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A Test Rig for LDV and Seeding Characterization for High Speed Turbomachinery Application: Experimental Results

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The accuracy and data rate of Laser Doppler Velocimetry (LDV) are strongly influenced by several parameters. To optimize measurements, a system for setting up the velocimeter, not influenced by the specific environment, is needed. It is necessary to choose several optical parameters, to evaluate insemination techniques (not influenced by specific flow fields) and to compare seeding performance in a right range of velocities. A supersonic wind tunnel was constructed, to evaluate the measurement LDV system in a range of velocities from 50 m/s to 450 m/s using various kinds of seeding. Tests were performed both in accelerating velocity zones and in the presence of shock waves. Comparative tests were made using suspension in water of various materials as seeding: Polystyrene (PSL), microballoons, four kinds of commercial aluminum oxide powder in distillate (pH = 6) and acid water (pH = 2), plus other oxides like TiO_2 and ZrO_2.

Keywords: Laser Doppler Velocimetry (LDV); Seeding; Aluminum Oxide; PSL; TiO_2; ZrO_2

1. INTRODUCTION

In recent years Laser Doppler Velocimetry (LDV) has acquired more and more importance, thanks to its characteristics of measurement versatility and non-intrusivity. In parallel, to achieve significant and more and more accurate measurements, the development of usable seeding characterization methods is necessary. As is well known with LDV systems measurement is strictly linked to the insemination system and the seeding itself (Degrez-Reithmuller, 1994), since its velocity is measured. So to get the right information from flow the seeding has to achieve a speed as near as possible to that of the flow and follows, with the shortest delay, each flow speed variation. LDV measurements have all the advantages provided by non-intrusivity, extreme versatility of the system, lack of contact with the flow (it is possible to get measurements in critical environments and conditions for many other measurement systems), spot like dimensions of measurement volume and by high frequency response, but is linked to the kind of seeding used and to its characteristics. Knowing the characteristics and the behavior of the different seedings allows one to choose the best one for each conditions and type of measurement that has to be made and also evaluation of errors done. Previous research (Heltsley, 1985) has shown the behavior of seeding in flows with variable velocity and in the presence of a shock. In this experimental campaign comparison is made between the behaviors and characteristics of different seedings using a wind tunnel developed ad hoc, starting from the assertions of Terry-Mueller (1985) and using an inseminating system that follows the suggestions of Rebush (1985). This allows measurement of the performance of various seedings, even the most recent on the market, helping to the operator to choose the best seeding for each turbomachinery applications.

2. MEASUREMENT SYSTEM

To evaluate correctly the behavior of the different seedings usable in turbomachinery application they are tested in a dedicated wind tunnel where a direct flow speed measurement is associated with the seeding velocity read by LDV system. For this purpose a specific wind tunnel was built

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and equipped with optical access and pressure taps for flow speed measurement.

2.1. Wind Tunnel

The tunnel (Figures 1–3) is made up of a convergent-divergent nozzle where the flow can expand up to Mach 2.2. Regulation is achieved by variations of inlet Total Pressure that cause the change of flow speed and therefore the intensity of the shock if present. So it is possible to study the behavior of the seeding when there is a flow speed step (instant variation). The convergent-divergent nozzle has a rectangular section with a 30×30 throat section and 30×60 mm outlet section.

The convergent profile has the shape of an ellipse branch with semiaxis of 150 and 110 mm; the divergent part is a cone with opening semiangle of 2°. One of the walls (front wall) is made with a long optical glass that allows access to the laser beams (Figure 1). On the other wall (rear wall), at mid vane, there are 100 pressure taps at a distance of 6 mm along the whole nozzle length (Figure 2). The static pressure measurement allows to find out the real flow speed in each tunnel section.

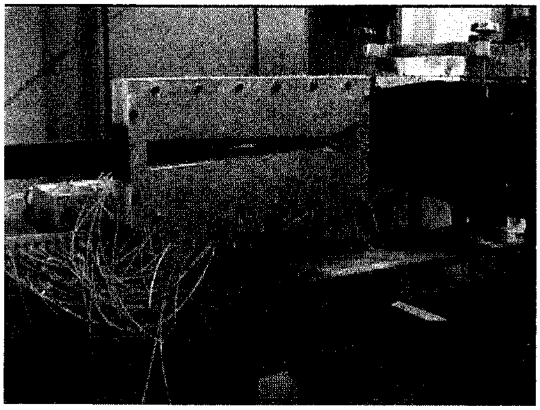


FIGURE 1 Convergent-divergent nozzle (front wall).

FIGURE 2 Rear wall wind tunnel–pipes connected to the pressure taps along the whole nozzle.

The nozzle is supplied with pressurized air up to 6 bar. The calm chamber, appropriately designed for realizing correct flow inlet into the nozzle, has its upper face made of transparent material for checking any seeding accumulation or incorrect insemination. Upstream to the calm chamber is the seeding device by which seeding is introduced into the flow.

A schematic representation of the wind tunnel is reported in Figure 3.

Direct real flow velocity measurement allows a basic and immediate comparison with velocity taken by LDV measurement, highlighting each inaccuracy and differences linked to seeding, LDV setup, etc.

Another very important aspect is the quality of the glass used as optical access. It must not change in any way the light signal that passes through it, introducing interference fringes distortion. Planarity studies of two kinds of optical access used are reported in Figure 4.

It can be clearly seen that commercial glass, even if it is of very high quality, is definitely shoddier than optical glass. Therefore the authors do not recommend the use of the former for turbomachinery measurements where high accuracy and good characteristics are needed.

In Figure 5 wind tunnel characterization achieved by changing calm chamber Total Pressure is reported. The collapsing of the curves indicates good repeatability of

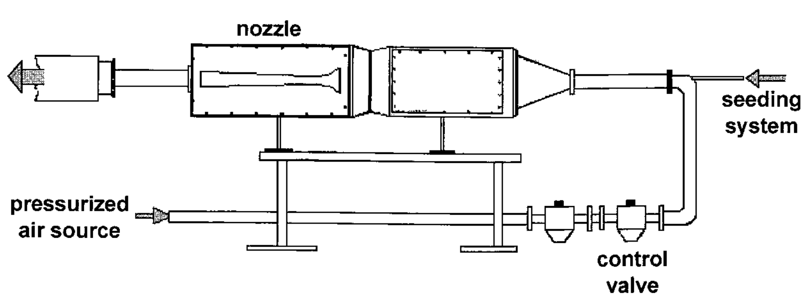


FIGURE 3 Wind tunnel schematic representation.

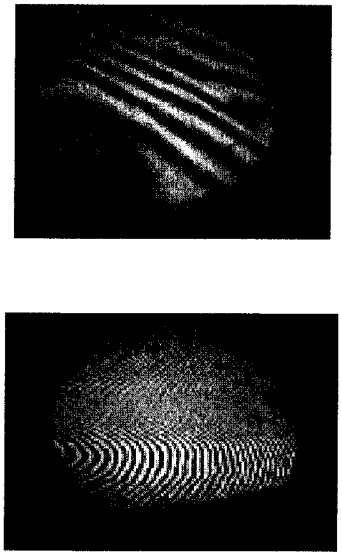


FIGURE 4 Planarity studies of optical glass used (top) and of a high quality commercial glass (bottom).

conditions, simple and stable regulation, which are very important for simulating turbomachinery operating conditions. Shocks and their stability are well visible on this.

2.2. Inseminating System

The flow insemination system is made by an injector (Figure 6), where dilution air flows, ending with a small convergent-divergent nozzle in whose throat the four small seeding ducts (0.5 mm) meet. So simply switching from one to another ducts it is possible to carry out tests with different seedings in the same conditions. The depression caused by the dilution air passage (rate about 100/1 ÷ 1000/1) sucks the seeding directly form the container where it is kept in suspension. In some working condition (high-pressure machines), for correct insemination, it could be necessary to pressurize the seeding container. Entering seeding flow regulation is achieved both changing the

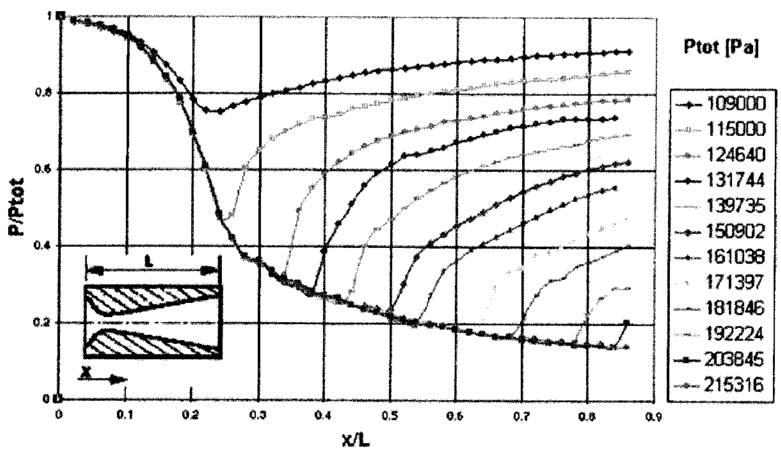


FIGURE 5 Pressure courses in the nozzle changing the upstream pressure conditions (See Colour Plate at back of issue.).

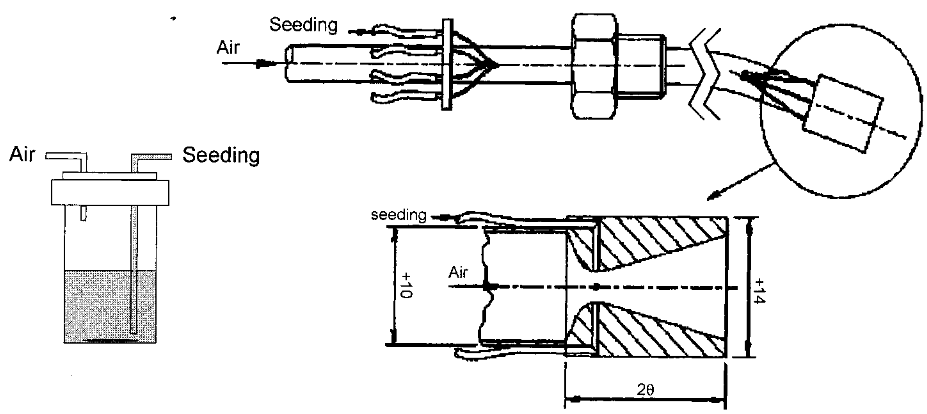


FIGURE 6 Outline of pressurized container, insemination device, and detail of its nozzle.

pressure of the seeding container and changing the dilution air flow. A further regulation is achieved with four needle throttle installed between the suspension and the seeding device.

Usually suspension in distillate water at 10% in seeding weight is realized, except for Polystyrene for which the problem of particles haste is resolved by keeping it in the same solution in which nucleation takes place. An ultrasonic bath is sometimes used for breaking possible aggregates of seeding particles and for preventing their formation during preparation. Acid suspensions are tested according to the proposals of Wernet (1994) for preventing particle adhesion (Aluminum and other Metallic Oxides). In the case of PSL the suspension derives directly from the forming process adjusted in our department starting from what suggested by Nichols (1987). During the tests suspension is kept moving by a rotating magnetic field. In Figure 6 the outline of the insemination device is reported.

2.3. LDV System

The 2D LDV used consists of a 6W argon-ion Laser source, a fiber drive and optic fiber for transmitting and receiving signals, Digital Signal Analyzer (DSA3000) by Aerometrics and a 3-axis system with three closed loop step-by-step motors by Unidex. In tests reported optics with a focal length of 500 mm and 300 mm were used. These provided different volume measurement dimensions, and maximum speed measurable. The characteristics of the measurement volumes and laser beams are reported in Table I.

3. SEEDING TESTED

In the LDV system measurement is strictly linked, considering its validity, to seeding characteristics. For each seeding the ability to follow a flow with variable speed becomes very important. So it is necessary to locate the range where the difference between the velocity achieved by the seeding particle and that of the flow is sufficiently small. In the tests carried out many other studied seeding characteristics were also evaluated: the running costs or frequency necessary for cleaning optical access for taking out film caused by seeding adhesion.

TABLE I Measurement volume characteristics for optics and laser beam wavelengths

	Optic of 500 mm		Optic of 300 mm	
Color	Green	Blue	Green	Blue
λ (nm)	514,4	488	514,4	488
d_m (mm)	0.142	0.135	0.0858	0.0814
l_m (mm)	2.548	2.417	0.919	0.872
δ (μm)	4.60	4.36	2.77	2.63
N_{fr}	31	31	31	31
v_{max} (m/s)	552	523	332	315

Seven types of seeding were tested: Polystyrene (PSL), Titanium Oxide (TiO_2), Zirconium Oxide (ZrO_2) and four kinds of Aluminum Oxide: AKP15, AKP30 (produced by Sumitono) and those produced by Alfa and by Buehler. Seeding physical characteristics and their pictures taken with a scanning electron microscope of the used seeding are here reported (Table II, Figures 7–13).

TABLE II Physical characteristics of the studied seeding

	$\O_{med}$ (μm)	Refrac. Index	Fus. T. (°C)	Dens. (g/cm^3)
PSL	0.8	1.6	< 200	1.05
TiO_2	2	2.53	< 3000	3.84
ZrO_2	1–3	2.19	≈ 2700	5.49
AKP15	0.62	1.76	≈ 2000	3.99
AKP30	0.39	1.76	≈ 2000	3.99
Alfa All.	1	1.76	≈ 2000	3.99
Buehler	0.3	1.76	≈ 2000	3.99

FIGURE 7 Buehler Aluminum Oxide.

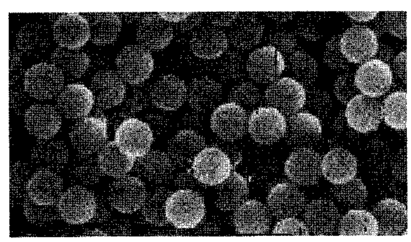


FIGURE 8 Polystyrene.

FIGURE 9 AKP15 Aluminum Oxide.

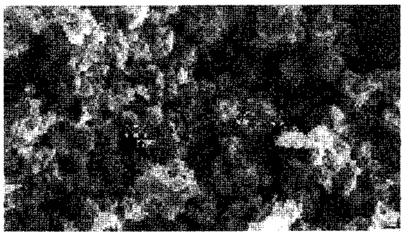


FIGURE 10 Titanium Oxide.

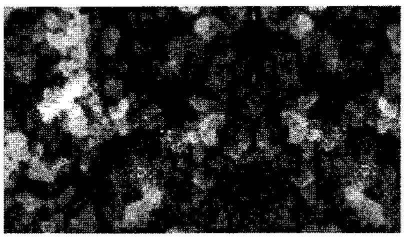


FIGURE 11 AKP30 Aluminum Oxide.

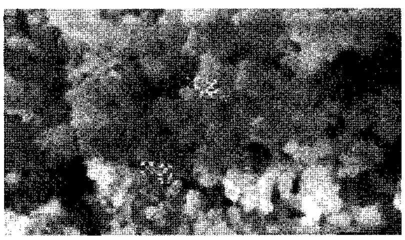


FIGURE 12 Zirconium Oxide.

FIGURE 13 Alfa Aluminum Oxide.

As can be clearly seen, Polystyrene (Figure 8) has a perfectly monodispersed shape with almost perfectly spherical particles. These are the best conditions for applying a Mie's theory (Born-Wolf, 1975) to evaluate the necessary powers and the expected data rate but the complexity of the typical turbomachinery measurement environments lead to the carrying out of tests for directly achieving the expected information. The other Oxides have much rougher surfaces, and this, on the one hand increases the refraction index but, on the other, causes a scattered signal with more noise and makes the different particles follow the flow in a different way according to the way in which they are hit. These particles, moreover, have a distribution that penalizes them increasing dispersion. Among these, the Titanium Oxide (Figure 10) is the one with the highest refraction index, keeping low density and dimensions. Among the different tested Aluminum Oxides the one with the best characteristics seems to be the one produced by Buehler (Figure 7). At the same density it is the one with the smallest dimensions and so a behavior less influenced by inertia than the others is expected. Inertia is a limiting factor for Zirconium Oxide (Figure 12) given its considerable density. Another interesting parameter is the fusion temperature because it limits the seeding using range itself: for example in measurements with temperatures up to 150–200°C Polystyrene can not be used while Aluminum Oxides allow measurements even in combustion chambers.

4. TESTS RESULTS IN ACCELERATING FLOW

Seeding characterization is carry out both in accelerating flow and in the presence of shocks. Tests in accelerating flow were taken placing the measurement volume in the first part of the nozzle (before the throat) comparing the velocity measured with LDV for each seeding with the real one of the flow. In this part of tunnel there is a very strong flow acceleration: 0–350 m/s in few millimeters. The tests take place with optics with focal distances of both 500 mm and 300 mm until velocities of 450 m/s. In Figure 14 seeding velocity versus air velocity for each seeding is reported.

For speeds up to 200 m/s the differences between the seedings are very small, at higher velocity the differences become more pronounced. Among the seedings tested, the one that best represents flow conditions is without doubt Polystyrene, which has an error that in the worst condition ($v > 400$ m/s) is never over 5–6%. Among the other oxides the best are AKP15 Aluminum Oxide and Buehler Aluminum Oxide, practically equivalent, with maximum errors about 10–12%. Zirconium and Titanium Oxide

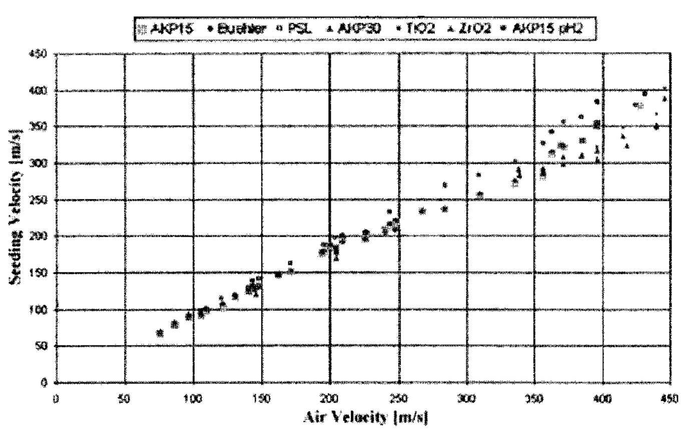


FIGURE 14 Seeding velocity versus flow velocity.

gave the highest data rates, but have, especially the second one, rather high errors (up to 14% for TiO_2 and up to 17% for l'ZrO_2). AKP15 Aluminum Oxide was tested in suspension with different pH according to the theory of Wernet-Shock (1994) for evaluating the influence of this parameter on sedimentation velocity and conglomerate formation. In our tests pH influence could not be sufficiently evaluated, as long as it remained in an acid range (even if distant from zero charge point $pH_{pzc} = 9$). The light acid pH can also be reached without introducing any chemical product (HCl), but only by contact between distillate water and CO_2 present in the atmosphere during the mixing carry out for preparing suspension.

5. TESTS RESULTS ON SHOCK

To evaluate the dynamic response of different types of seeding, tests in the presence of shocks of different intensity took place. Seven different flow conditions were realized by changing the Total Pressure in the calm chamber, corresponding to maximum velocity achieved and shock intensity endured by the flow increasing as follows:

109 kpa($v_{max} \approx 215$ m/s)	135 kpa($v_{max} \approx 430$ m/s)
115 kpa($v_{max} \approx 335$ m/s)	150 kpa($v_{max} \approx 445$ m/s)
124 kpa($v_{max} \approx 405$ m/s)	160 kpa($v_{max} \approx 465$ m/s)
	170 kpa($v_{max} \approx 480$ m/s)

The velocity curves obtained for that Total Pressures for each seeding, some comparison graphs and respective velocity root mean square (RMS) are reported in Figures 15–25. In those graphs, as comparison, is also reported the velocity curves obtained by pneumatic measurement.

In any case it was noticed that where a shock takes place the RMS values are 4–5 times greater. This characteristic can be used to locate the shock section when velocity course do not allow to do that accurately. This can be

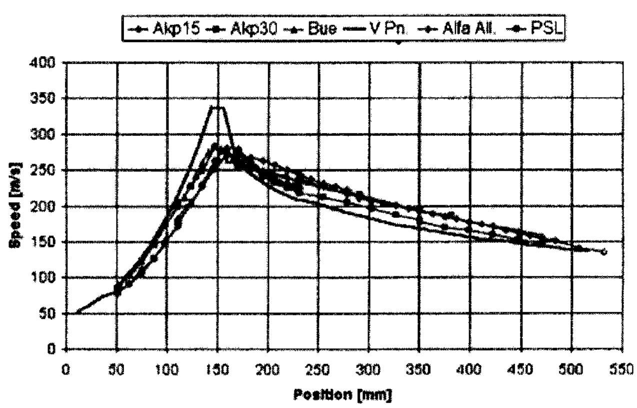


FIGURE 15 Seeding RMS for Po = 115 kPa (See Colour Plate at back of issue.).

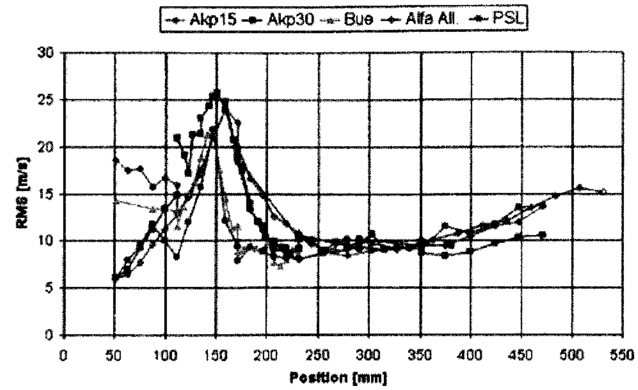


FIGURE 16 Seeding RMS for Po = 115 kPa (See Colour Plate at back of issue.).

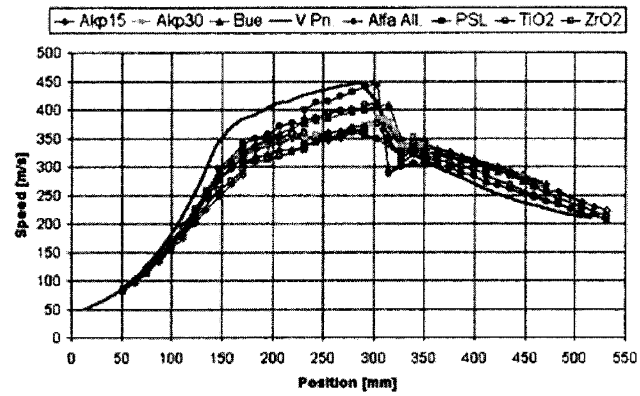


FIGURE 17 Seeding velocity for Po = 150 kPa (See Colour Plate at back of issue.).

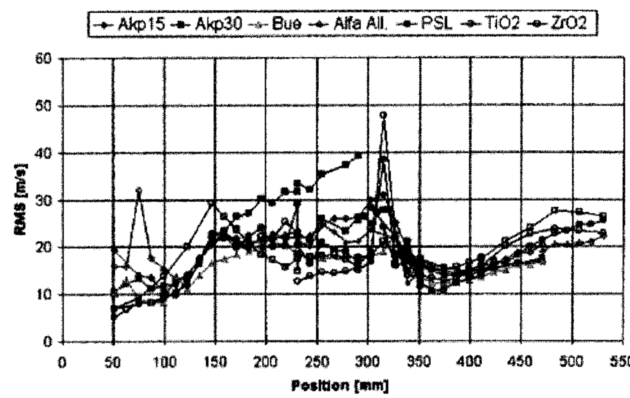


FIGURE 18 Seeding RMS for Po = 150 kPa (See Colour Plate at back of issue.).

clearly seen in Figures 15 and 16 where the calm chamber total pressure is 115 kPa and the velocities courses are very smooth. In this case locating the shock section using the velocity course is difficult, but the RMS trend gives accurate information. Also in the inlet zone (first part of the nozzle) greater RMS values are found even if in this case the type of growth changes very greatly with seeding.

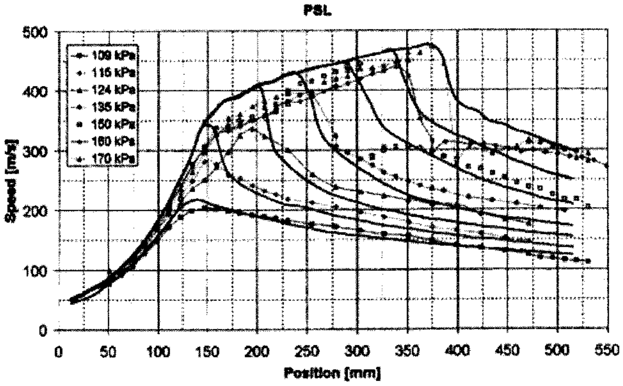


FIGURE 19 PSL velocity (See Colour Plate at back of issue.).

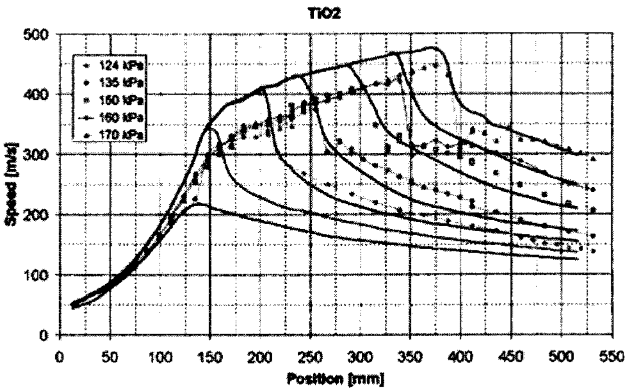


FIGURE 20 TiO_2 velocity (See Colour Plate at back of issue.).

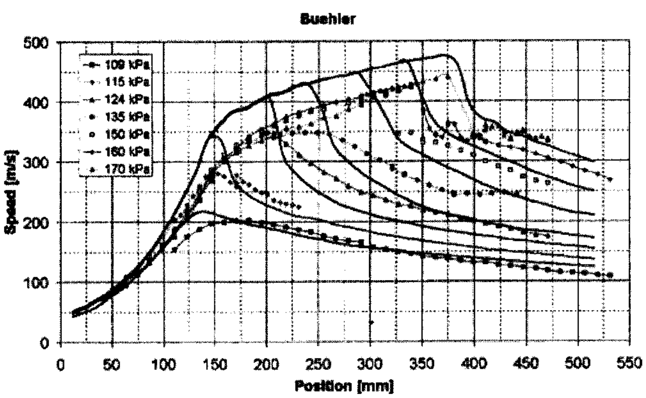


FIGURE 21 Buehler Aluminum Oxide velocity (See Colour Plate at back of issue.).

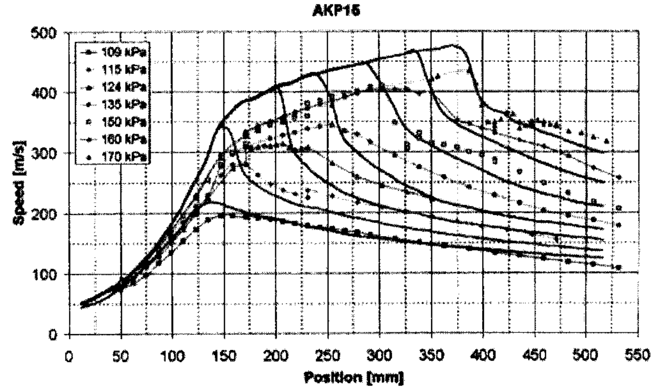


FIGURE 22 AKP15 Aluminum Oxide velocity (See Colour Plate at back of issue.).

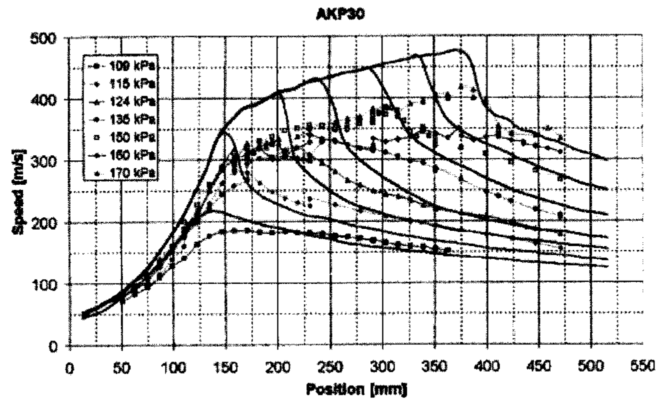


FIGURE 23 AKP30 Aluminum Oxide velocity (See Colour Plate at back of issue.).

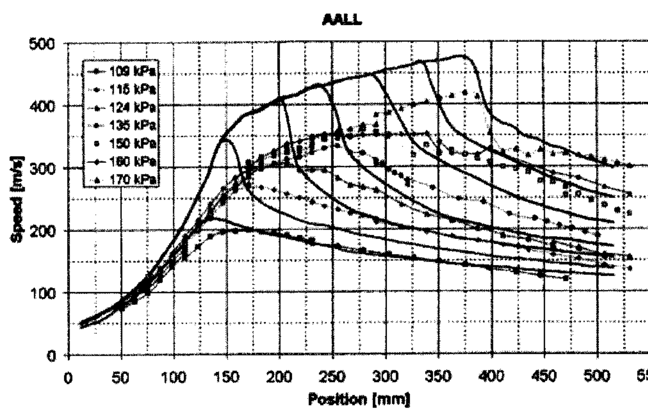


FIGURE 24 Alfa Aluminum Oxide velocity (See Colour Plate at back of issue.).

This effect is due to the fact that in the first sections of the nozzle the velocities are still very low and so seeding tends to adhere to the glass, making it dirty and making measurement more difficult. The same thing can happen in the final sections of the nozzle, downstream of the shock, where speeds can be low again. The curves obtained were compared with those obtained by direct pressure measurement. In this way it was possible to locate the delay with which seeding feels the shock and the difference between the maximum seeding and flow velocity. In our setup the flow velocity can be measured only in presence of pressure taps (each 6 mm). This forbids to have an enough accurate evaluation of the spatial delay with which seeding feels the shock. In any case analyzing the experimental data it is

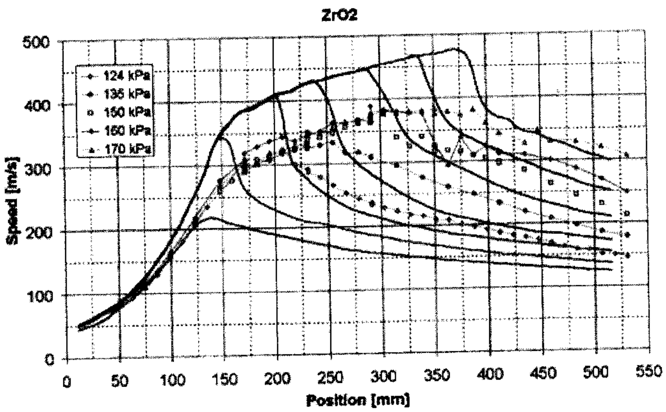
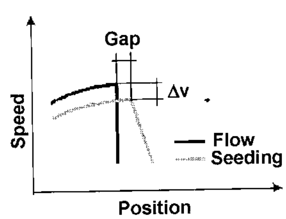


FIGURE 25 ZrO_2 velocity (See Colour Plate at back of issue.).

possible to see that the best seeding is PSL that usually present delays 3–4 times smaller than other seedings. Evaluation of the distance used by the seeding to conform with flow velocity after the shock is much more difficult. It was decide to use RMS trend as reference. After the peak in the shock section, the RMS value returns to levels comparable with those before the shock, with a delay during which the flow has covered the space that the authors define "Relaxation Space". In Table III the rates ($\Delta v/v^{*}100$) of speed gap and flow velocity just before the shock of each seeding are reported (see the graph near Tab. III). The results when Total Pressure is 115 kPa are not reported since in that case, the shock is approximately in the throat section and this causes not reliable measurements. The Polystyrene speed gap value for Total Pressure about 124 kPa is not reported too. How can be seen from Figure 19 some problem due to shock and wind tunnel stability occurs.

For pressures in calm chambers under 135 kPa, the shock is just after the throat after a brief section where the

TABLE III Percentage speed gap ($\Delta v/v^{*}100$)



	Calm chamber total press. (kpa)					
	170	160	150	135	124	109
AKP15	8,8	14,6	15,9	19,8	22,3	9,7
AKP30	16,0	25,5	14,3	23,1	18,8	14,4
Alfa All.	12,0	24,5	20,6	22,4	24,3	7,9
Buehler	7,1	8,2	8,5	18,9	15,6	6,5
PSL	0,6	6,0	0,7	8,2	...	6,0
TiO_2	5,9	9,7	8,3	12,8	17,8	...
ZrO_2	19,7	18,9	15,7	22,4	20,0	...

flow speed increases greatly. Such strong acceleration is not followed by the seeding that remains at lower velocities: this explains why when the shock occurs the difference between the flow and seeding speed is so big. The same is also true for higher pressures if big inertia seedings like Zirconium Oxides are used.

Analyzing Figures 19–25 can be clearly seen the difference between a good seeding that strictly follows the flow and a bad one that keep itself on much lower speed. *Polystyrene* (PSL) is the seeding that has the best behavior both for speed gap, even lower than 1%, and for RMS trend consistency (big values only in the zone involved by the shock). It has an excellent response and high data rate. The tendency was noticed, however, for the optical access glass to get dirty. Among all seedings it is the one that has showed greatest sensitivity to velocity changing and is the one that best follows real flow velocity.

Also *Titanium Oxide* (TiO_2) keeps itself at very low speed gap value, only slightly bigger than those of Polystyrene, quite different from *Zirconium Oxide* (ZrO_2) that has rather high gaps and speed gaps. Both of these oxides showed excellent scattering properties and did not adhere to the optical glass. Their weight made them settle very quickly. For ZrO_2 it was noticed that velocity distributions after the shock had two maximum peaks, very probably due to the not homogenous particles size distribution that has maximums for values between 1–3 μm as claimed by the manufactures.

In the case of Aluminum Oxide, the *Buehler* variety has good sensitivity to shock and high velocity as predictable, considering its small dimensions. Moreover, the glass does not become very dirty except for the shock section. *AKP15* also has good sensitivity and guarantees even greater cleanliness than the Buehler variety. It has no deposit even in the shock section. *AKP30* has the same compactness and weight as AKP15, but with much less satisfactory results. *Alfa* Aluminum Oxide has very similar characteristics to Buehler as far as compactness and weight are concerned, but the results achieved were not very satisfactory. The great inertia of these particles (the dimensions are much bigger than those of the other kinds of Aluminum Oxides) does not allow them to reach flow velocity and follow it well in the presence of speed gradients. The seeding characterization carried out allows choice of the best seeding for any different application and measurement typology.

6. GRID MEASUREMENTS IN THE NOZZLE

To simulate some turbomachinery situation (centrifugal compressor diffuser) wind tunnel set up was modified by placing a blade in the divergent part; the velocity in the

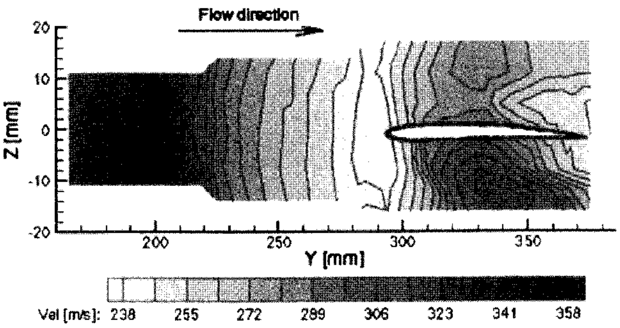


FIGURE 26 Flow velocity field around a blade.

nozzle was verified. Subsequently the results of tests carried out with Buehler Aluminum Oxide are reported. The measures were made using a rectangular grid scheme (42 traverse with 6 measurement position each). The upper and lower limits of each grid were taken as near as possible to the walls. The results are shown in Figure 26.

As can be seen it is possible to locate the supersonic zone on the left and the shock zone where the speed goes down quickly. In figure it is also possible to see two flow acceleration zones over and under the blade due to vane squeezing.

7. CONCLUSIONS

From study of the different seedings it emerges that Polystyrene behaves best, is able to follow better than others the flow velocity course. It also behaves best in the in presence of quick velocity changing (it is the first to feel the speed changing and the first to conform with that after the shock). It reaches the highest velocity and the lowest downstream. The section where it feels the velocity decreasing is quite the same as the one located by the pneumatic curve. This is more rare for the others seeding. This is probably due to the low inertia of seeding that has a very low specific weight. Finally data rate characteristics are very high (values up to 25000–35000 sample/second were achieved in turbomachinery applications), and particles velocity distribution very good. This is probably because, as can be seen, the seeding produced and tested in our department, in relation of other seeding, is extraordinarily mono-dispersed and the particles are all spherical, thus having excellent Signal to Noise Ratio for use with LDV system. The only flaw of PSL is the low fusion temperature that limits its use in turbomachinery. Dirt on optical access could be limited by carefully controlling the seeding flow. Another possible drawback is the easiness with which it tends to close the seeding inlet ducts, especially when they are very small (ducts of 0.4–0.5 mm were used). When the conditions do not allow use of PSL (temperature greater than 150–200°C), it is better to use Aluminum Oxide. This, even if it is less able to follow the flow, particularly when there are velocity variations (worse dynamic response), could resist up to 2000°C. Among the Aluminum Oxides studied, the best was without doubt the Buehler variety since it is the one that follows flow behavior best. The Aluminum Oxide suspension preparation needs some attention and care because it tends to form conglomerates and deposits. This does not happen when using Polystyrene.

In the case of Titanium and Zirconium Oxides, a good response for the former was noticed, almost comparable with PSL, while for the latter weight and consequent inertia greatly limit its use. One should add in favor of Titanium Oxide that the great scattering index makes small quantities of seeding necessary for measurements. Even in this case temperatures can reach 3000°C.

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NOMENCLATURE

d_m	width of measurement volume (mm)
l_m	length of measurement volume (mm)
λ	wave length of laser beam (nm)
δ	distance between interference fringes (μm)
N_{fr}	number of interference fringes in measurement volume
$v_{\max}$	maximum speed measurable with acquisition system used (m/s)

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