

Photon Doppler Velocimetry Measurements of Shock Wave - Particle Curtain Interactions

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ABSTRACT

Single wavelength Photon Doppler Velocimetry measurements of shock interactions with both mono and polydisperse particle curtains are performed in the LANL Horizontal Shock Tube. Measurements in the monodisperse case are validated using planar Mie scattering and time-resolved shadowgraphy. Shadowgraphy data is also used to estimate span-wise averaged volume fraction in the monodisperse case. These validated measurements are used to calculate a high time-resolution estimate of particle drag and particle Reynolds number in a low volume fraction and low Mach number regime.

1. Introduction

Photon Doppler Velocimetry (PDV) (Moro, 2014) is routinely used for velocity measurements of high-speed surfaces where a reflecting surface is easily identified. PDV uses widely available components developed by the telecoms industry that enable the construction of measurement systems using off the shelf parts (Strand III, 2020). PDV is a technique that is typically fielded using fiber optic collimators as both the probe source and the collecting detector. Continuous laser light is launched along a line of sight, and Doppler-shifted reflections are collected from along that line of sight back to the original fiber optic probe. The collected light is mixed with either the original laser light source (homodyne) or one with a slight baseline shift (heterodyne) to avoid self-correlation at zero velocity. The mixed light interferes to create a lower-frequency beat pattern which can be recorded on a high speed digitizer, and the signal can be analyzed using Fourier transforms to recover the summed velocity signal of all reflected sources along the line of sight.

In experiments where particles are present, such as when ejecta are launched from surfaces undergoing shock acceleration (Ling et al., 2024; Izard et al., 2018), the signal that is measured by PDV can become difficult to interpret. At high particle volume fractions an outward signal leaving a probe now undergoes multiple scattering events, where the signal experiences a doppler shift at each scattering event that changes the frequency as a function of the relative velocity between particles. The signal that a PDV probe receives will now have a frequency content that is spread out and potentially shifted such that the true velocity is not identifiable (Don Jayamanne et al., 2024).

These effects have motivated the pursuit of a simplified way to explore PDV measurements of particle clouds in a controlled environment. The goals of this work are three-fold. The first goal is to develop a high repetition rate experiment platform for shock-particle curtain interaction that can validate PDV as a measurement of particle cloud velocities. The second goal is to probe the physics of post-shock particle motion as a function of shock strength, volume fraction, and particle properties. The third goal is to develop and validate a multi-wavelength PDV system to enable measurements through particle clouds while simultaneously inferring cloud properties. This paper will focus on the first and second goals.

The experiments described here employ multiple diagnostics to characterize the particle curtain and validate PDV measurements. Time-resolved shadowgraphy provides an estimate of volume fraction in low volume fraction cases assuming single scattering. Multi-frame planar Mie scattering allows Particle Image Velocimetry (PIV) to extract velocity distributions. Three PDV probes positioned at different heights downstream of the particle curtain use independent heterodyne channels for simultaneous velocity measurements.

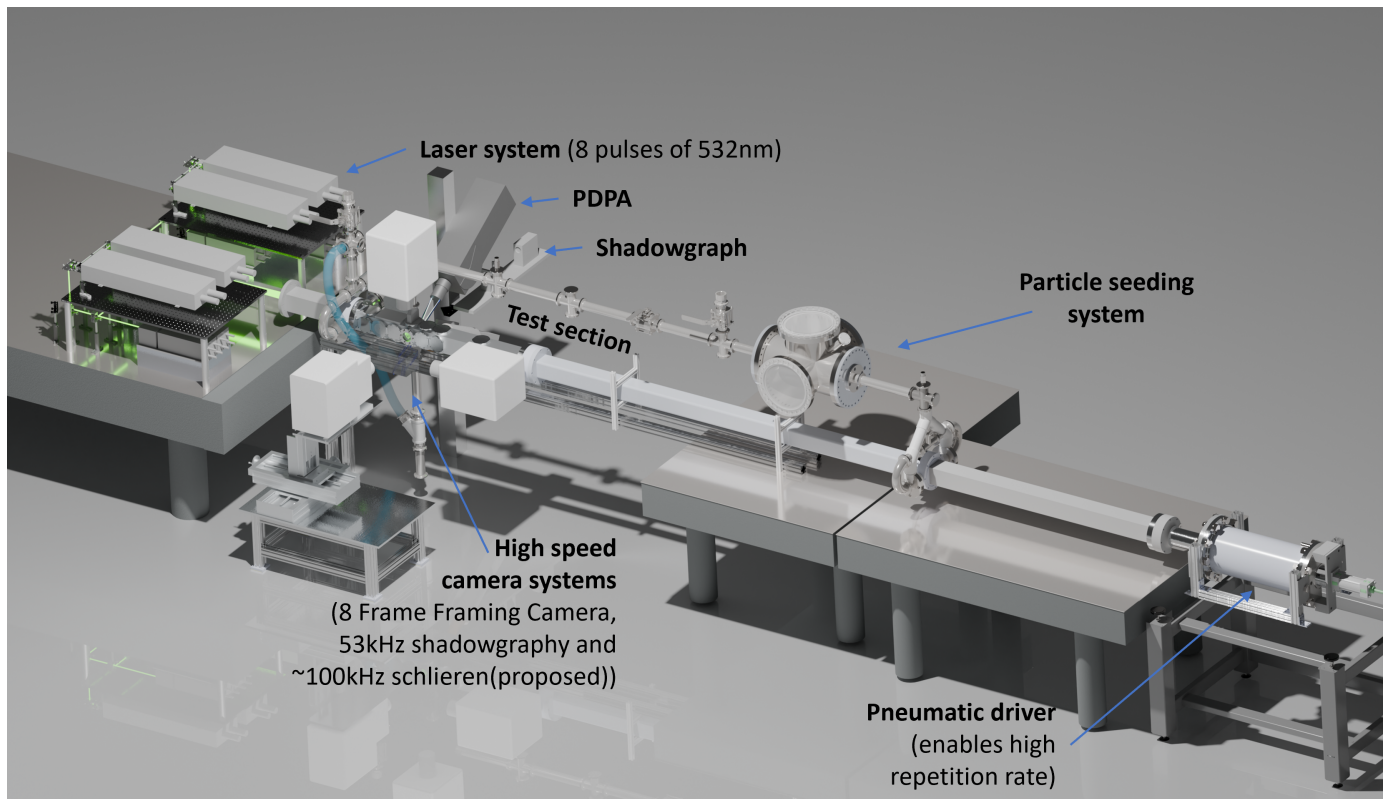


Figure 1. Horizontal Shock Tube Experiment layout. The laser system generates 8 pulses that are shaped into co-aligned laser sheets to enable planar Mie scattering measurements. The test section, where the particle curtain is injected, has optical access with a set of three cameras aligned with two beam splitters allowing each camera to share the same field of view. The shadowgraph system is composed of a 5mW 532nm continuous wave laser, a spherical lens, a pinhole and a parabolic mirror to generate a 3in diameter collimated beam. The pneumatic driver system generates a shock wave and enables a high rate of experiments.

2. Methodology

The horizontal shock tube (HST) (Martinez et al., 2014) at the Los Alamos National Laboratory (LANL) is shown in Fig. 1. The shock tube has been modified to enable experiments exploring particle curtain–shockwave interactions. Previous work in the HST, reported by Bordoloi et al. (2017), has focused on monodisperse (single size) individual particle drag behavior. The facility has been modified to enable the creation of a localized particle curtain.

The initial condition, shown in Fig.2, is a 3mm wide particle curtain in ambient air. This is generated using a powder spray gun with pressurized air. The flow rate through the gun controls the amount of particles that become entrained in the flow, thereby controlling the volume fraction, though we are limited to low volume fractions using this injection method.

The experiments use an array of diagnostics: Pressure transducers, PDV, multi-frame planar Mie scattering and time-resolved shadowgraphy.

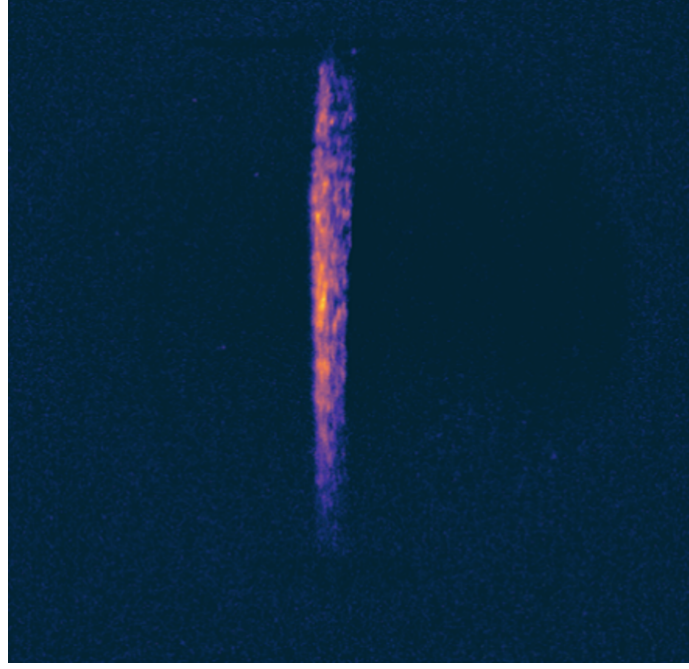


Figure 2. Experiment initial condition showing a planar Mie scattering image of the 3mm wide particle curtain.

Pressure transducers are located along the test section to record the passage of the incident shock and the reflected shock. The incident shock strength can be found and the resulting thermodynamic state can be estimated from 1D gas dynamics relations.

Three PDV probes are mounted downstream of the particle curtain. They are mounted at the centerline of the shock tube and they are vertically separated with their approximate line of sight shown in Fig. 3. A Quantifi photonics PDV system is used to generate three separate pairs of target laser signals at 1550 nm and reference signals at 1550.004 nm. The target signals are emitted by the PDV probes toward the curtain. The Doppler shifted signal received by each probe is coupled with the reference signal and then sent to a digitizer. The resulting electrical signal is read by a 5 GS/s oscilloscope. A windowed fast Fourier transform is applied to the resulting signal; this creates a spectrogram where the frequency axis is transformed to velocity using the relation (Strand III, 2020):

$$v = \frac{\lambda_0}{2} ((f_d - f_{ref}) - (f_0 - f_{ref})) \quad (1)$$

where λ_0 is the wavelength of the target laser, f_d is the Doppler shifted frequency that is received by the probe, f_{ref} is the frequency of the reference laser that the returned Doppler shifted signal is combined with, and f_0 is the target laser frequency.

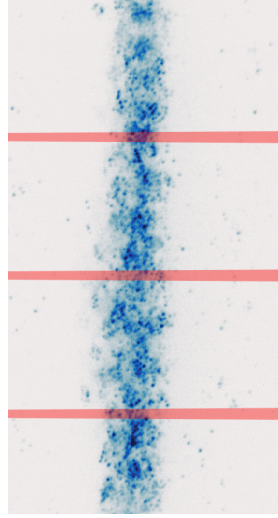


Figure 3. A characteristic first planar Mie scattering frame shortly after initial shock interaction with the estimated line of sight of the three PDV probes overlaid. (Both are false color and contrast enhanced)

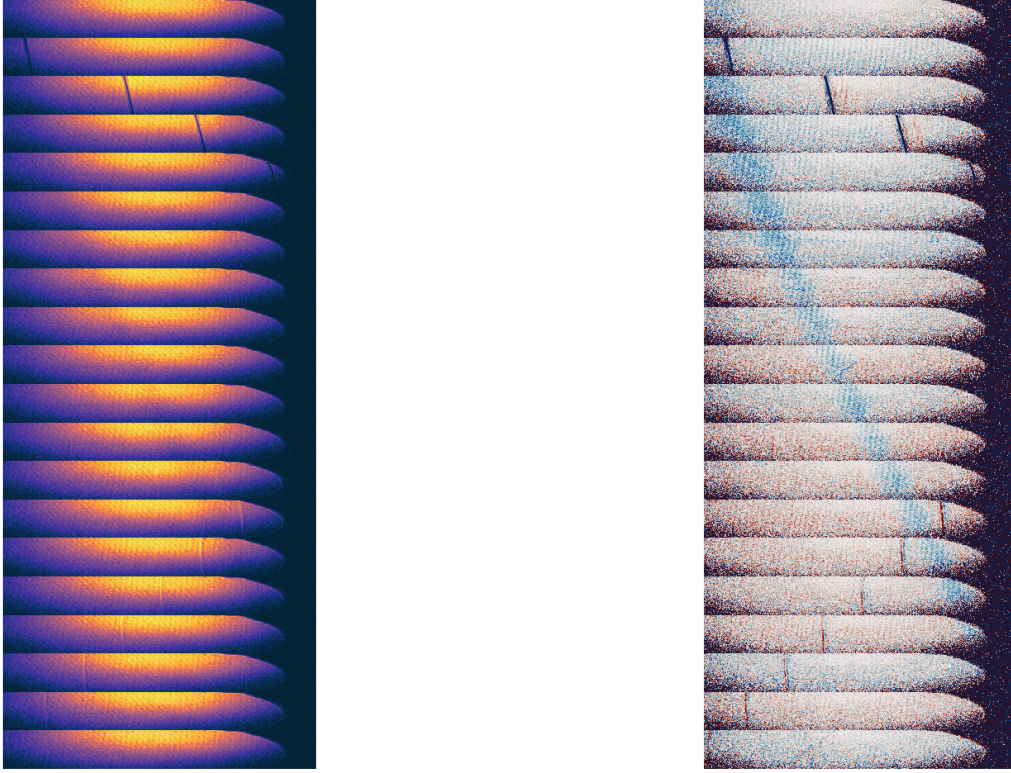
Simultaneously, multi-frame planar Mie scattering is used to capture the spatial structure of the curtain offset from the centerline of the shock tube over time to enable the use of Particle Image Velocimetry (PIV) to extract baseline velocity distributions for comparison to the PDV measurements. A Specialized imaging 16-frame framing camera is used to capture light from 8 laser pulses. These pulses are generated by 4 dual head 532 nm Nd:YAG lasers and they are formed into a laser sheet by a set of beam forming optics.

Time-resolved shadowgraphy is used to characterize the shock-curtain interaction, measure shock speed, and estimate volume fraction. This setup uses a Phantom V2640 at 53,000 fps to capture images every $18.8 \mu\text{s}$. A Thorlabs 5mW 532 nm CW laser is used as a coherent light source, this is passed through a spherical lens through a $20 \mu\text{m}$ pinhole and then reflected off a 3 in parabolic mirror to produce an approximately 3 in diameter collimated beam that passes through the test section of the HST.

Figure 4 shows tiles of image frames, Fig. 4 a) shows the time evolution of raw shadowgraph frames while Fig. 4 b) shows $(I(x, y, t) - I_0(x, y)) / I_0(x, y)$ highlighting the drop in signal due to the presence of the particle curtain. The incident shock can be clearly seen traveling from left to right in frames 2, 3 and 4 and a weak wave can be seen from frame 14 onward traveling right to left that is a reflection of the incident shock off the PDV mount.

If we know the material properties of the particle cloud, specifically the scattering cross-section σ_{sca} , we can approximate the number density by measuring the drop in signal due to single scattering events (KERKER, 1969):

$$I/I_0 = \exp(-N\sigma_{sca}L) \quad (2)$$



(a) Tiled raw shadowgraph frames, with time evolving from top to bottom (b) Tiled background subtracted and normalized shadowgraph frames, with time evolving from top to bottom

Figure 4. Time evolution of an example a) raw and b) processed shadowgraph measurement. The innerframe time is $18.9\mu\text{s}$ with the total time shown approximately $378\mu\text{s}$.

such that we can calculate the number density N averaged over the width L of the shock tube. The span-wise averaged number density N , averaged over the height of the shock tube, is shown in Fig. 5. If we know the volume of a single particle, we can then estimate the volume fraction of the particle curtain.

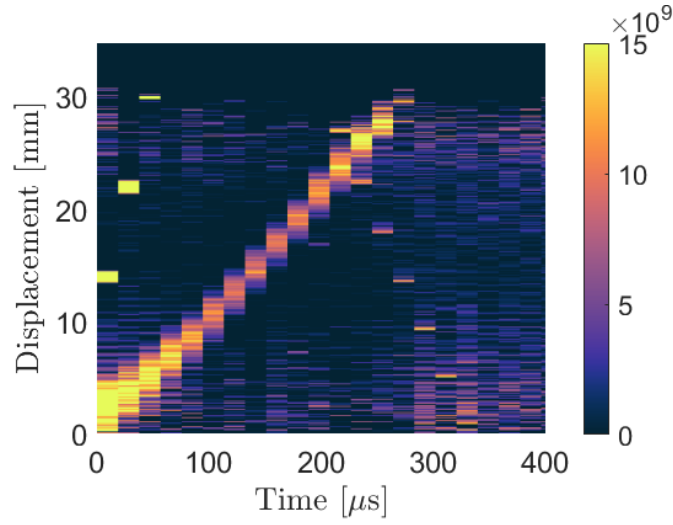


Figure 5. Spanwise-averaged number density N as a function of time and location in the shock tube viewing window

Performing a windowed fast Fourier transform on the signal from PDV measurements leads to a spectrogram that shows the intensity of the signal at a given frequency as a function of time. Using Eq. 1, the raw spectrogram (Fig. 6a) can be transformed from frequency space to velocity space accounting for drift in f_0 and f_{ref} . This is shown in Fig. 6b.

Specifying a region of the spectrogram that is free of a measured signal allows the construction of an empirical PDF. A windowing operation can then be performed that calculates the KL divergence between the empirical PDF of the signal intensity within the window and the empirical noise PDF (Anderson & Haas, 2011).

$$A_{signal,ij} = \mathcal{D}_{KL}(P_{signal,ij} || P_{noise}) \quad (3)$$

where the indices i and j denote the window indices. This divergence can then be used as a mask to identify the true signal. Figure 6c shows masked spectrograms that extract PDV signal from the

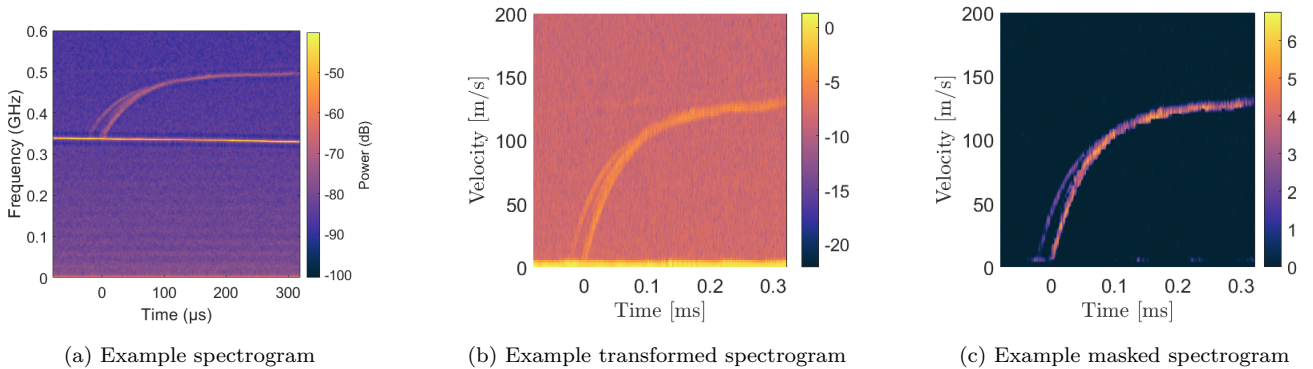


Figure 6. Time evolution of an example a) raw, b) processed and c) masked shadowgraph measurement

background noise.

3. Results

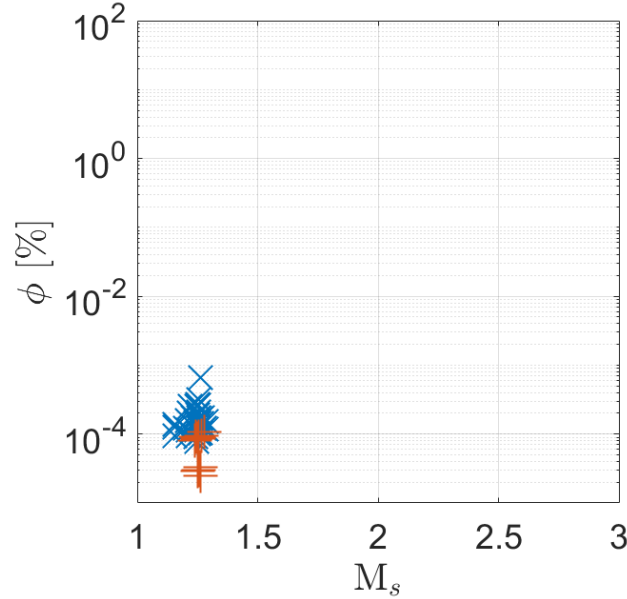


Figure 7. Mach number and particle volume fraction parameter space showing the grouping of current experiments in the low Mach and low volume fraction region. Crosses denote monodisperse experiments and plusses denote polydisperse experiments.

Initial experiments have explored the very low volume fraction and low Mach number regime (Fig. 7 shows the volume fraction and mach number phase space we are aiming to explore) to enable validation of PDV measurements and test the experimental setup. Two sets of experiments were conducted with different distributions of particle diameters: monodisperse (using PMMA plastic spheres) and polydisperse (using EMB10 glass spheres) particle curtains. The diameter of the PMMA particles approximately follow a normal distribution with a mean of $7.9 \mu\text{m}$ and a standard deviation of $0.1 \mu\text{m}$ and the diameter of EMB10 particles approximately follow a lognormal distribution with mean $4.6 \mu\text{m}$ and a standard deviation of $2.4 \mu\text{m}$.

Figure 8 shows a comparison of results for representative mono- and polydisperse experiments. Mie scattering (Fig. 8(a,b)) shows the stratification due to differential drag experienced by particles of different sizes. Ensembles of particle trajectories (Fig. 8(c,d)) based on the measured particle size distributions and initial particle curtain width provide an expected set of traces for comparison to the experimental results. The monodisperse case shows a very tight velocity trajectory, which is matched by the PDV traces. The polydisperse case shows a very broad set of velocity trajectories. The PDV results (Fig. 8(e,f)) in this case do show a broader set of velocity trajectories, however we don't see the very fastest or slowest predicted trajectories. These experiments were conducted with converging PDV probes so the low volume fraction and reduced line of sight may contribute to missing these traces if they truly exist. The scattering signal at these particle sizes may also

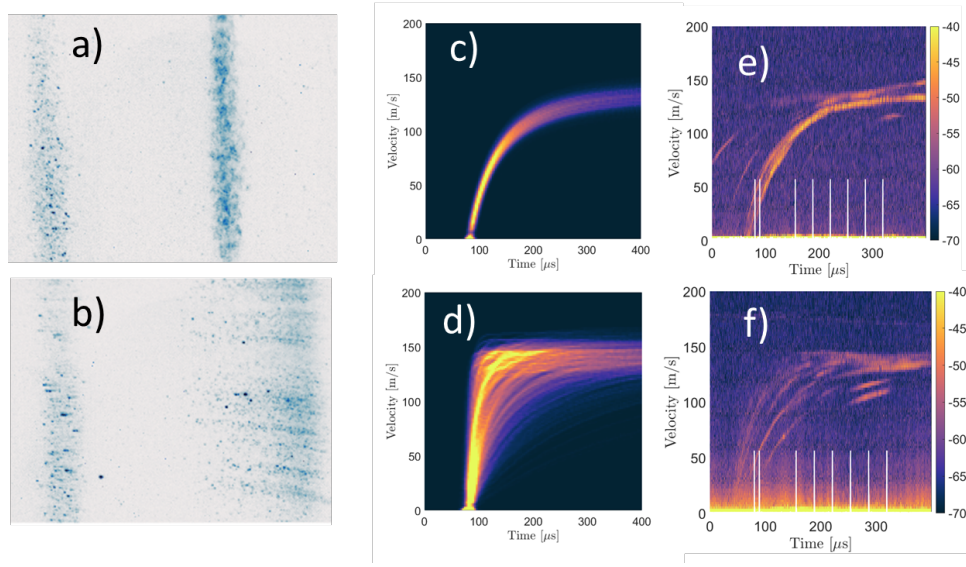


Figure 8. Comparison of experiment results between monodisperse (a,c,e) and polydisperse (b,d,f) particle curtain experiments. Mie scattering frames 1 and 8 are shown together (a,b). An ensemble of Parmar particle trajectories predicted using the known distribution of particle sizes are shown (c,d). Example PDV spectrograms are displayed with the timing of the 8 Mie scattering frames shown as white tick marks on the time axis (e,f).

contribute to not seeing these extremes; adding probes with different wavelengths may allow us to investigate this.

Figure 9 shows the compilation of three diagnostics for one example monodisperse experiment: PDV, Mie scattering, and shadowgraphy. The plots show the trajectory of the center of the particle curtain as a function of time. Figure 9a shows the motion of the centerline of the curtain which is manually extracted from all three diagnostics. Figure 9b shows a probabilistic integration of the PDV signal, treating each time step as independent velocity and displacement distributions. This treats finding displacement as a forward Euler integration of velocity

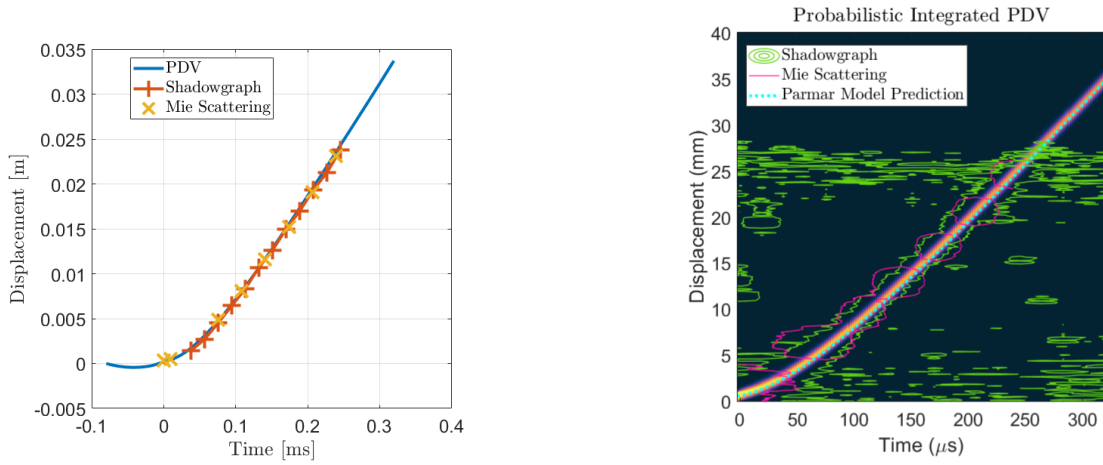
$$x_{n+1} = x_n + v(t_n)\Delta t \quad (4)$$

such that the probability density of displacement at timestep $n + 1$, $P_{X_{n+1}}(x_{n+1})$, can be written as a convolution between the probability density of displacement at timestep n and the probability density of velocity at timestep n

$$P_{X_{n+1}}(x_{n+1}) = \int_{-\infty}^{\infty} P_{X_n}(x) P_{v_n}\left(\frac{x_{n+1} - x}{\Delta t}\right) dx \quad (5)$$

The PDF of velocity is calculated from the spectrogram, with intensity used as an empirical PDF.

The probabilistic displacement is overlaid with contours of height averaged signal from Mie scattering and Shadowgraphy. With the agreement between the three diagnostics, PDV measure-



(a) Displacement of the center of the particle curtain as a function of time comparing estimates from the three implemented diagnostics.

(b) Compilation of probabilistic displacement calculated from from PDV spectrogram, contours of shock-tube height averaged Mie scattering intensity contour and shock-tube height averaged number density contour for a representative monodisperse experiment.

Figure 9. Example results showing the corroboration of PDV measurements of particle displacement (indirectly by measurement of particle velocity) by both Mie scattering and shadowgraph measurements. a) shows comparison of curtain centerline trajectory which was extracted from PDV results by extracting the velocity trajectory by hand and performing numerical integration. b) instead shows a probabilistic integration treating the spectrogram intensity as a PDF and each time step as an independent distribution.

ments can be used to estimate drag and particle Reynolds number. In this work the PDV signal is recorded at 2 GHz.

With PDV measurements corroborated by both Mie scattering and shadowgraphy diagnostics, the high time resolution PDV measurements can be used to estimate drag. Figure 10 shows an ensemble of drag–Reynolds number curves from a set of ~ 20 monodisperse experiments. The velocity profiles for each experiment were extracted from the corresponding PDV spectrogram and then numerically differentiated to calculate the drag coefficient and Reynolds number as function of time using

$$C_D = \frac{4}{3} \frac{\rho_p}{\rho_g} \frac{\ddot{x}_p}{(u_g - \dot{x}_p)^2} \quad (6)$$

$$Re_p = \frac{\rho_g d_p |u_g - \dot{x}_p|}{\mu_g} \quad (7)$$

where d_p is the particle diameter, ρ_p is the particle density, ρ_g is the post-shock gas density, u_g is the post-shock bulk gas velocity, μ_g is the post-shock gas viscosity and $\dot{x}_p$ is the instantaneous particle velocity from PDV. $\ddot{x}_p$ is the particle acceleration.

The pink dotted curves in Fig. 10 correspond to the maximum ($9\mu\text{m}$) of the monodisperse (PMMA) particle size distribution and the green dashed curves correspond to the minimum ($7\mu\text{m}$). The

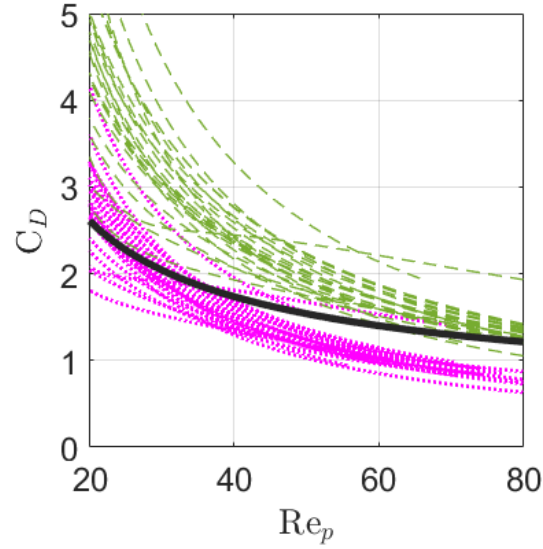
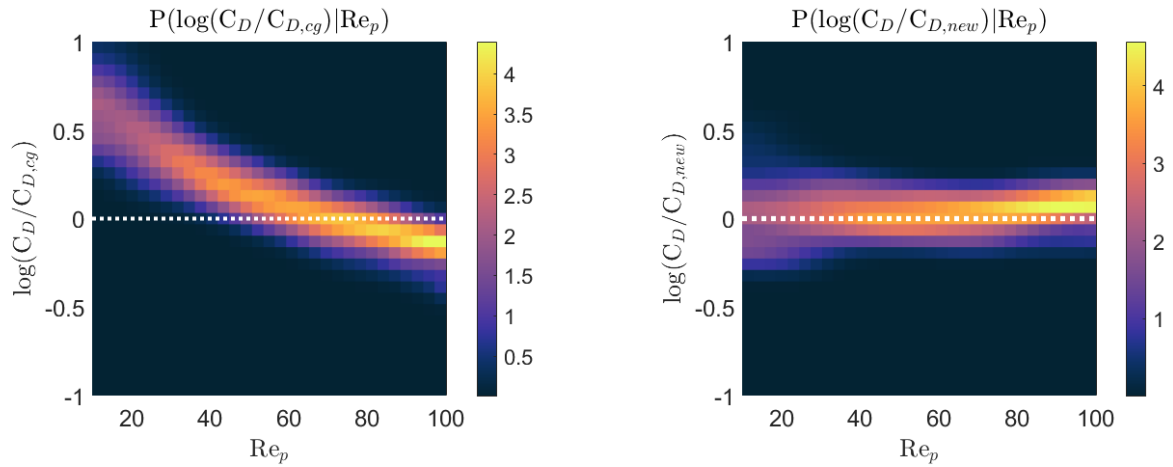


Figure 10. Ensemble of drag curves from 20 experiments derived from PDV measurements, accounting for the lack of knowledge of what given particles the PDV probes may be seeing. Green dashed lines correspond to the maximum particle size ($9 \mu\text{m}$) and pink dotted line correspond to the minimum particle size ($7 \mu\text{m}$). The black solid line is the standard drag curve (Eq. 8)



(a) Conditional PDF of the ratio of measured drag coefficient to predicted standard drag for a given particle Reynolds number.

(b) Conditional PDF of the ratio of measured drag coefficient to predicted new drag for a given particle Reynolds number.

Figure 11. Conditional PDFs of normalized measured particle drag for a given measured particle Reynolds number.
a) Normalization is the standard drag (Eq. 8), b) Normalization is the proposed drag (Eq. 9)

uncertainty in particle size for a given particle size is the main source of uncertainty in this drag measurement. If the true particle trajectories observed by PDV correspond to particles with the mean size, the observed drag is approximately 30% higher than the nominal standard drag (black curve) proposed by Parmar et al. (2009) between $Re_p = 20$ and $Re_p = 50$. The Parmar model is a modification of the Clift & Gauvin (1971) quasi-steady drag equation that includes modifications for high volume fraction and high Mach number regimes. In this work these modifications are negligible.

Following Clift & Gauvin (1971), the standard quasi-steady drag takes the form:

$$C_D(Re_p) = \frac{24}{Re_p} \left(1 + 0.15Re_p^{0.687}\right) + \frac{0.42}{1 + \frac{42500}{Re_p^{1.16}}} \quad (8)$$

Figure 11a shows the conditional PDF of the ratio of measured drag to CG standard drag (Eq. 8) for a given particle Reynolds number. A value of zero would indicate that the measured drag is exactly predicted by the CG drag. The conditional PDF shows a divergence from standard drag that agrees with Martinez et al. (2014). Using the ensemble of approximately 20 monodisperse experiments a new proposed model for post shock particle drag takes the form:

$$C_D(Re_p) = 14.44e^{-0.109Re_p} + 3.32e^{-0.014Re_p} \quad (9)$$

Figure 11b shows the conditional PDF of the ratio of measured drag to the proposed drag model (Eq. 9). This shows a stronger agreement.

4. Conclusions

The horizontal shock tube at LANL has been modified to enable shock – particle curtain experiments. Planar Mie scattering and shadowgraph diagnostics have been deployed to validate photon Doppler velocimetry measurements. Monodisperse particle curtain experiments show excellent agreement between PDV, Mie scattering and shadowgraph measurements of particle trajectories. Validated PDV measurements at low volume fraction enable high time resolution measurements of particle drag leading to improved estimates of drag coefficients and particle Reynolds number showing behavior consistent with previous single particle experiments that showed higher drag than predicted by standard drag models. Polydisperse particle curtain experiments were also performed that show the stratification of particles as a function of particle size, though the resulting PDV measurements do not show the expected range of trajectories, pointing to changes, such as increased PDV probe divergence, that can be implemented in the experimental setup for the low volume fraction regime. Future work will move toward higher volume fraction particle curtains and higher Mach number shocks.

Nomenclature

λ_0	Target Laser Wavelength [m]
f_0	Target Laser Frequency [m^{-1}]
f_{ref}	Reference Laser Frequency [m^{-1}]
f_d	Doppler Shifted Laser Frequency [m^{-1}]
N	Particle Number Density [$\#/\text{m}^3$]
σ_{sca}	Mie Scattering Cross-section [m^2]
C_D	Particle Drag Coefficient [-]
Re_p	Particle Reynolds Number [-]

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