studied by Hwang [4]. The coal dust particle size was up to 44 μm. Later, the effect of particle size on dust dispersion [5] and Magnus force [6] were studied. Fedorov [7] in his review paper discussed the significant body of work related to shock interaction with dust layers. According to Federov's conclusion, the dust lifting from a packed bed does not depend on the layer depth. However, curving of the layer surface and particle density do have important effects on the lifting height.

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Some of the other studies focused on the dust lifting problem in conjunction with combustion problems and with detonation, which is usually called a layered detonation. In 2005 and 2012, Klemens *et al.* studied shock interaction with coal dust and silica dust in a shock tube to identify important parameters such as the time delay in lifting the dust from the layer and the dust concentration gradient behind the propagating shock [8]. For the numerical part of their research, they considered two approaches: Eulerian and Lagrangian for modeling the dispersion of coal dust. In spite of all the efforts, it is still difficult to describe the dust entrainment mechanism, and more, detailed data are needed. As a result, the conclusive model to simulate the exact entrainment process is yet to be built.

The process of dust lifting and two-phase flows were also comprehensively studied numerically [7]-[15]. However, there is no mathematical model that can describe all stages of the process of dust lifting, including the propagation of wave processes in the layer retaining cohesion, the processes of turbulent mixing, and the specific features of the force interaction of the phases [7]. GexCon released the first version of the CFD code, DESC 1.0, in June 2006 which has been used to develop a dispersion model of coal dust behind a propagating shock wave [14]. Ilea et al. [15] incorporated polydispersity effects by modeling dust lifting behind a propagating shock wave using the Eulerian-Lagrangian method. Many works have compared the Eulerian-Lagrangian method with the Eulerian-Eulerian method and have concluded that the Eulerian-Lagrangian method is a better approach. Although much input has been given towards numerical analysis of the dust dispersion phenomenon, experimental validation is required.

With this is mind, a new facility for the study of shock waves over a dust layer has been developed. The shock tube has optical access to provide high-speed flow visualization. Also, a direct photographic technique should be synchronized with the shock wave motion in order to track the particle motion. The following paper first describes details on this new facility, including the hardware design and the experimental procedures. An example experimental result is also provided.

2 Facility

A new test section was designed for an existing shock tube, and the previous test section was replaced. The current test section is designed to handle shock velocities up to Mach 2 with an initial pressure of 1 atm, and it is capable of holding pressures up to 15 atm behind the reflected shock wave. Higher Mach numbers are achievable with initial pressures below 1 atm. Conditions behind the reflected shock wave determine the upper bounds on allowable shock strength. The possibility of a dump tank being added in the future would allow even greater shock strengths, if necessary.

The shock tube is constructed of 304 Stainless Steel with a round driver section and square driven section. The driver section is 7.6 cm in diameter and 1.5 meters in length. The driven section is approximately 10.8 × 10.8 cm and 3.9 meters long. The shock velocity is determined by a series of pressure transducers connected to three timing gates (Fluke PM6666 counters). Of the three timing intervals, one is before the dust layer test section, one spans the test section, and one is after the test section. By running shocks with and without a dust layer present, the effect the dust layer has on shock velocity may be observed.

The test section is comprised of ob-round windows on the top, left, and right sides, and a dust pan on the bottom side. The left and right windows are each 5.1 by 30.5 cm and allow for viewing of the dust layer and fluid interface, particularly for shadowgraph and schlieren techniques. The top window is 2.5 by 30.5 cm and allows for the future use of a laser sheet for scattering and other techniques in which a laser sheet is projected through the top window onto the test area, and scattering is observed through the side windows. Dust is placed in an easy-to-remove dust pan with a dust deposit area of 27.3 cm by 7.0 cm. The dust pan has four secure, removable inserts which allow for the adjustment of the dust layer thickness in 3.2-mm increments between 3.2 and 12.7 mm. Figure 1 shows a photograph of the modified facility with the new test section, and Fig. 2 shows a schematic of the test section area.

Fig. 1 Shock tube with new dust-layer test section; dust pan and inserts are displayed on the optical table

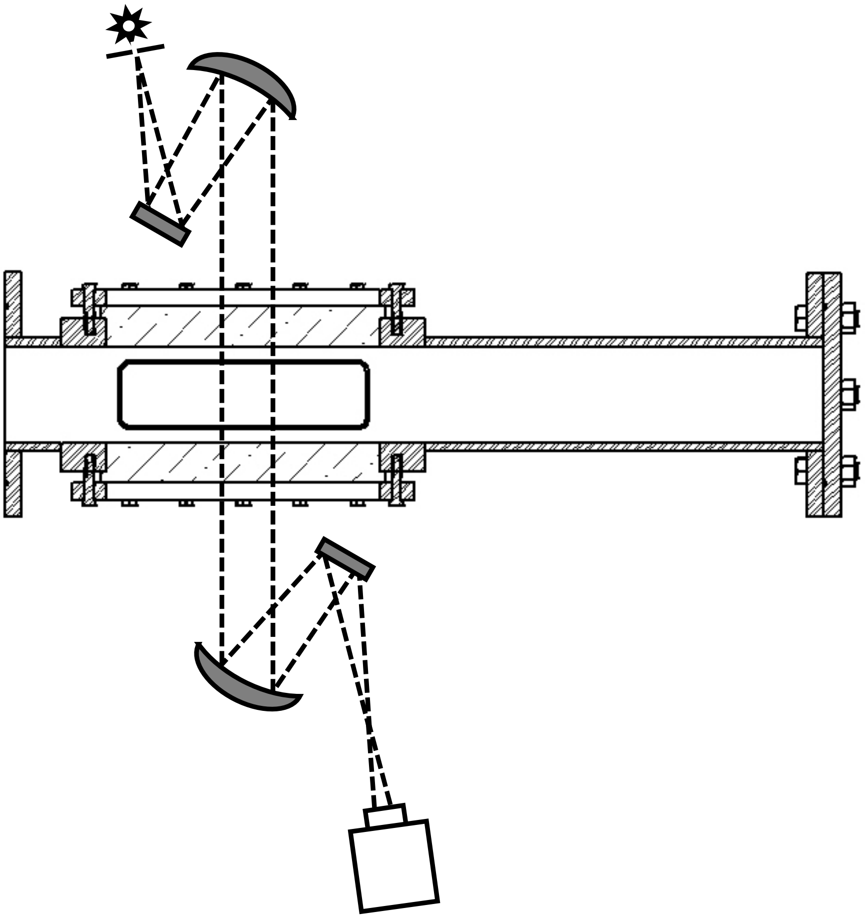

Fig. 2 Schematic of dust layer test section shadowgraph, top view cut-away

3 Experimental Setup

Experimental variables include initial pressure, Mach number, dust layer thickness, and characteristics of the dust itself. The pressure is controlled through the shock tube's vacuum manifold, while the Mach number is altered by changing the diaphragms and driving gas species. The dust and dust layer thickness are changed using a removable dust pan section with removable inserts. Thin, polycarbonate diaphragms are used with either Helium or Nitrogen as the driving gas, typically 0.1 to 0.3 mm. Initial tests were being carried out with dry, 40-μm limestone dust in air. Care must be taken to avoid dust particle combustion for potentially reactive dust species such as coal dust. In this case, pure Nitrogen should be used as the driven gas because it is non-reactive and has similar properties to air.

For the present paper, the shadowgraph technique was employed for flow field visualization. The present experimental viewing area is approximately 76 mm wide by 50 mm high, with the width being limited by the concave mirror diameter and by the height of the window; larger-diameter concave mirrors would allow for a wider viewing area. A Photron Fastcam SA1.1 high-speed camera at a frame rate of 15,000 fps was used in conjunction with am Oriel 70-W Hg-Ze lamp to capture the fluid and dust-layer interaction. The exposure time for the data shown herein was set at 10 μs.

Particle lifting is measured with respect to shock wave propagation. Dust rise in the y-direction can be compared with shock wave propagation past a corresponding x-location. Dust rise is determined by examining the shadowgraph images. The corresponding shock wave propagation is derived from the shock velocity and time recorded by the camera using a known camera trigger location. Figure 3 shows a typical image sequence at a 333-μs interval, starting in the top, left corner. Note the passage of the incident, normal shock wave, followed by the subsequent movement of the dust layer. For the experiment shown in Fig. 3, the limestone dust layer was 3.2 mm, and the shock Mach number was 1.2.

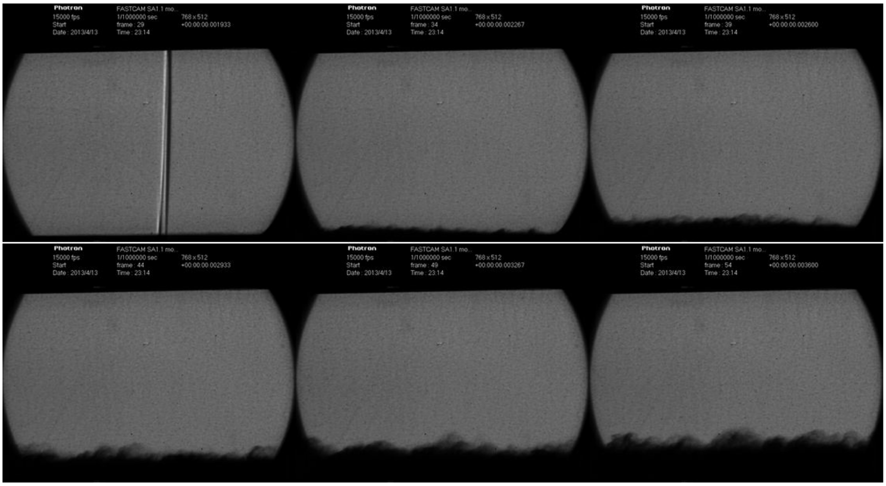

Fig. 3 Images of air and limestone dust (40 μm) interaction in the flow behind a shock wave with M = 1.2. The dust layer was 3.2 mm deep, and the time difference between the images shown is 333 μs for a 15,000 fps frame rate and 10-μs exposure time.

4 Conclusion

To ensure safety regarding dust explosion hazards, it is important to study the dust lifting process experimentally and identify important parameters that will be valuable for development and validation of numerical predictions of this phenomenon. A new shock-tube test section was developed which allows for shadowgraph or laser scattering techniques to track dust layer particle motion with respect to shock wave propagation. The test section was designed to handle an initial pressure of 1 atm with an incident shock wave velocity up to Mach 2 to mimic real-world conditions. Initial characterization experiments have been performed, and some of the results were presented in this paper.

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