

# ASSESSMENT OF FREE STREAM SEEDER PERFORMANCE FOR VELOCIMETRY IN A SCRAMJET COMBUSTOR

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## Abstract

A free stream seeder designed to produce particles to conduct particle image velocimetry (PIV) in a scramjet combustor was studied. Using a probe and filter paper coupled to a vacuum pump, samples were collected from the output of the seeder in conditions near to those that are encountered in PIV studies. The filter paper samples were imaged using a scanning electron microscope (SEM) to obtain qualitative and quantitative data about the particles being generated. The seeder was able to produce 0.27  $\mu\text{m}$  diameter particles, near the target size of 0.30  $\mu\text{m}$ . The light scattering and flow tracking abilities of the particles were also examined with the results indicating that the particles will perform well in scramjet combustor PIV research.

## Nomenclature

$C_D$	= drag coefficient
$C_s$	= scattering cross section
$d_p$	= particle diameter
$dV_p/dt$	= acceleration of the particle
$f_c$	= turbulence frequency
$I_o$	= laser intensity
$K_{sp}$	= ratio of specific heats
$M_p$	= relative Mach number
$P_s$	= total scattered power
$R$	= specific gas constant
$Re$	= Reynolds number
$T$	= temperature
$\overline{u_p^2}/\overline{u_f^2}$	= relative fluctuation intensities of particle and fluid motions
$V_g$	= velocity of the fluid
$V_p$	= velocity of the particle
$\mu$	= viscosity of the fluid
$\rho_g$	= density of the fluid
$\rho_p$	= density of the particle
$\omega_c$	= angular frequency of turbulent motion

## Introduction

Particle Image Velocimetry (PIV) has become a common non-intrusive method that is used by experimentalists to investigate complex flow fields. The

key advantage is that PIV can be applied in high speed flows without the flow being disturbed by the presence of probes<sup>1</sup>. However, the technique relies upon using a suitable seeding concentration with appropriately sized, uniform particles to produce quality results. Proper particle size means that the particles are large enough to provide a strong signal to noise ratio but also small enough to faithfully track the flow. Uniform seeding size helps avoid excessive intensity from larger particles and background noise from smaller particles<sup>2, 3</sup>. A number of methods exist for producing such seeding, but the present study is concerned with the application of PIV in the University of Virginia Supersonic Combustion Facility<sup>4,5</sup> where high temperature and velocity make most seeding methods unfeasible.

The supersonic combustion facility is a continuous running, open wind tunnel design that produces a vitiate-free Mach 2 flow. Mach 5 flight enthalpy of a scramjet is simulated using electrical resistance heaters, and supersonic combustion of hydrogen is studied using a single 10-deg unswept ramp fuel injector. Temperatures approach 1200 K during mixing and 1800 K during combustion. In order to obtain velocity information on the entire flow field resulting from the combustion process using PIV, both the fuel and free streams must be seeded with particles. Although PIV data has been taken from the fuel stream<sup>6</sup>, no data has been taken from the free stream since an effective seeder has yet to be implemented. Because the free stream has a flow rate approximately 250 times that of the fuel stream, a different style particle seeder is needed for the free stream. The current work is aimed at the design and assessment of such a free stream seeder and the particles produced.

Extensive literature exists for different methods of particle seeding<sup>1-3</sup>. Condensation and atomization are the most common for liquid droplets whereas atomization and fluidized beds are the most common for solid particles. Atomizers can disperse solid particles in an evaporating liquid or create high vapor pressure droplets in a low vapor pressure liquid<sup>1</sup>. In a fluidized bed, particles are suspended in a chamber and then drawn out of the top for dispersion into a flow<sup>2</sup>. Smoke machines may also be used to seed gas flows. The literature also presents a variety of particle types. Some of the more common particles used in gas flows

include oils, polystyrene, titanium dioxide ( $\text{TiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ), and silica ( $\text{SiO}_2$ ). For high temperature flows, such as the one in consideration that can reach over 1800 K, the particles must have a sufficiently high melting or boiling temperature in order to scatter light prior to breaking down.

The desired particle size is a critical decision in PIV implementation as well. The choice of optimal diameter for seeding particles is a compromise between an adequate response of the particles to changes in the flow, requiring small diameters, and high signal to noise ratio of the scattered light signal, necessitating large diameters<sup>2</sup>. Past work at the supersonic combustion scramjet facility has indicated that 0.3  $\mu\text{m}$  diameter sized particles are a suitable balance between flow tracking and light scattering ability for the current PIV work<sup>6</sup>.

A free stream seeder using silica particles using a fluidized bed was chosen for implementation. The seeder design is discussed later. Although the silica particles are specified at 0.25  $\mu\text{m}$  diameter by the manufacturer, it can not be assumed that the seeders are producing particles of this size. This is because particles this small tend to agglomerate, especially after periods of storage or exposure to humidity. Thus, it is necessary to assess the performance of the seeding system by measuring the output particle size.

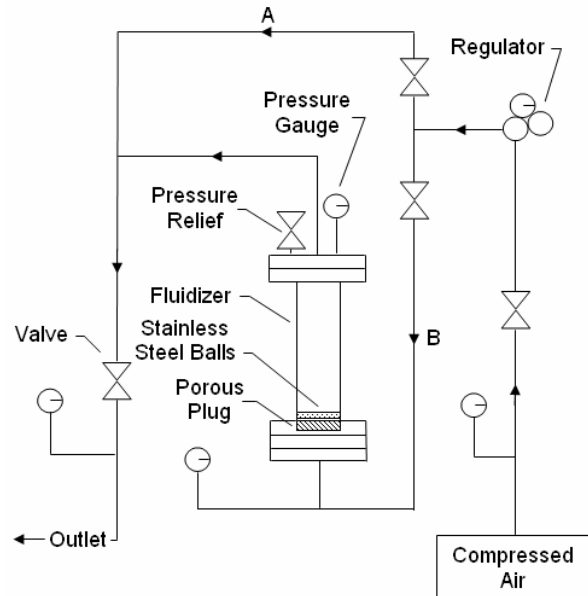
This paper presents the design of a free stream seeder and the results of an experiment aimed at measuring the particle output size by the seeder. In the experiment, particles were sampled from seeded air flow using a probe and filter paper. The particle size was determined directly by analyzing images from a scanning electron microscope (SEM) of the particles on the filter paper. These results will be presented along with a discussion on the theoretical light scattering and flow tracking ability of the particles output by the seeder.

### Design

The free stream seeder was designed with four main criteria: 1) output particle size and particle size distribution, 2) output particle number density, 3) operating pressure and pressure drop, and 4) controllability. The first point emphasizes the need to design a seeder that produces particles near 0.3  $\mu\text{m}$  in size as required by PIV experiments. The number density is critical since at least 15 particles are recommended per PIV interrogation region<sup>7</sup>. However, the density must not be too high either as this can lead to difficulty in distinguishing individual particles. The seeder also needs to operate at pressures higher than the flow in which the particles will be injected, but the operating pressure should be minimized above that point to reduce pressure vessel design requirements.

Likewise, the pressure drop in the seeder should be minimized since a larger pressure drop requires a higher initial pressure. Finally, the seeder should have controllability over the output number density so that seeding can be adjusted as necessary during PIV experiments.

The free stream seeder is shown schematically in Fig. 2. The flow was split, with Path A bypassing the fluidizer and Path B going to the fluidizer. During the experiment, all of the flow was directed into the fluidizer with Path A remaining closed. Once particles rose to the top of the fluidizer, they were brought to the exit of the seeder for injection into the flow.



**Figure 2: Schematic of free stream seeder apparatus.**

An approximately 1.5 cm thick layer of stainless steel balls at the bottom of the fluidizing chamber was used in order to disperse random jets being produced by the porous plug. A particle shearing nozzle, which is used in the fuel stream seeder, was not possible since the flow rates necessary for such a design would introduce too much unheated air into the wind tunnel. The shearing nozzle works by injecting particles transversely into a high speed flow, which effectively shears apart agglomerates.

Amorphous silica microspheres with a manufacturer specified diameter of 0.25  $\mu\text{m}$  +/- 0.05  $\mu\text{m}$  and particle density of 2000  $\text{kg}/\text{m}^3$  were chosen as seeding particles. Although no melting point is specified by the manufacturer, amorphous silica's melting and boiling points are over 1700 K and 2200 K, which means particle breakdown during combustion testing is not expected.

The seeder was designed to operate at 410 kPa with little or no pressure drop, which is well within the

design criteria. Additionally, the seeding density could be controlled by adjusting the seeder's supply pressure or by changing the amount of flow between the Path A and Path B.

### Experimental Technique

Several possibilities were considered for examining the sizes of particles output by the seeder. Measuring particles from PIV images taken during experiments would be the most convenient way of obtaining particle size; however, the PIV equipment used at the scramjet combustion facility is only capable of 9  $\mu\text{m}$  resolution, which won't provide any useful information on the size of sub-micron sized particles. Alternatively, a laser can be used to observe a particle's diffraction or aerodynamic flight time<sup>8</sup>. The former method correlates the intensity and angle of light scattered by the particles to their size. The latter method looks at the deceleration of a particle between two light sources and then determines particle size using the known density of the particle material. However, since both methods assume spherical particles, incorrect results would be found if the particles are not spherical. This assumption was not made for the silica particles.

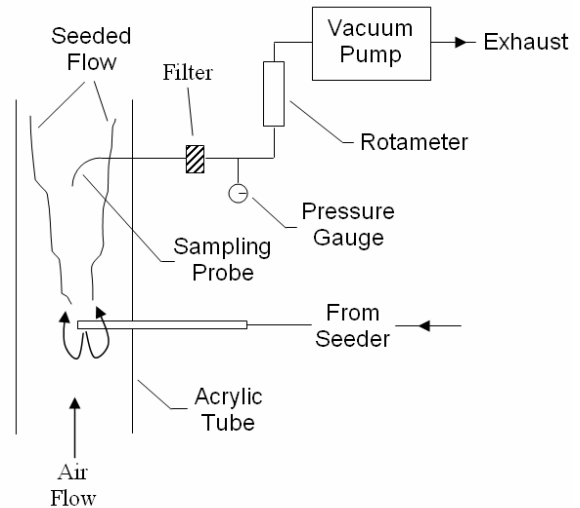
In the end, the output seeded flow was sampled directly using a probe and filter paper coupled to a vacuum pump. The particles could not be sampled from the free stream in experimental conditions due to the high temperatures and velocities involved. Therefore, an experiment was designed for collecting samples from the seeder that enabled the operation of the seeder as close as possible to normal conditions. A flow was seeded that was similar to that of an actual combustion experiment, and then particles were sampled from that flow. The details of the experiment are presented in Table 1.

**Table 1: Test Conditions**

Parameter	Free Stream
Seeder Gas	N <sub>2</sub>
Particle type	0.25 $\mu\text{m}$ SiO <sub>2</sub>
Primary filter paper	0.1 $\mu\text{m}$
Rotameter flow rate	5 ft <sup>3</sup> /hr
Exposure times	30 s, 2 min, 5 min

The free stream seeder was tested in a flow through an acrylic tube created by a blower at room temperature. The flow created by the blower was similar to that encountered at the point of injection in the scramjet combustion facility. An overview of the setup is given in Fig. 4. The particle laden air from the seeder was injected against the flow direction using the actual wind tunnel free stream injector. A 1.32 mm diameter sampling probe constructed out of Inconel

tubing was used and placed approximately 32 mm downstream of the injector. The velocity of the air flow in the acrylic tube was measured using a pitot tube with the results indicating that the flow needed to be sampled at 0.17 m<sup>3</sup>/hr in order to ensure isokinetic sampling. Isokinetic sampling requires that the flow rate into the probe be the same as the flow rate in the acrylic tube so that biasing towards sampling smaller or larger particles does not occur. The air was pulled through 0.1  $\mu\text{m}$  filter paper using a vacuum pump along with a rotameter and vacuum gauge to verify flow conditions.



**Figure 4: Overview of free stream seeder experimental setup.**

Nitrogen was used in the free stream seeder instead of air, which will be used in wind tunnel applications, since compressed nitrogen was readily available. The static pressure of the fluidizer was also changed from normal wind tunnel operating conditions. Normally, the fluidizer operates at a maximum of 410 kPa (roughly 160 kPa above the tunnel's total operating pressure of 250 kPa). Pressures higher than this in the fluidizer will introduce an unwanted amount of unheated air into the wind tunnel free stream. The fluidizer was operated at 70 kPa above the total pressure in the acrylic tube at 270 kPa. The total pressure in the acrylic tube was 200 kPa. Thus, a higher seeding density could be achieved at higher pressures in the fluidizer during wind tunnel operation than was done by this experiment.

The samples were imaged using a scanning electron microscope (SEM). A square, roughly 1 cm in length, was cut out from each sample so that the samples would fit on the SEM mounting blocks and mounted for inspection. Samples were also coated with a 10-20 nm layer of gold palladium to reduce image drifting under high magnification due to a charge

buildup, which resulted from the filter paper being non-conductive.

### Image Processing

The non-homogeneous nature of the filter paper made it very difficult for computer programs to discern between the particles and filter paper. As a result, no automated processes were created that could successfully extract quantitative data from the SEM images. Therefore, the image processing for the samples was performed manually. The particles' characteristic lengths were measured using an image viewer, where a particle's longest linear dimension was defined as its characteristic length, which would also be assumed to represent its diameter. This length was measured in pixels and then converted to metric units using a reference scale included on the SEM images. The results that will be presented were obtained from the same magnification, 3000x. However, the analysis was conducted at other magnifications to check for consistency.

### Results & Discussion

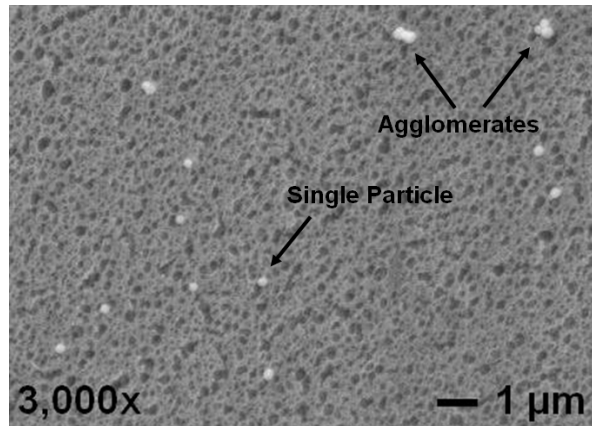
Several of the properties of the particles from the seeder are presented in this section. First, particle shape and size are discussed as obtained from direct analysis of the SEM images. Then the particles' abilities to scatter light and accurately track high speed and turbulent flows are examined.

#### Particle Shape

Using the SEM to create images of samples also enabled a close up look at the shape of sampled particles. Fig. 4 shows particles at 3000x. As can be seen in the figure, the primary silica particles were all nearly spherical. However, agglomerated particle sets, seen as one large particle in PIV experiments, were not spherical. Later analysis will assume a spherical shape for all particles and particle sets.

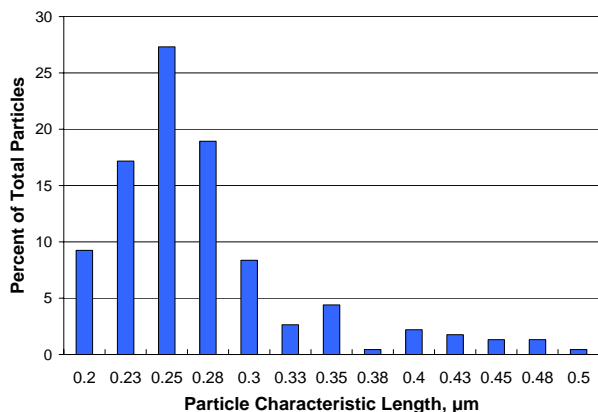
#### Particle Size

A histogram and cumulative distribution for the particle sizes are reported in Figs. 5-6, respectively. The histogram was truncated at 0.5  $\mu\text{m}$  since the remaining particles were only a few percent of the total particle count. The seeder's largest measured particle was 0.78  $\mu\text{m}$  and composed of four agglomerated primary particles. The data was collected from 227 measured particles in four images. Only the 2 and 5 minute run time samples were used in the analysis since the SEM images from the 30 second run time were blurry and would introduce unnecessary error.



**Figure 4: SEM image of particles captured on filter paper.**

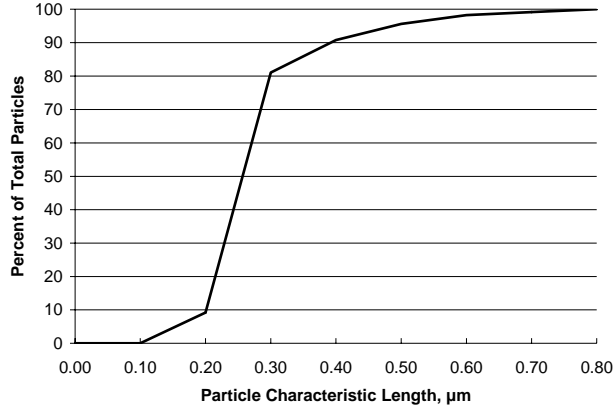
The free stream seeder's average output particle size was 0.27  $\mu\text{m}$ . It is interesting to note that 198 of the 227 particles counted were composed of only a single primary particle. The average size of the primary silica particles was 0.24  $\mu\text{m}$ , which is in agreement with the manufacturer specified size of 0.25  $\mu\text{m} \pm 0.05 \mu\text{m}$ . A vast majority of the remaining particles were composed of only two primary particles. Thus, it is seen that the seeder is successful at breaking down agglomerates.



**Figure 5: Histogram of particle sizes.**

#### Light Scattering

As mentioned earlier, the light scattering ability of a particle is critical to its effectiveness at providing useful knowledge of the flow. Too large of particles will saturate light sensing equipment while too small of particles will only generate noise. The theoretical light scattering cross section was calculated for the particles obtained during the experiment using the approach taken in Ref. 9.

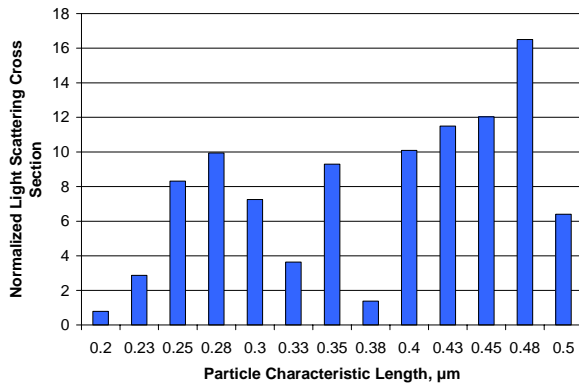


**Figure 6: Cumulative particle size distribution.**

Equation (1), given by Ref. 2, gives the relation for light scattering cross section,  $C_s$ , where  $P_s$  is the total scattered power and  $I_o$  is the laser intensity incident on the particle. It was assumed that the particles would scatter light according to Mie theory based on particle sizes. It was also assumed that  $C_s$  scaled to the particle characteristic length raised to the sixth power, and that observation angle could be neglected, which is sensitive to particle size. Fig. 7, showing the light scattering cross section, was produced using the particle size distribution shown in Fig. 6 using a linear weighted average.

$$C_s \equiv \frac{P_s}{I_o} \quad (1)$$

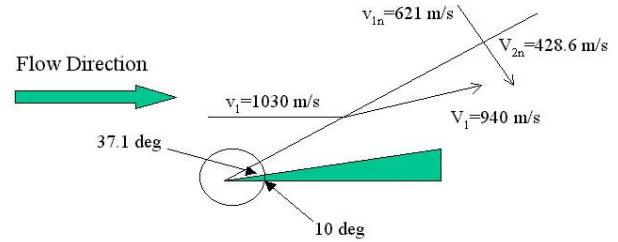
The analysis shows that the silica particles scatter light fairly evenly over the range of particle sizes. The signal to noise ratio produced by the particles in PIV tests, therefore, should be excellent for obtaining quality data. The larger particles will not saturate PIV sensing equipment, and the smaller particles will not degrade the data with background noise.



**Figure 7: Normalized Mie light scattering cross section.**

## Flow Tracking

Flow across an oblique shock wave is first considered in order to investigate each particle's flow tracking ability using the approach used in Ref. 9. Since the step change in velocity across a shock is nearly instantaneous, studying a particle's ability to track such a change is a convenient way to measure its flow tracking ability across to a large disturbance. The case considered is depicted in Fig. 8, where an oblique shock is generated in a Mach 2 flow with a velocity of 1030 m/s over a 10-deg wedge. These conditions were chosen as they are typical of the conditions seen in Ref. 4 and 5. The velocity vectors  $V_1$  and  $V_2$  shown in Fig. 8 correspond to the streamline velocities upstream and downstream of the shock, respectively, and  $V_{1n}$  and  $V_{2n}$  the velocity components normal to the shock.



**Figure 8: Oblique shock formation in air on a 10-degree wedge (reproduced from Ref. 9 with permission).**

The approach taken by Meyers in Ref. 3 was used to calculate the particle acceleration after the oblique shock. As explained in Meyers, since the particle density is much greater than that of the fluid, the particle motion can be adequately described using only Stoke's drag as the force term. The particle acceleration can then be given as follows:

$$\frac{dV_p}{dt} = \frac{3 C_D \mu Re}{4 \rho_p d_p^2} (V_g - V_p) \quad (2)$$

In Eq. 2,  $dV_p/dt$  is the acceleration of the particle,  $C_D$  is the drag coefficient, defined in Eq. 3a,  $Re$  is the effective Reynolds number between the gas and particle, defined in Eq. 3d,  $\mu$  is the viscosity of the fluid,  $\rho_p$  is the density of the particle,  $d_p$  is the diameter of the particle,  $V_g$  is the velocity of the fluid, and  $V_p$  is the velocity of the particle. In Eq. 3c,  $M_p$  is the relative Mach number,  $K_{sp}$  is the ratio of specific heats, and  $T$  is the temperature.

$$C_D = \frac{\bar{C}_D + \frac{51.1}{\text{Re}} M_p}{1.0 + 0.256 M_p \left( \bar{C}_D + \frac{51.1}{\text{Re}} M_p \right)} \quad (3a)$$

where

$$\bar{C}_D = \frac{24}{\text{Re}} + 0.4 + 1.6e^{-0.028 \text{Re}^{0.82}} \quad (3b)$$

$$M_p = \frac{|V_g - V_p|}{\sqrt{K_{sp} RT}} \quad (3c)$$

$$\text{Re} = \frac{\rho_g |V_g - V_p| d_p}{\mu} \quad (3d)$$

The model presented assumes spherical particles. The input parameters for the analysis are summarized in Table 2. By applying this particle drag model to the particle distributions shown earlier, it was possible to determine the proportion of particles accurately tracking the flow at a distance downstream of the shock.

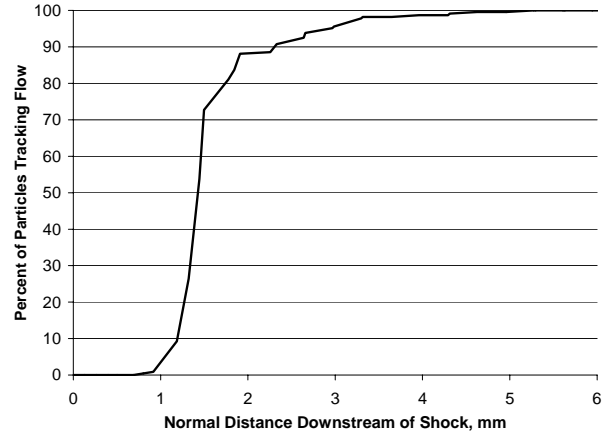
**Table 2: Flow tracking calculation input parameters**

Parameter	Value
$V_{n1}$ , m/s	621.0
$V_{n2}$ , m/s	428.6
Gas density behind shock, kg/m <sup>3</sup>	0.22
Specific heat ratio behind shock	1.34
Gas constant behind shock, J/kg K	287
Static temp. behind shock, K	667

A particle was considered to be effectively tracking the flow if its velocity was within 10 % of the fluid velocity. Fig. 9 shows the proportion of particles tracking the flow as a function of the normal distance downstream of the shock. Nearly 90 % of the particles are tracking the flow 2 mm downstream of the shock. However, the diagnostic equipment used in PIV experiments is capable of resolution on the order of 1 mm where very few particles are tracking the flow. If a strong disturbance, such as a shock, is encountered in PIV studies, this would cause the shock structure to appear smeared in results.

A particle's response to turbulence was also considered. The approach used by Melling in Ref. 2 is used here. A particle was considered to be responding to turbulence in the flow if the ratio of the fluctuation intensities of the particle and fluid motion, the left hand side of Eq. (4a), were equal to 0.95. The fluid viscosity,  $\mu$ , in Eq. (4b) was found using Sutherland's model. The angular frequency of turbulent motion,  $\omega_c$ , and the

frequency of turbulent motion,  $f_c$ , are related in Eq. (4c).



**Figure 9: Particle tracking behavior downstream of an oblique shock wave.**

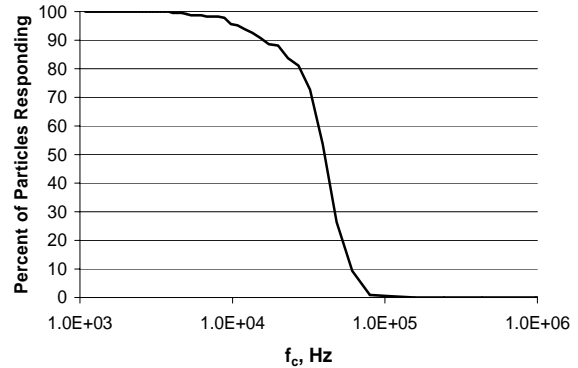
$$\frac{u_p^2}{u_f^2} = \left( 1 + \frac{\omega_c}{C} \right)^{-1} \quad (4a)$$

where

$$C = \frac{18\mu}{\rho_p d_p^2} \quad (4b)$$

$$\omega_c = f_c \cdot 2\pi \quad (4c)$$

The plot in Fig. 10 shows the percentage of particles responding to a given turbulence in the flow. All of the particles are capable of responding to turbulence frequencies less than 10<sup>3</sup> Hz, and 95 % of the particles will respond to frequencies less than 10<sup>4</sup> Hz.



**Fig. 10: Particle frequency response.**

### Conclusion

A particle seeder designed for use in the free stream of a scramjet combustor has been presented. An

experiment was performed to assess the output particle size from the seeder. Particles were sampled from the seeded gas from the seeder using a probe and filter coupled to a vacuum pump system. The filter paper was imaged using an SEM so that the particle characteristic length of the output particles could be determined. The seeder produced an average particle size of 0.27  $\mu\text{m}$ . SEM images showed that the primary silica particles were nearly spherical.

Predictions on the light scattering and flow tracking ability of the particles were made assuming all particles were spherical. Using a Mie scattering model, it was seen that particles over the whole range of sizes obtained from the seeder scattered similar amounts of light. This means that data acquired in future PIV tests using this seeder will have excellent signal to noise ratios. The flow tracking ability of the particles was also presented by using a Stoke's drag model. At 2 mm normal distance downstream of an oblique shock, it was predicted that 90 % of the particles were capable of accurately tracking the flow. Although this is exceptional performance, it does mean that discontinuities in the flow will appear slightly smeared in PIV results. It was also seen that 95 % of the particles are capable of responding to turbulence frequencies of up to  $10^4$  Hz.

The experimental results indicate that a fluidized bed can be used with great success in generating non-agglomerated, uniform seeding particles from silica powder for PIV experiments. Moreover, the particles output by such a seeder have excellent light scattering and flow tracking properties. Future work includes implementing the free stream seeder in the supersonic scramjet combustion facility and evaluating the quality of the data against the predictions presented in this paper.

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