Seeding for Laser Velocimetry in Confined Supersonic Flows With Shocks

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IN CONFINED SUPERSONIC FLOWS WITH SHOCKS

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INTRODUCTION

There is a lack of firm conclusions or recommendations in the open literature to guide laser velocimeter (LV) users in minimizing the uncertainty of LV data acquired in confined supersonic flows with steep velocity gradients. This fact led the NASA Lewis Research Center (LeRC) in Cleveland (Ohio, USA), and the Institute of Propulsion Technology of DLR in Cologne (Germany) to a joint research effort to improve reliability of LV measurements in supersonic flows. Over the years, NASA and DLR have developed different expertise in laser velocimetry, using different LV systems: Doppler and two-spot (L2F). The goal of the joint program is to improve the reliability of LV measurements by comparing results from experiments in confined supersonic flows performed under identical test conditions but using two different LV systems and several seed particle generators. Initial experiments conducted at the NASA LeRC are reported in this paper. The experiments were performed in a narrow channel with Mach number 2.5 flow containing an oblique shock wave generated by an immersed 25-dg wedge.

BACKGROUND

Laser velocimetry (LV) is approaching the state of a mature experimental technique. Advances in laser Doppler anemometer (LDA) signal processors allow reliable measurement of signal frequencies up to 100 MHz. The advent of LDA frequency-based processors allows measurements at poor signal-to-noise ratios (SNR). Integrated optics and fiber-optics links have solved many problems in optical access to measurement locations in complicated flow arrangements.

The only aspect of laser velocimetry that has not progressed at all in recent years is the technique of flow seeding, which seems to be a straightforward, uncomplicated task without the sophistication of LV signal processing. Consequently, very often, not enough attention is paid to flow-seeding problems, and lessons learned in low-speed subsonic flows are often directly applied to high-speed flow situations. Unfortunately, such an approach may result in serious measurement errors in high-speed flows with steep velocity gradients.

If a laser velocimeter system (optics and electronics) is viewed as a black box, then the signal generating seed particles are the actual velocity transducers. From this point of view, laser velocimetry (including all particle tracing optical techniques) is unique in that it is the only experimental technique in fluid dynamics where measurements at high flow velocities are often carried out using "uncalibrated transducers".

In theory, the requirements for seeding in high-speed flows with steep velocity gradients are simple: light, monodispersed, spherical particles with high surface reflectivity at the wavelength of detectable laser light. The low particle density is required to enable particles to follow the rapid flow changes. Monodispersity is crucial for post-measurement corrections of recorded velocities to true flow velocities and minimizing apparent velocity turbulence in regions of steep velocity gradients. High reflectivity should assure a good SNR for the LV signal. In practice, however, meeting these requirements at the point of measurement is very difficult.

SEEDING METHODS FOR SUBSONIC FLOWS

In subsonic applications, seed particles can be injected into the flow in solid, liquid, or gaseous forms. The available dry powders consist of polydispersed, non-spherical particles of relatively high density. The mechanics of dry particle delivery systems is complicated; particles tend to agglomerate in the delivery mechanism, which results in clusters of large particles injected into the flow. Consequently, the resulting seed particles follow flow changes poorly.

From a practical point of view, it is much easier to spray fluids into the airflow than to inject powders. Several well established methods can be categorized into five groups: (1) spraying a volatile carrier liquid that contains solid particles; (2) spraying non-volatile liquids dispersed into small droplets; (3) atomizing liquids and

injecting the mist into the flow; (4) vaporizing a liquid and injecting the resulting fog into the flow; and (5) burning (or reacting) solid or liquid components and injecting the resulting smoke. All these methods are used in subsonic flows with good results, however, the user must remember that there are some limitations.

The first method (Group 1) uses a carrier liquid with polystyrene latex (PSL) spheres. This approach relies on evaporation of the volatile carrier liquid (alcohol) and leaving the solid PSL spheres in the flow. The evaporation process has to be completed in the flow ahead of the point of measurement. The major advantage is that the resulting seeds are monodispersed with a known diameter.

The second method (Group 2, non-volatile liquid droplets) generates relatively large polydispersed droplets. Various separators or impactors are applied to narrow the droplet size range. In reality, the size spectrum at the point of measurement is not known with sufficient accuracy.

The third method (Group 3, liquid atomizing) generates polydispersed submicron-size fine droplets. A number of seeds may be below the detectable size for LDA systems. Scattered light from undetectable particles generates a high level of background noise that results in a significant decrease in SNR.

The fourth method (Group 4, vaporization e.g. "theatrical smoke") and the fifth method (Group 5, burning products - smoke bombs) are used only marginally.

SEEDING IN SUPERSONIC FLOWS

Several researchers have experimented with various seeding techniques in supersonic flows. Parobek et al. (1986) and O'Heren et al. (1983) discussed flow experiments that were carried out in boundary layers or free stream conditions without shocks in the flow. The experiment of Lepicovsky et al. (1985) dealt with free jets seeded with aluminum oxide powder. Samimy & Abu-Hijleh (1989) pointed out significant effects of laser Doppler velocimeter (LDV) system parameters on the results obtained in high-speed flows using polydispersed seed particles. In many instances parameters such as laser power, photomultiplier tube (PMT) gain, LV processor gain and threshold, and others are set subjectively and inconsistently, which results in large experimental errors.
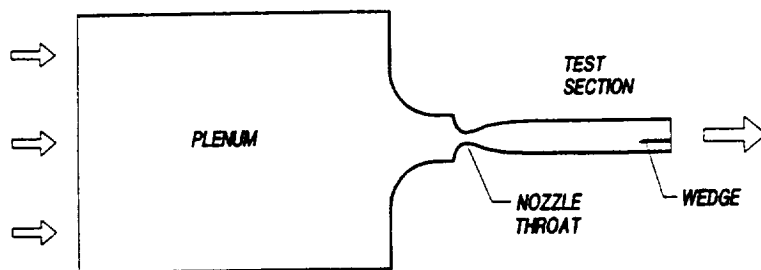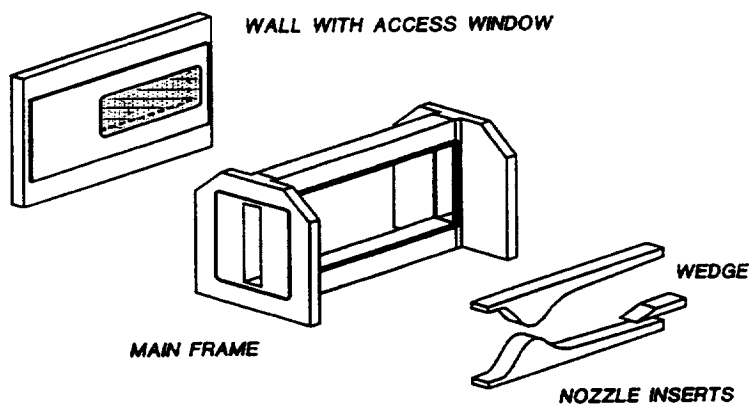

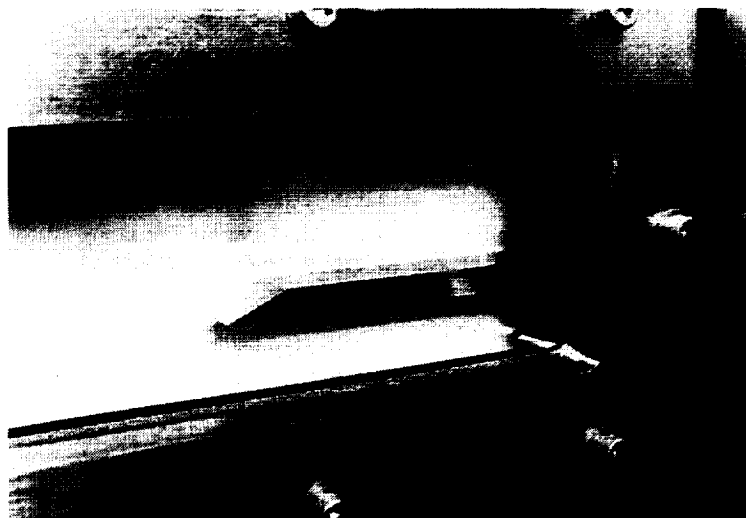Figure 1. Supersonic wind tunnel.

Figure 2. Supersonic test section.

Figure 3. Supersonic test section.

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Intuitively, monodispersed seeds (e.g. PSL particles, Group 1) are the most suitable ones for applications in confined supersonic flows. It is our experience, however, that the presence of carrier-liquid vapors in the flow constitutes a significant problem. In supersonic flows, due to the flow acceleration between the plenum and the test point conditions, the flow temperature drops below the dew point and the carrier liquid vapors condense back on the PSL spheres. The process results in liquid droplets of various diameters larger than the individual PSL spheres. The carrier liquid droplets around the PSL spheres are then the actual signal generators. As a result, we may know the PSL particle diameter exactly, but we do not know the diameter of the signal generating droplets.

The Group 4 and 5 methods lead to different difficulties. The fourth method (vaporization) often results in massive condensation at the beginning of the supersonic velocity region. Frequently the condensate accumulates on the test-channel walls and is driven over the access windows. Liquid on the windows causes detrimental laser beam refractions, which results in losing the beam intersection and measurement volume.

Finally, using the last method (smoke bombs) leads to heavy depositions of soot or tar-like substances on flow surfaces and access windows, resulting very often in short test runs and costly cleanups. In our experience these last two methods are not suitable for confined supersonic flows.

TEST APPARATUS

A supersonic wind tunnel with a test section free stream Mach number of 2.5 was designed and tested to provide a research tool for development work on LV flow-seeding techniques [Bruckner & Lepicovsky (1994)]. A schematic diagram of the tunnel is shown in Figure 1. The tunnel consists of a cylindrical plenum of internal volume of $1 \ m^3$ and an exit bellmouth with an attached convergent-divergent nozzle, followed by a straight duct 813 mm long that maintains a supersonic flow along the entire length. The nozzle was designed for Mach number 2.5. The nozzle throat area is 25 by 36 mm, resulting in a plenum/throat contraction ratio of 650:1. A drawing of the test section is shown in Figure 2; and a photograph in Figure 3. A 25-dg wedge, located in the test section, generates an oblique shock at its tip followed by an expansion fan at the end of the wedge. The wedge is 21 mm wide. There is a 7.5 mm gap between the side walls and the wedge.

The LV system used in this study is a two-component, backscatter system assembled from DANTEC and TSI optical components. The system uses a Coherent Ar-Ion laser operated at total power of 2 W; the receiving optics has an f-number of 2.5 and a focal length of 250 mm; the fringe spacing for channel 1 (green) is 11.16 μm and 10.78 μm for channel 2 (blue); the diameter of the

measurement volume is 120 μm. A TSI IF750 processor collected the LV data.

The flow was seeded in the plenum, ahead of the supersonic nozzle and the test section. Location of the seeding sprayers or tubes is depicted separately for each case described.

A schematic diagram of the flow structure generated in the test section by the inserted wedge is in Figure 4. The coordinate system used in the experiments is depicted in Figure 5.
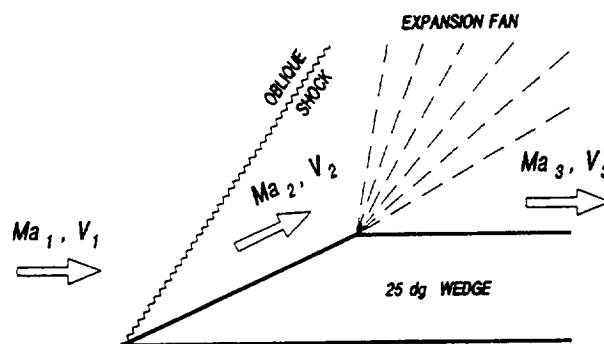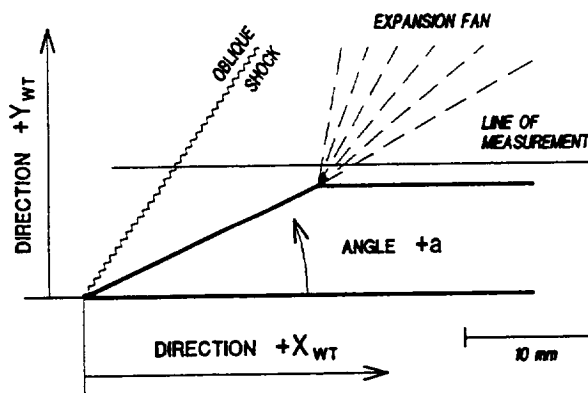

Figure 4. Shock wave structure.

Figure 5. Test coordinate system.

RESULTS AND ANALYSIS

Three sets of results in this paper summarize the initial experiments conducted on Group 1 to 3 seeders at NASA LeRC. Each set consists of plots of velocity, velocity-angle distributions, and velocity histogram data. There is also a sketch for each particular seeding configuration.

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Velocity and velocity-angle plots show variations over the oblique shock and expansion fan region. The velocity based on pressure measurements and 1-D theory of compressible flow is also shown in the plots. The tunnel velocity ahead of the shock wave was determined from the plenum total pressure and temperature and wall static

pressure close to the wedge tip. In the velocity histogram plots, the data is shown for both velocity components at several axial positions in the investigated region.

The first set of data (Figures 6 to 9) shows the results using the NASA seeder with polystyrene latex particles (PSL) suspended in alcohol. The PSL particle diameter was 1.1 μm. This seeder fits the Group 1 description presented above. As seen from the velocity and velocity-angle distributions (Figures 6 and 7), the seeded particles follow the flow changes extremely poorly. The seeder sprayer injects the alcohol/particle mixture perpendicular to the flow (Figure 8, Seeder A3). It must be stressed here that no differences appeared whether the seeding was with an alcohol/PSL mixture or with pure alcohol only. Obviously, the LV signal was generated by alcohol droplets only and the droplets may or may not have contained the PSL particles inside. Consequently, the assumption that the carrier liquid evaporates and the PSL particles will generate the LV signal is not valid here. This is a textbook example of possible large errors in LV data if users extrapolate experiences from subsonic to supersonic laser velocimetry. The plots in Figures 6, 7, and 9 are for pure alcohol only. The histograms in Figure 9 show a single peak behind the oblique shock for both channels, which may indicate more or less uniform diameter for all the droplets. There was no visible contamination of the window in the shock region for pure alcohol. For the mixture alcohol/PSL, a noticeable window contamination with the PSL particles was observed in the wedge region.
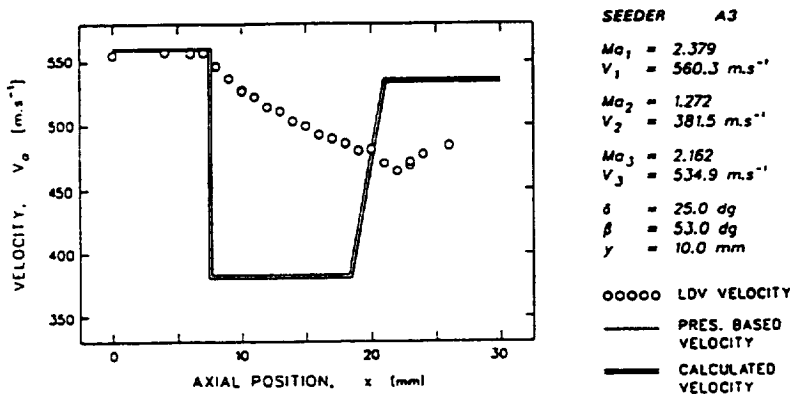

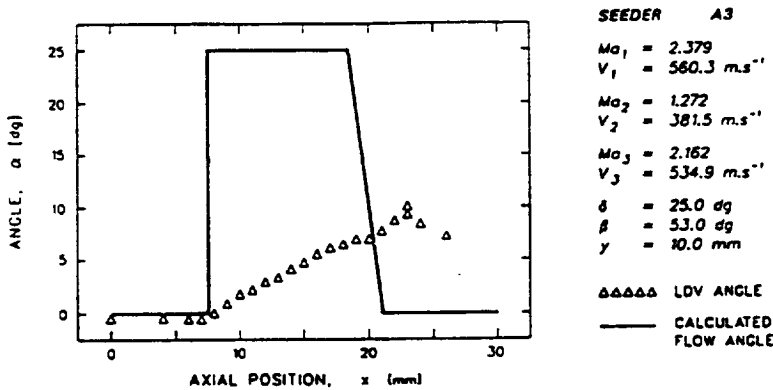*Figure 6.   Velocity distribution   (Seeder A3).*

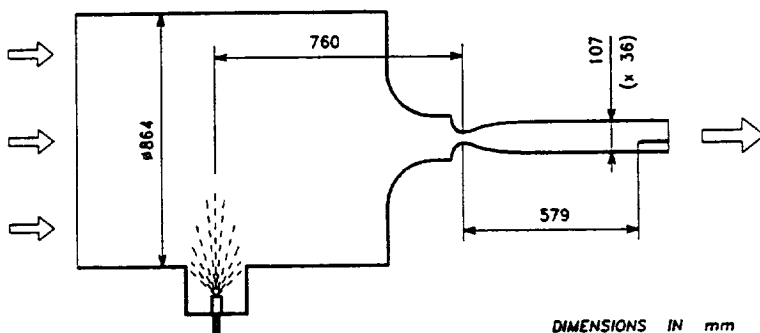*Figure 7.   Flow angle distribution   (Seeder A3).*

There is an interesting detail in the expansion fan region. For the case of volatile fluid (pure alcohol), the velocity recovery behind the expansion fan is clearly noticeable. Further, the histograms for this region at $x_{WT} = 20$ and 22 exhibit two peaks. This may indicate changes in diameter for some droplets in the region between the shock and the fan.

Figure 8.   Test configuration   (Seeder A3).

The second set of data (Figures 10 to 13) was acquired using a seeder equipped with a Laskin nozzle generating oil droplets (glycol). This seeder belongs in Group 2 as outlined above. Detailed description of the seeder is given by Rabe & Sabroske (1994). The seeder performed very well in subsonic applications [Rabe & Sabroske (1994)], however, in our particular case the performance was not satisfactory. The velocity and velocity-angle distribution plots in Figures 10 and 11 indicate that here again the
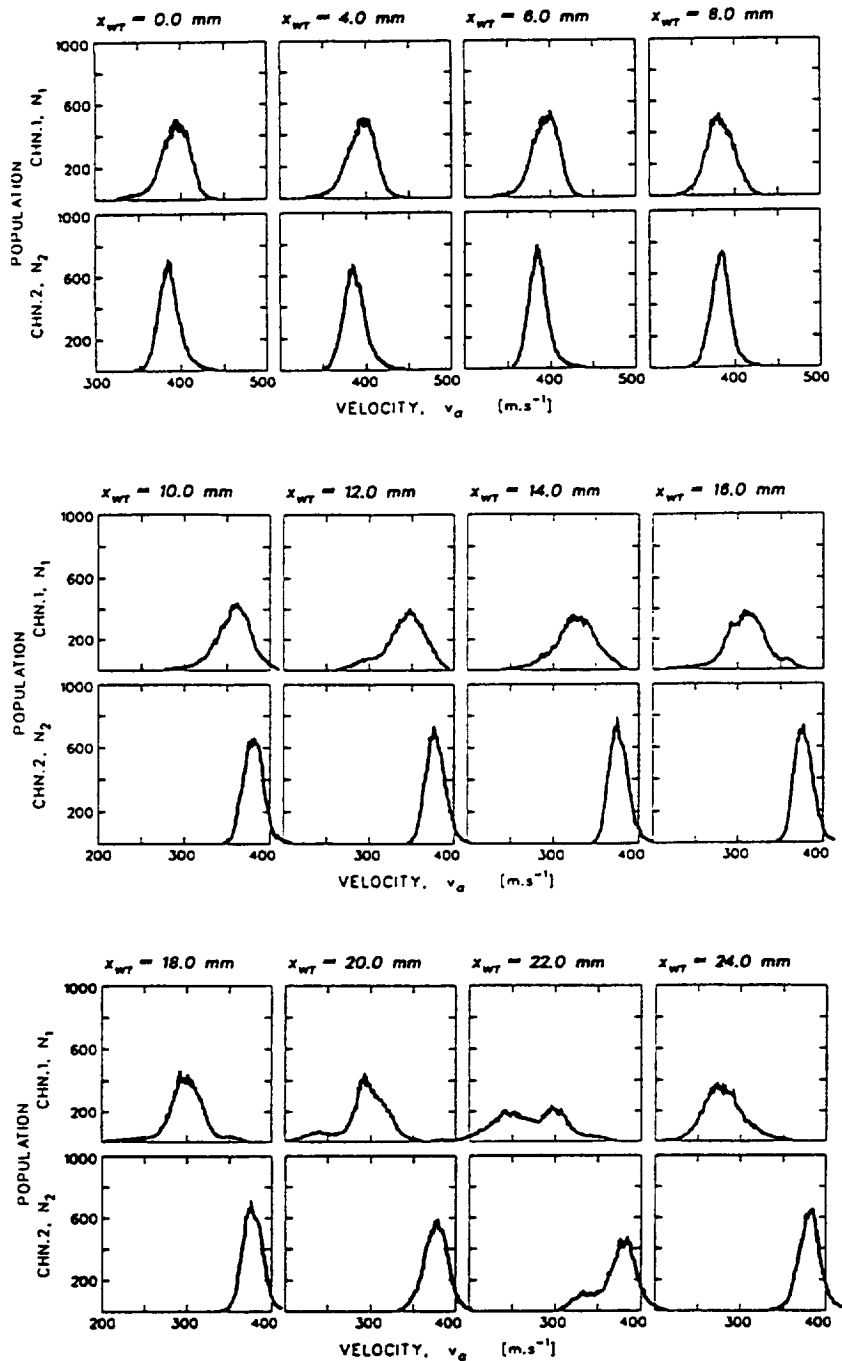
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Figure 9. Velocity histograms (Seeder A3).

$x_{WT} = 10$ and 12 and single peak histograms on channel 2. The two-peak histograms cannot be attributed to oblique shock wave oscillations. It seems that the left peak on channel 1 migrates to a lower velocity region faster than the right peak with increasing distance from the shock. A possible explanation is that the seeder generates 'two groups' of droplets of different mean diameters.

The third set (Figures 14 to 16) shows the results for a seeder based on the TSI six jet atomizer. The seeder belongs to Group 3. The seeds were injected in the flow in the same way as shown in Figure 12. The velocity and angle distributions indicate satisfactory agreement with expected flow velocity and angle variations. Generally, the results are good; however, some problems are not yet fully understood. First, when we used pure alcohol in the atomizer, no LV velocity data were recorded; the PMT signal contained only noise. This indicates that the size of the seeds was below the detection limit. Then, PSL particles of $1.1 \ \mu m$ in diameter were mixed with alcohol. The data in Figures 14 through 16 were acquired for the alcohol/PSL mixture. Even after adding the PSL particles, we still could not detect any data in front of the shock wave (very low SNR); however, behind the shock there was a strong LV signal. A very sharp and repeatable divide appeared to be at $x_{WT} = 9$, just past the oblique shock. The sharp divide indicates a sudden change in the seed visibility (increased SNR).

At this point, we can only speculate on the physics behind these observations. A sudden increase in visibility can be caused by several factors such as increased particle size or drop in the background noise or increased particle surface reflectivity. There is also a possibility of coalescence of particles behind the shock. The effect of agglomerating submicron particles into larger droplets behind the shock would be twofold. First, it would lead to a larger diameter in the resulting droplets; second, it would lower the background noise radiation by reducing the population of fine submicron particles. In
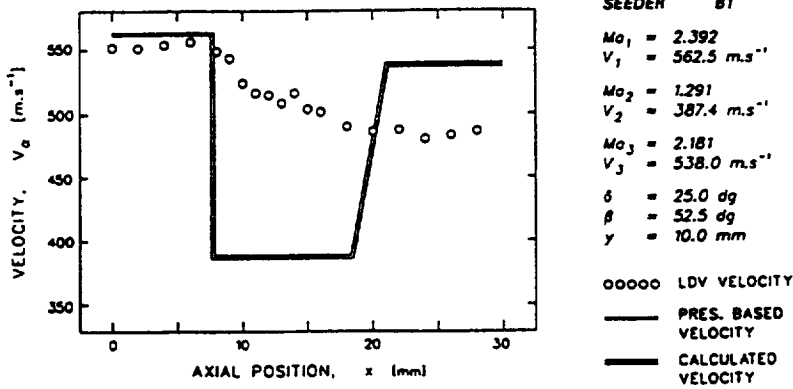
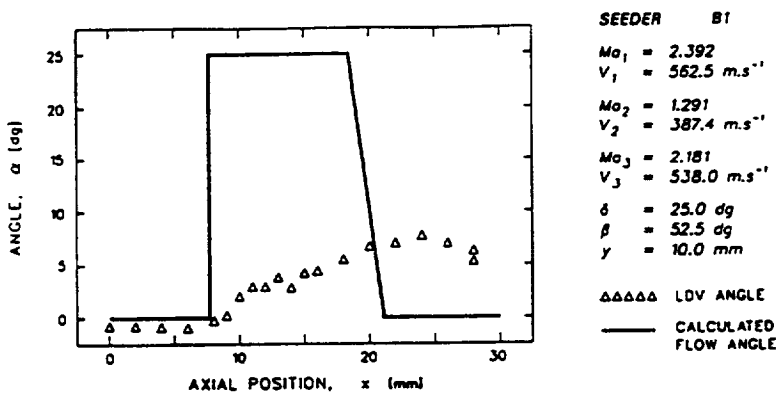seeder produced oil·droplets that follow the flow changes poorly. The position of the seeder delivery tube is shown in Figure 12. A glance at velocity and angle-distributions reveals that there is barely any improvement over the results from the first set. The velocity histogram plots (Figure 13) show deterioration of the LV signal in the shock wave region (there was noticeable contamination on the inside of the window at $x_{WT} = 6$ and 8). After the shock, there are dual-peak histograms on channel 1 for

Figure 10 panel data:

SEEDER B1

Mo_1 = 2.392
V_1 = 562.5 m.s⁻¹

Mo_2 = 1.291
V_2 = 387.4 m.s⁻¹

Mo_3 = 2.181
V_3 = 538.0 m.s⁻¹

δ = 25.0 dg
β = 52.5 dg
γ = 10.0 mm

ooooo LDV VELOCITY
——— PRES. BASED VELOCITY
——— CALCULATED VELOCITY

Figure 10. Velocity distribution (Seeder B1).

Figure 11 panel data:

SEEDER B1

Mo_1 = 2.392
V_1 = 562.5 m.s⁻¹

Mo_2 = 1.291
V_2 = 387.4 m.s⁻¹

Mo_3 = 2.181
V_3 = 538.0 m.s⁻¹

δ = 25.0 dg
β = 52.5 dg
γ = 10.0 mm

△△△△△ LDV ANGLE
——— CALCULATED FLOW ANGLE

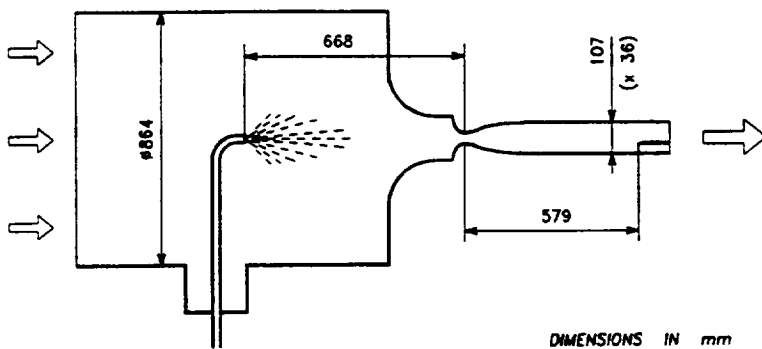*Figure 11. Flow angle distribution (Seeder B1).*

DIMENSIONS IN mm

Figure 12. Test configuration (Seeders B1 and D1).

any case, the LV signal behind the shock is generated by relatively small diameter seeds as manifested in the velocity and angle distributions in Figures 14 and 15. Obviously, additional effort is needed to explain these observations fully.

CONCLUSIONS

The study demonstrated the possibility of large experimental errors in LV data acquired in confined supersonic flows with shock wave structures. The lessons learned about flow seeding at subsonic velocities cannot be blindly applied to supersonic flow conditions. Because our knowledge about seeding for confined supersonic flows is not adequate, we recommend always arranging for a pilot experiment using a wedge shock generator to test particle response at the point of measurement. Of course, the pilot tests should be run at the actual flow conditions of the desired experiment, using the actual seeding technique. The settings of the LV system should be maintained between the pilot study and actual testing. It is our experience that the experimenter should rely on a tested seed-particle response at particular flow conditions rather than rely on knowledge of seed particle sizes acquired by other means e.g. out of flow particle sizers.

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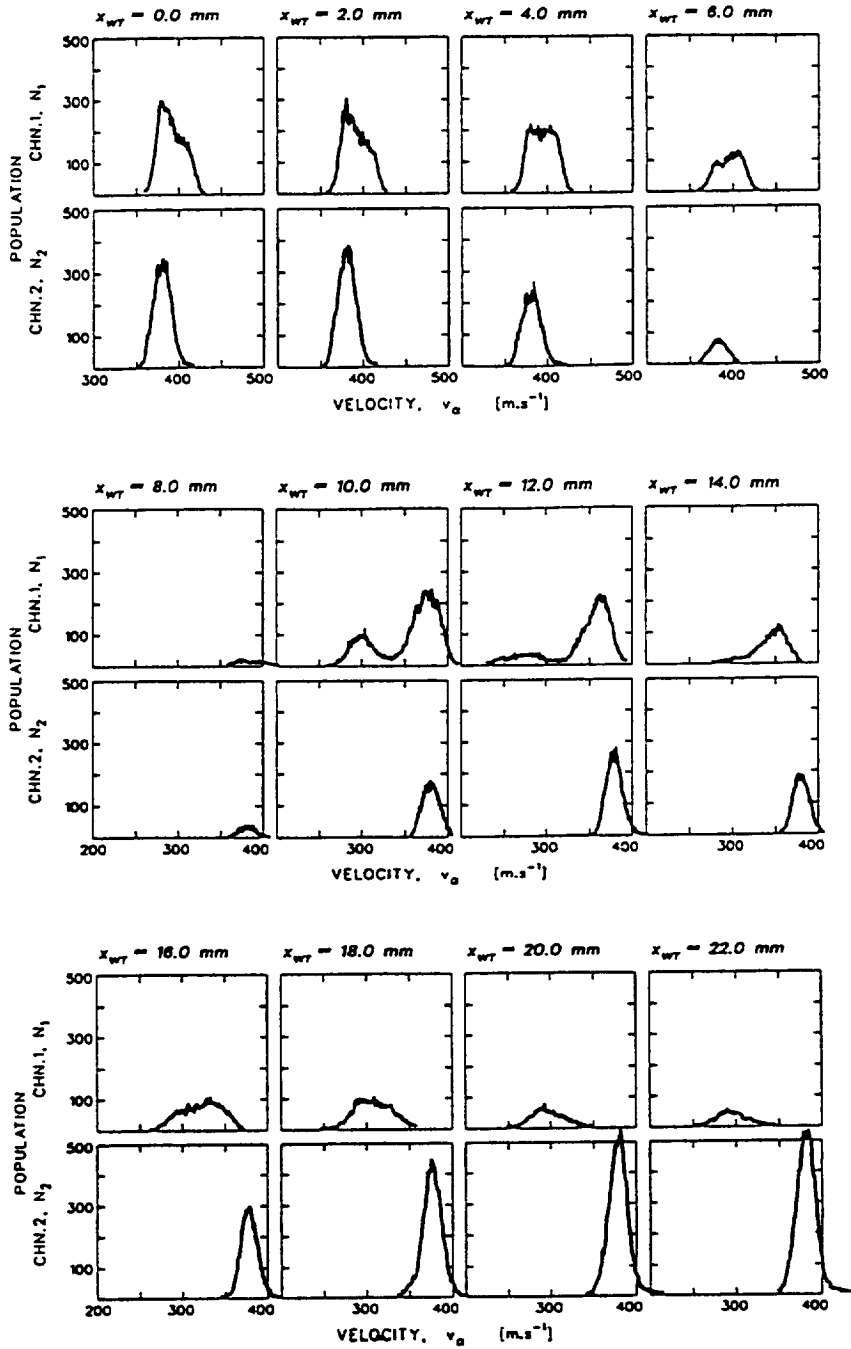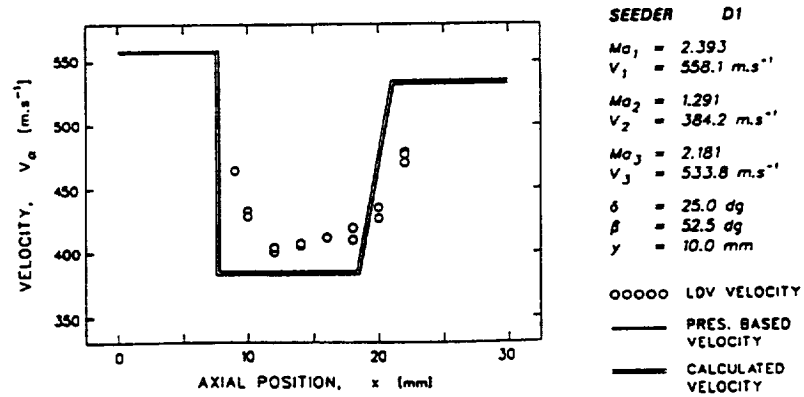

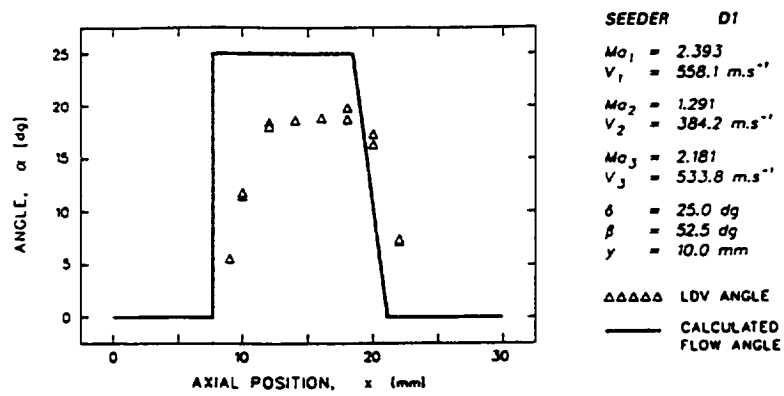*Figure 13. Velocity histograms (Seeder B1).*

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SEEDER   D1

Ma_1 = 2.393
V_1 = 558.1 m.s⁻¹

Ma_2 = 1.291
V_2 = 384.2 m.s⁻¹

Ma_3 = 2.181
V_3 = 533.8 m.s⁻¹

δ = 25.0 dg
β = 52.5 dg
y = 10.0 mm

ooooo LDV VELOCITY

—— PRES. BASED
     VELOCITY

—— CALCULATED
     VELOCITY

Figure 14.   Velocity distribution   (Seeder D1).

SEEDER   D1

Ma_1 = 2.393
V_1 = 558.1 m.s⁻¹

Ma_2 = 1.291
V_2 = 384.2 m.s⁻¹

Ma_3 = 2.181
V_3 = 533.8 m.s⁻¹

δ = 25.0 dg
β = 52.5 dg
y = 10.0 mm

△△△△△ LDV ANGLE

—— CALCULATED
     FLOW ANGLE

Figure 15.   Flow angle distribution   (Seeder D1).

Figure 16. Velocity histograms (Seeder D1).

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13. ABSTRACT (Maximum 200 words)

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