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Towards Particle Image Velocimetry Measurements during Shock-Particle Curtain Interactions

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1 Introduction

Shock-induced particle transport is critical in many multiphase phenomena including heterogeneous detonations, where solid particles are initially mixed with explosive material [1]. In these applications solid particles are densely distributed in a gas-solid flow resulting in complex dynamics.

To gain understanding of the particle dynamics associated with multiphase detonations, a multiphase shock tube (MST) has been used to obtain data of particle transport in compressible, dense gas-solid flows [2]. This was accomplished by driving a planar shock wave into a dense ‘particle curtain’ of 115-micron glass spheres having an initial volume fraction of about 20% and measuring the subsequent particle transport with high-speed pressure data and time-resolved schlieren imaging. The data showed that following the impingement of the incident shock, the particle curtain propagated downstream while spreading more rapidly than was predicted by standard drag laws. Ling et al. [3] used the MST data to validate new drag models and were able to show that dense particle distributions lead to a significant increase in interphase momentum transfer and a prolonged flow unsteadiness.

Flash radiography has also been applied in the MST to overcome the optical opacity of the dense particle curtain towards visible light. The diagnostic was able to quantify the spatial evolution of the particle curtain as it spread and propagated downstream at five different times during the shock-particle interaction [4]. However, flash x-ray systems are inherently limited to one shot per shock tube experiment, which puts practical limits on the temporal information to be gained from such experiments.

Spatially and time-resolved data during shock particle interactions are ultimately required to understand and quantify the interphase momentum transfer between the gas and particles. To date, experiments in the MST have mostly focused mostly on measurements of the solid particles within the curtain.

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Though valuable, the diagnostics used thus far have been not been able to quantify the interphase momentum transfer. Specifically, spatial information within the optically dense particle curtain was not possible with the high-speed schlieren imaging and the flash x-ray data lacked temporal resolution.

Measurements of the gas phase provide an alternative towards overcoming these obstacles. A particularly attractive option is particle image velocimetry (PIV), which can provide spatially and temporally resolved gas velocity data in high-speed compressible flows [5]. The current paper describes progress towards time-resolved PIV measurements of the gas phase during shock particle interactions. Time-resolved PIV of the transients within the empty shock tube is first presented. PIV measurements during shock-particle interactions using a conventional 10-Hz PIV system follow. The end goal is to make time-resolved PIV measurements during shock-particle interactions, though such data are beyond the scope of the current paper.

2 Experimental Program

A schematic and photo of the multiphase shock tube are shown in Fig. 1. The driver section is made from pipe with an inner diameter of about 89 mm and the driven section consists of square tubing with an inner width of about 76 mm. Measurements [2] have shown the shock to be planar upon arrival at the test section. Experiments were conducted at shock Mach numbers M_s of 1.44 and 1.68. The driven gas was air at an initial temperature of about 300 K and an initial atmospheric pressure of about 84.1 kPa.

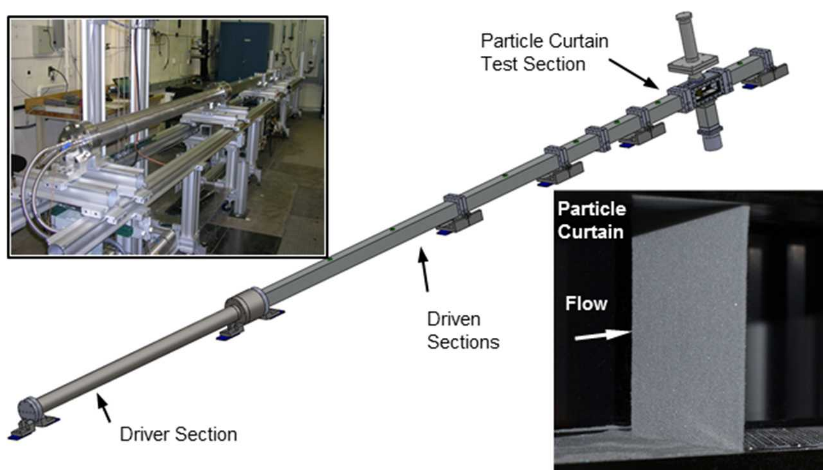

Fig. 1 The multiphase shock tube (MST) and the particle curtain made up of 100-micron glass spheres at a volume fraction of about 21%

The unique aspect of the MST is its ability to provide multiphase flows within the dense gas-solid regime by introducing a gravity-fed particle curtain. Prior to an experiment, soda lime particles sieved to a diameter distribution of 106-125 microns rest on an initially closed gate valve. The gate valve opens and the particles flow through a beveled slit in the test section ceiling. The particles exit the test section through a similar slit in the floor and then enter a particle collector reservoir. The shock tube is fired after the particle curtain flow stabilizes after about 100 milliseconds. The slit has a spanwise width of 68.6 mm, or about 87% of the test section width, with streamwise thickness 3.2 mm. The gravity-fed seeding apparatus shapes the particles into what is termed the particle curtain, which narrows to a streamwise thickness of about 2 mm for the bottom 75% of the test section height. Figure 1 shows a photo of the particle curtain acquired at an oblique angle. Under the assumption of a uniform particle distribution, the particle volume fraction has been measured to be about 20% at the center of the curtain. The particles flow at a velocity of about 0.9 m/s, which makes them essentially frozen compared to the shock velocities.

Previous PIV measurements in shock tubes have typically been limited to low repetition rates allowing for only one realization to be obtained in the millisecond test times of a shock tube [1]. Recent advances and the commercialization of pulse-burst laser technology, however, have made time-resolved PIV in high-speed flows [2] a feasible and attractive option to overcome this limitation.

Here, time-resolved PIV measurements of the baseline shock-induced flow are made as a first trial of the diagnostic in the MST. A Quasi-Modo (Spectral Energies, LLC) burst-mode laser fired at a repetition rate of 50 kHz provided the light source at 50 mJ per pulse. The duration of the burst was 10.2 ms, which is greater than the typical test times in the MST. The laser was operated in a doublet mode where the separation time between each pulse of the doublet could be varied to produce the appropriate displacements. Typical separation times were about 2 μs. Seed particles were produced using a TSI fog generator. Typical sheet-forming optics were used to shape the 1.5-mm thick laser sheet shown in Fig. 2a. Two Photron (SA-Z) cameras were placed side-by-side to extend the field-of-view while maintaining spatial resolution. Each camera was operated at 100 kHz to frame-straddle the 50 kHz doublets. The pixel resolution

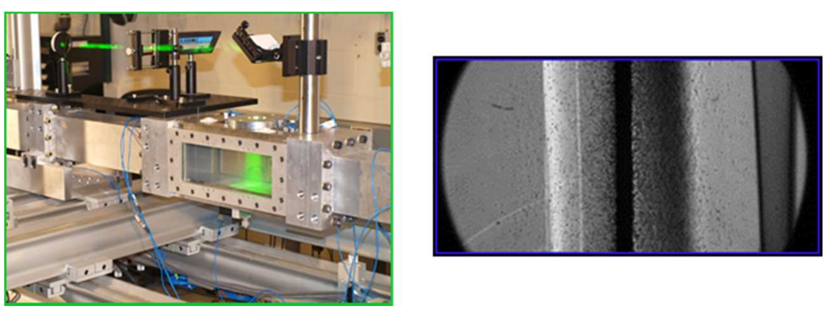

Fig. 2 **(a)** Laser sheet in the baseline (empty) MST test section. **(b)** Schlieren image following the impingement of a Mach 1.66 shock wave [2]. The flow is left-to-right, the curtain (image center) is seen in shadow reflected (white) and transmitted (black) shocks are observed.

of each camera was 680 × 340. The PIV images were processed with the LaVision (Davis 8.2) software package to a final interrogation window of 24 × 24 pixels^2 (1.8 × 1.8 mm^2) with a 50% overlap between windows.

A 20-Hz PIV system was also used to make preliminary gas velocity measurements during a shock-particle curtain interaction. In this case, the laser source was a Litron (Nano S Piv). A single Redlake (Megaplus ES4.0) having a resolution of 2048 × 2048 pixels^2 imaged an interaction region upstream of the particle curtain. As shown in Fig. 2a, the reflected shock will propagate through this imaging area. The final interrogation window for the 20-Hz data was 32 × 32 pixels^2 (0.8 × 0.8 mm^2) and the final vector field used a 50% overlap.

3 Results and Discussion

Streamwise velocity u contours obtained upstream of a M_s = 1.44 shock-particle curtain interaction are shown in Fig. 3. The coordinate origin corresponds to the streamwise and wall-normal center of the curtain. Each

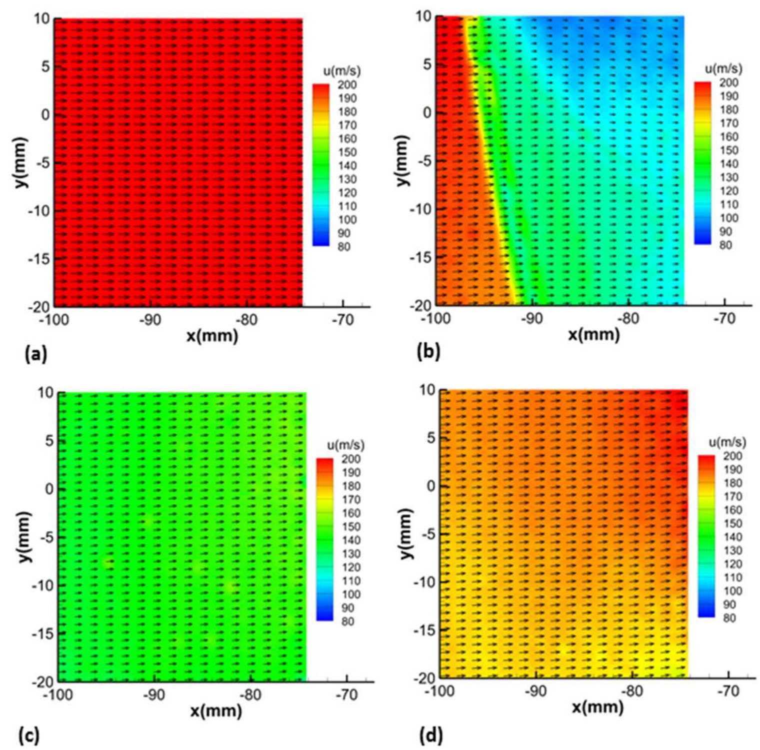

Fig. 3 Streamwise velocity contours and vectors obtained upstream of the interaction of a Mach 1.44 shock wave with the dense particle curtain. Flow is left-to-right. **(a)** t_i = -0.04 ms. **(b)** t_i = 0.11 ms. **(c)** t_i = 0.36 ms. **(d)** t_i = 1.16 ms.

subfigure was obtained from a separate shock tube shot using the 20-Hz PIV system at interaction times t_i ranging from -0.04 ms – 1.16 ms, where t_i = 0 corresponds to the impingement of the incident shock on the curtain. These first data were obtained using a wider than normal particle diameter distribution of about 88 µm – 149 µm and a greater than normal particle buildup was present on the floor upstream and downstream of the curtain prior to a test. These data are therefore considered preliminary, but are nevertheless, useful for proof-of-concept purposes and to identify overall trends. At t_i = -0.04 ms (Fig. 3a), the incident shock has propagated through the field-of-view resulting in a nearly one-dimensional core flow having velocity of about 220 m/s. 0.15 ms later (Fig. 3b), the curtain-reflected shock has traveled through most of the vector field and the streamwise velocity slows to a minimum of about 100 m/s. With continuing time, the streamwise velocity accelerates to roughly 145 m/s at t_i = 0.36 ms (Fig. 3c) and to about 180 m/s at t_i = 1.16 ms (Fig. 3d). This acceleration likely occurs with an equilibration in flow properties across the streamwise width of the curtain, which has been measured to occur in the interaction pressure field [2].

Streamwise velocity contours obtained with the time-resolved PIV system during a M_s = 1.68 experiment in the empty shock tube are shown in Fig. 4. In

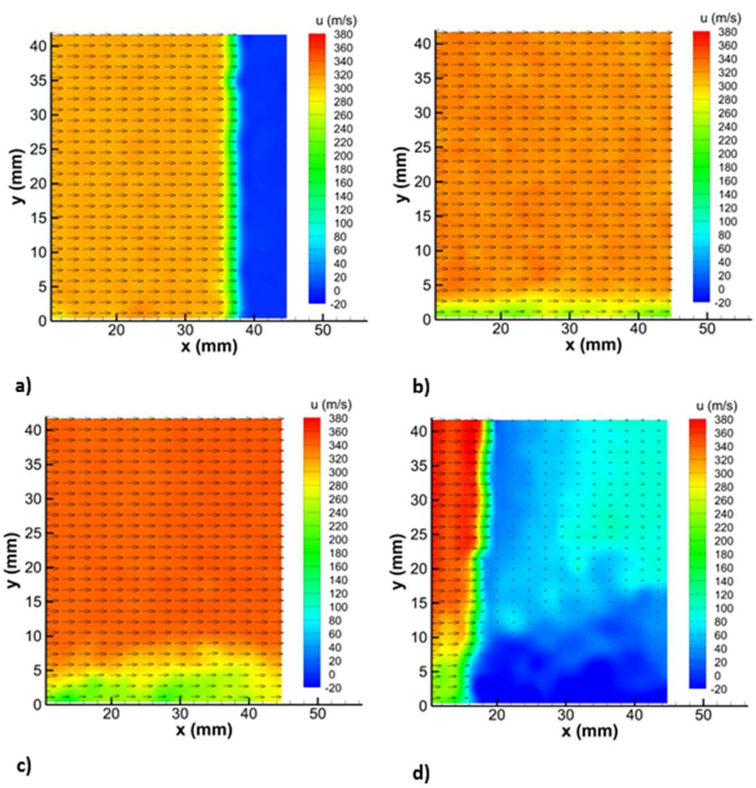

Fig. 4 Streamwise velocity contours and vectors obtained in a M_s = 1.68 shock-induced flow. Flow is left-to-right. **(a)** t = 0.02 ms. **(b)** t = 0.82 ms. **(c)** t = 1.64 ms. **(d)** t = 2.84 ms.

this case, the coordinate origin is at the lower wall and the field-of-view extends just past the wall-normal center of the test section (y = 39.6 mm). Time t = 0 is defined to occur when the incident shock in the streamwise center of the field-of-view. In Fig. 4a, the incident shock has propagated through most of the field inducing a one-dimensional flow having velocity of about 315 m/s. The relaxation distance through this shock wave gives a seed particle size of about 1.3 µm. 0.8 ms later (Fig. 4b), boundary layer growth on the lower wall is evident and by t = 1.62 ms (Fig. 4c) the boundary layer has thickened further. Finally at t = 2.84 ms (Fig. 4d), the end-wall reflected shock has traveled through most of the field-of-view, resulting in reverse flow at y = 0.

The centerline flow velocity (averaged over y of 30 mm – 42 mm) is shown in Fig. 5a as a function of time. Following the incident shock (t = 0), the centerline velocity increases by about 20% prior to the arrival of the reflected shock at t = 2.84 ms. Streamwise velocity profiles, averaged over the entire streamwise domain, and obtained at six different times are given in Fig. 5b, where it can be seen that the 99% boundary layer thickness increases from about 3 mm at 0.1 ms to about 13 mm at 2.4 ms. The increased core velocity over time is likely explained by this boundary layer growth [5].

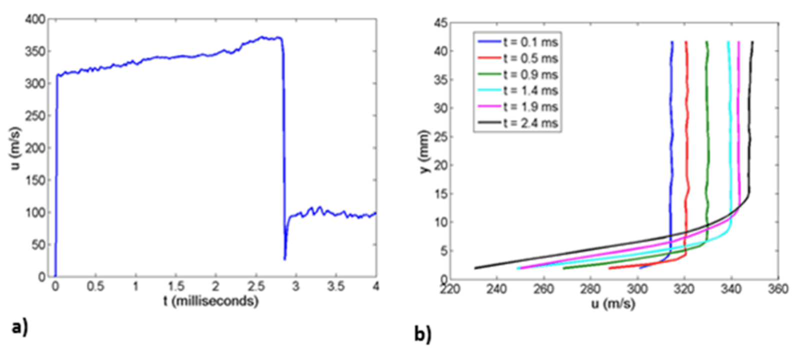

Fig. 5 **(a)** Core velocity in the M_s = 1.68 shock-induced flow as a function of time. **(b)** Streamwise velocity profiles at six different interaction times.

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