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PDV experiments on shock-loaded particles

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Abstract. We present results from PDV (Photonic Doppler Velocimetry, also known as HetV - Heterodyne Velocimetry) experiments in which particles are ejected from shock-loaded metallic plates. The shocks induced in the samples are generated using high-explosive plane-wave generators. We manage to accelerate calibrated particles placed in the spot facings of a metal transmitter. These micron-sized spherical particles are made of copper or gold. The slowing down of the particles in air is observed; using their dragging behavior, we can therefore roughly infer both initial velocity and diameter distributions.

1. Introduction

A shock-loaded plate can undergo a variety of damages at its rear face such as spalling or ejection of particle clouds. The crossing of release waves is responsible for spalling. Several failure criteria exist such as Cut-off, Tuler-Butcher [1] or Kanel [2]. In case of particle-cloud production, two main mechanisms are responsible: microjetting (solid particles resulted from jets of hollow microcharges due to the machining grooves as presented in figure 1) [3] and the induced melting of the material [4]. These particles may reach velocities up to a dozen of kilometers per second. These mechanisms are not fully theoretically predicted yet but some models exist [5-8]. When hydrodynamic codes fail to simulate (too) small microcharges and their fragmentation, approaches based on molecular dynamics are used to model microjetting in very small samples (around 100 nm in dimension) [8, 9]. Because of these difficulties, experiments are often required to estimate the generation of particles in Shock Physics.

![Figure 1. Schematics of the microjetting process.](image-url)

The particular case of tin microjetting has already been experimentally studied: melting in release [10], particle-size distribution [11], ejected mass [12], density and cloud velocity [13]. The large number of diagnostics is a consequence of the inverse problem difficulty; additional data are...

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needed to further constraint the particle source-term. Now, developments are mainly focused on Photonic Doppler Velocimetry (PDV) diagnostic [14] which provides access to the time-resolved velocity distribution within the particle cloud. Our first trials began in 2007 with tin microjetting [15].

Because of this lack of knowledge on particle-microjetting source-terms and transport into gases, we designed new experiments in which microjets are replaced by size-, matter- and shape-calibrated particles. This kind of experiments, as described in the present paper, would contribute to validate or reject particle-cloud dragging and photometric models. In addition, in order to compare experimental and simulated PDV spectrograms, optical calculations have also been carried out to estimate the attenuation and the backscattering of the (PDV) laser beam within the particle clouds.

It is also to be noted that similar experiments had been previously achieved: ones of them dedicated to the piezoelectric probe response with HE and spherical particles [16], others with a pulsed-laser shock generator and calibrated particles using frontal or tilted PDV probes [17].

2. Experimental description

2.1. Experimental setup

The experimental setup is described on figure 2. An octogen high-explosive 100-mm-diameter Plane Wave Generator was used to generate an isochronous shockwave inside a set of transmitters (number and material depending on the shot). The last transmitter was machined with 8 spot facings (15-mm in diameter and 1-mm in depth) receiving the samples. The samples consisted of either a thin layer (a few tens of µm in thickness) of calibrated particles or a 2-mm-thick, micro-machined tin plate (machined grooves are of few µm in depth and tens µm in width). Some spot facings were left empty to provide free surface velocity measurements and give access to the shock characteristics within the upper transmitter. The diagnostics were composed of different probes (PDV, Asay foils, piezoelectric pins) aiming at the samples. The PDV signals were processed by a Short Time Fourier Transform (STFT) with a 50-ns Hamming window width.

When the shockwave broke through the transmitter/particle powder interface, particles got accelerated up to 4,000 m/s in our experiments while the free surface velocity reaches 1,550 m/s. Similarly, when the shockwave broke out at the tin-plate rear face (and sets it in motion at 1,800 m/s), particles got generated with velocities

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Figure 2. Schematics of the experimental setup.

Figure 3. Expected physical behaviors after shock break-out.
of about 2,600 m/s. This acceleration was so quick that it is not resolved by the PDV diagnostic (i.e. less than 30 ns). Four experiments were performed; their specifications are described on table 1.

2.2. Expected physical behaviors

The expected physical behaviors during the experiment are described in figure 3, in the case of the PDV diagnostic with the particle-powder target. When the shockwave reaches the particles, they are suddenly accelerated and followed by a shockwave propagating in the air. After a few microseconds, this shockwave catches up with the cloud of particles, modifying their dragging behavior because of the shock-induced air velocity. Due to both particle absorption and scattering, the PDV probing laser beam gets attenuated by the particle cloud and measurements are limited to a given front layer of the cloud, its extinction is high enough to make the free surface invisible to the PDV measurement. The backscattered light is collected by the PDV probe and analyzed to infer the cloud-velocity distribution. It was not sure that the smallest particles (~ 1 µm) were detected. Simulations performed with Hésione Eulerian hydrodynamic code show that no spalling occurs within the spot-facing bottom wall (spalling in the transmitter could generate additional particles within the cloud). Simulations also plainly display the jets generated at the chamfer of the spot facing edge and converging (with velocities higher than 2 km/s) to the cloud axis.

Table 1. Experiment details. Shots #1 to #3 are based on the same mechanical design: the only differences lying on the probe and target type. Shot #4 is based on a modified design to avoid reshock inside the upper transmitter.

| Shot number | Transmitters\(^a\) | Diagnostics | Targets: particle powder or tin plate. | Free surface velocities [µm/µs] |
|-------------|---------------------|-------------|--------------------------------------|-------------------------------|
| #1          | Copper 5 mm, Denal\(^b\) 1 mm | 8x PDV      | 6x Copper Φ10 µm 2x Tin plate        | 1200 (0.34 µs) 1500         |
| Design #1   |                      |             |                                      |                               |
| #2          | (Same as #1)        | 8x PDV      | 3x Gold Φ3 µm 3x Gold Φ9 µm 1x Empty 1x Tin plate | 1200 (0.34 µs) 1500         |
| Design #1   |                      |             |                                      |                               |
| #3          | (Same as #1)        | 3x PDV      | 6x Gold Φ9 µm 2x Tin plate           | 1200 (0.34 µs) 1500         |
| Design #1   |                      |             |                                      |                               |
| #4          | Copper 5 mm, Denal\(^b\) 3 mm, Copper 1 mm | 8x PDV      | 6x Gold Φ9 µm 1x Empty 1x Tin plate  | 1550             |

\(^a\) Provided thicknesses correspond to the spot facing bottom.
\(^b\) Denal is a tungsten alloy.
\(^c\) Results are not discussed in this paper.

2.3. Free surface and particle velocities

The free surface velocities measured on the spot-facing bottom are shown in figure 4. A double shock is obtained with design #1 while no reshock appears with design #2 as expected (though faint bounces remain). Note that the shock breaks out later with design #2 due to the (larger) transmitter thicknesses. In empty spot facings, the free surface velocity is the only reflector visible on the spectrogram for the first 5 µs after the shock break-out.

The slowing down of the particles can be observed on the two examples of PDV spectrograms provided in figure 5. Note that the smaller particles slow down faster than the larger ones: even though the dragging force is larger for the 9-µm-diameter particles, their inertia prevails compared to the 1-µm-diameter particles.
Other interesting physical information can be extracted from the spectrograms at later times: the first following data points could be attributed to the jets originating from the spot-facing chamfer crossing the PDV beam. Then, a track which might reveal the acceleration of the probe lens due to the impact of the particles, the effect of the shockwave reaching the probe and the shock transmitted in the fiber, can be observed.

The particle-cloud data bear a resemblance to those obtained with a gun shot on micro-machined tin plates [15] for their granular aspect. Butter et al. [7] obtained different results with PDV: discrete objects like bubble and spike velocities had been observed. We believe that the difference is due to the size ratio (and wavelength) between their experiments (around 100 µm) and Mercier’s ones (few µm) causing the production of bigger objects observable during several microseconds.

Note, as mentioned earlier, measurements are limited to a given front layer of the cloud and the free surface is not visible on these spectrograms.

Figure 4. Free surface velocities at the spot-facing bottom.

Figure 5. PDV spectrograms with the gold particles (shot #2). The left one is obtained with 1-µm-diameter particles and the right one with 9-µm-diameter particles. The deposited powder mass were respectively 71 and 88 mg/cm².

2.4. Areal mass measurement

Several areal mass probes were used on shot #3 with 9-µm gold particles. The deposited mass was approximately equal to 40 mg/cm² for all spot facings on this shot. These probes are usually used in vacuum experiments; the relevant value should be here the linear momentum because of the variation of particle velocities due to dragging. The velocity of particles used to calculate areal mass is 1800 m/s; it is estimated from the spectrogram and it introduces an uncertainty on the areal mass.

Two Asay foils were placed at 4 and 8 mm from the spot facings. The total areal mass obtained for an inelastic impact is 12 mg/cm². Three reasons may explain the difference: the perforation of the foil by particles, a partial acceleration of the deposited powder or the catching-up of the particles by the free surface. In addition two piezoelectric probes (PZT and LN) placed at 8 mm detected respectively 28 and 35 mg/cm². However, the strain put on these probes was higher than the reliance strain limit (as described in reference [18]).
3. Short analysis

3.1. Dragging model for a single particle

According to Cloutman [19], for a spherical particle immersed in a fluid, the particle relative velocity \( w(t) = v(t) - u_{\text{gas}} \) as a function of time can be expressed as follows:

\[
Re(t) = \frac{\rho_{\text{gas}} |w(t)| d_p}{\mu_{\text{gas}}}
\]

(1)

\[
Re > 1000, \quad w(t) = (A(t - t_0) + w_0^{-1})^{-1}, \quad A = \frac{3\rho_{\text{gas}} 0.424}{4\rho_{\text{metal}} d_p}
\]

(2)

\[
Re \leq 1000, \quad w(t) = \left( \frac{w_0^{-2/3} + C}{e^{2/3} \sqrt{B(t-t_0)} - C} \right)^{-3/2} B = \frac{18\mu_{\text{gas}}}{\rho_{\text{gas}} N_p^2}, \quad C = \frac{\rho_{\text{gas}} (d_p / \mu_{\text{gas}})^{2/3}}{6}
\]

(3)

where \( Re \) is the Reynolds number (equation (1)), \( w_0 \) the initial relative velocity, \( d_p \) the particle diameter, \( \rho_{\text{metal}} \) the particle density, \( \rho_{\text{gas}} \) the gas density, \( \mu_{\text{gas}} \) the gas dynamic viscosity and \( u_{\text{gas}} \) the fluid velocity.

At first, the particle size distribution is guessed to be homogeneous within the cloud. At equal velocity, the smaller particles slow down faster than the larger ones and progressively disappear from the head of the cloud. As a result, the upper part of the particle-cloud spectrogram, corresponding to the front layer of the cloud, provides quantitative data on this phenomenon. We used equations (2) and (3) to fit the upper part of the first few microseconds of the particle-cloud spectrogram and thus provide the particles parameters (initial velocity and diameter) as a function of time. The moment when the shockwave overtook the particles may be inferred from spectrograms (respectively 17 and 20 µs) and sets a upper time limit for this model (which assumes \( u_{\text{gas}} = 0 \)). Assuming both no particle fragmentation and no shockwave, the obtained particles diameters provide an estimate of the range of the initial particle diameter distribution within the cloud (see [15] for an example on tin).

For instance, in case of shot #2 with 1-µm-diameter gold particle powder (see figure 5), the obtained initial velocity range is [2000-2450 m/s] and the obtained diameter range is [0.5-1.8 µm], which is compatible with the range specified by the supplier ([0.8-1.5 µm]). The fragmentation of the particles may be expected due to a high break-out pressure or high relative velocities and in this case mostly happens close to the jump-off time. Therefore, this approach can reveal the fragmented particle diameter distribution. This hypothesis might explain the results with 9-µm particles; the obtained ranges are [2200-3000 m/s] and [0.7-2.0 µm], which is inferior to the manufacturer range ([5.5-9.0 µm]).

3.2. A global approach to simulate a cloud

The previous approach is limited to an estimate of the range of the initial particle diameter distribution within the cloud. We designed a 1D code, based on the equations (2) and (3), which allows us to fit the experimental PDV spectrogram with a simulated spectrogram. In this code, the distributions of the initial velocity and particle diameters follow respectively normal and log-normal laws.

The simulation of the spectrogram is performed assuming that all the particles do not interact with each other. The gas is supposed to be air at the standard conditions of pressure and temperature. In this case, the shock-wave velocity is equal to 1.22 times the transmitter free-surface velocity (for the particle powder targets). The code produces the cloud particle (current) velocity and diameter distributions as a function of time. Then, locations of the particles (versus time) as a function of their diameters are inferred. Finally, by accounting for the attenuation and the scattering of the probing laser beam through the cloud and by calculating the level backscattered light power using Mie theory [20], the simulated noise-free spectrogram is computed and compared to the experimental one.

For instance, in case of shot #2 and the 1-µm-diameter gold particle powder, the obtained particle (log-normal) distribution of the simulated spectrogram is \((d, \sigma_d) = (0.7, 0.2) \mu m\) (see figure 6). This solution which is not unique appears to underestimate the
particle diameters, showing that while this preliminary code provides a rough estimate of the particle
diameters, it needs to be optimized for a better precision.

Figure 6. Alternating slices of experimental PDV spectrogram (1-µm-diameter gold particles,
shot #2) and simulated one (in red). The initial velocity and particle distributions of the simulated
spectrogram are \((\bar{v}_0, \sigma_{v_0}) = (1900, 200) \text{ m/s} \) and \((\bar{d}, \sigma_{d}) = (0.7, 0.2) \mu m\).

4. Conclusion
We presented results from PDV (Photonic Doppler Velocimetry) experiments in which calibrated
(or not) particles were ejected from shock-loaded metallic plates. The slowing down of the particles in
air has been measured and the initial particle velocity and diameter distributions were inferred using
two methods. We firstly used a dragging model on maximum velocities measured by PDV. We also
designed a 1D code that accounts for the attenuation and the scattering of the probing laser beam
through the cloud, to fit the experimental PDV spectrogram with a simulated spectrogram. The
obtained results appear to underestimates the particle diameters, showing that while this preliminary
code provides a rough estimate of the particle diameters. These results might also show that micron-
sized calibrated particles fragment under HE shock or during the air entrance. The determination of the
source term is not unique in using the simulation of a particle-cloud PDV spectrogram. However this
approach gives a new analysis of PDV measurement, particularly in term of PDV-beam probing depth.
Furthermore, the confrontation between simulated and experimental spectrograms is a new constraint
that could be added to those supplied by density and areal density diagnostics.

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