Solid Particle Seeding using Cyclone Gas Flow for Optical Flow Visualization: Design Parameters to be Considered

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ABSTRACT

Flow Visualization is an evolving field that has many advantages over intrusive testing methods. Commonly employed methods of Flow Visualization include Particle Image Velocimetry, Planar Laser-Induced Fluorescence, Laser Doppler Velocimetry and Schlieren Imaging. These not only vary in terms of the type of visualization equipment used, but also in terms of the way in which the Flow is finally visualized. Flow Visualization begins with flow “seeding” i.e. the introduction of discrete & definite alien particles into the flow.

Seeding of Solid Particles in a compressible flow stream, using a Cyclone Jet is a much-favored and commonly employed method for Seeding, owing to its simplicity of design, construction and operation. Design Parameters that have to be considered for a cyclone-based seeding have been discussed in this paper, vis-à-vis the general properties of the seed particle and the nature of visualization techniques employed. An analytical view of Cyclone Seeding is also presented. Mei’s particle tracking model [5] is used as a base reference for the flow visualization. A simple design which was used for Particle Image Velocimetry testing, is also described.

**Keywords**: Compressible Flow, Cyclone, Flow Visualization, Particle Image Velocimetry, Particle Tracking, Seeding

**Abbreviations**

\[ D_o = \text{Outlet diameter};\ D_i = \text{Inlet Diameter};\ H = \text{Seeder Height};\ a = \text{Seeder Base Radius};\ b = \text{Helix Pitch of the Jet Trajectory}, w.r.t. = \text{with respect to} \]
1 INTRODUCTION
Optical flow visualization techniques have gained ground over the last decade, primarily due to their non-intrusive nature. These techniques – popular among which are PIV, PLIF, LDV and Schlieren – all have a commonality, in that they rely on particle scattering of light [3]. Hence, the fidelity of the particles in representing the flow is determined by two aspects – the faithfulness of the particle in following the flow, and the scattering intensity of the particle with respect to the incident light. Smaller particles follow the flow more faithfully, whereas larger particle scatter light more effectively – this leads to an inconsistency between two important parameters that affect the result, and almost always a compromise is sought between the two.

The current paper will consider the first of the two parameters – faithfulness in flow representation – which is a direct result of the design of the seeder. In other words, uniform seeding is required to accurately represent the flow. The study will discuss design parameters that affect the output of the seeded flow, the quality of seeding and its effect on the image.

2 DESIGN PARAMETERS
The main design objectives to be achieved are compatibility with multiple particle types and uniform dispersion of seed within the flow. These are affected by the following design parameters: $\frac{\text{Height}}{\text{Diameter}}$ Ratio of the seeder, inlet height, inlet shape and orientation, and outlet position & diameter.

A General Design is described in Section 4 below. The Design Considerations described herein have been verified using the commercial CFD Software Fluent [2], and generated results have been reported.

3 DESIGN CONSIDERATIONS
3.1 Slenderness Ratio:
The ratio of the Seeder Height to the Diameter of the Base is the slenderness ratio. This design factor plays an important role in determining stagnation of the cyclone jet. Slenderness ratio and inlet angle together determine the helical path of the cyclone jet. Helix Equations governing the motion of the Jet are:

\[
\begin{align*}
    x &= a \cos(t) \\
    y &= a \sin(t) \\
    z &= bt
\end{align*}
\]

where $a$ is the radius of the helix (i.e. the base radius) and the pitch of the helix is $2\pi b$.

The length of a circular helix of radius $a$ and pitch $2\pi b$ in rectangular coordinates as:

$t \rightarrow (x, y, z) \equiv t \rightarrow (a \cos(t), a \sin(t), bt); \ t \in [0, H]$

is given by

\[
L = H \sqrt{a^2 + b^2}
\]
In this case, $L$ is the distance travelled by the Cyclone Jet over a Seeder of Height $H$, and is influenced by the radius $a$ and the pitch $2\pi b$.

Ideally, the Slenderness Ratio should lie between 5 and 8. Previous Research by Glass & Kennedy [4] has involved the use of a Height/Diameter Ratio of 5. Numerical testing, moreover, has shown that values near 8 function just as efficiently. (see Section 4 below) However, the cyclone jet trajectory is also a function of the Inlet Angle, in addition to the Height and Radius, and is expressed as a function of the pitch of the helix $b$. (see Section 3.4.1 below)

3.2 Inlet Height & Outlet Height:
The inlet should be positioned at about $0.8H$ or $0.9H$ from the base. This would allow for sufficient motion of the jet before particle entrainment from the particle bed at the base. These heights are however, only approximations. Inlets positioned mid-way between the base and outlet lead to formation of high-pitch helices (Fig. 1). These, in turn, cause direct scooping of the particles from the particle bed, which is a highly undesirable phenomenon. (See sec. 3.4.1 Inlet Angle) The flow of the jet from the inlet to the base is drive by external flow velocity (provided at inlet) and is impeded by friction from the seeder walls. The flow from the base to the outlet, in contrast, is driven by pressure. Thus, it is in the interest of seeding quality that the jet re-circulate at the base a few times to entrain particles before rising up to the outlet. It can be seen from (Fig. 5a) that quality seeding is achieved when the jet executes re-circulation at the particle bed. This also provides the additional momentum required to lift the heavier particles into the flow.

Inlet height is never an independent parameter, and is always determined relatively with respect to the outlet position. As shown in (Fig. 1), the streamlines indicate that if the outlet is positioned above the inlet, part of the fluid exits through the outlet without particle entrainment. This process is caused due to the fluid spread upon exit from the inlet pipe. This produces a non-uniformly seeded flow. The general schematic of such a seeded flow is as shown in (Fig. 2a).
Such a flow would have non-uniform seeding from the center outward, with the flow near the pipe walls having near-zero seeding. Consequently, this leads to overlap of multiple particles in the final images, leading to difficulty in matching the particles in successive images. For every 100 streamlines plotted, almost 25 experience a direct exit, which is a highly undesirable amount of flow that remains unseeded (Fig. 1).

To avoid this, the outlet is always sunk below the inlet level, with the seeder ceiling sealed off in an airtight fashion. As shown in (Fig. 4), designing an outlet in this manner causes upward spread to be redirected downward to the particle bed along with the main flow. Additionally, this redirected flow is not found to interfere with the main flow that occurs downward (Fig. 5a), because of the constancy of pitch of the trajectory.

**Figure 1.** Elevated Outlet, with inlet at 45° inclination halfway from base to outlet; high pitch helix trajectory; direct scooping of particles from bed; direct unseeded fluid exit through outlet.

![Figure 1](image)

**Figure 2a and Figure 2b (General Schematics).** Non-uniform seeding from pipe center outward, due to direct unseeded fluid exit through outlet (left); Uniform Seeding across pipe section (right)
The outlet can safely be sunk by a minimum of 1.5\(D_o\) units below the inlet, although this is only an approximation. By doing so, any upward spread of the inlet jet that occurs upon entry into the chamber can be prevented from directly exiting through the outlet, thus producing a uniform seeding across the pipe/flow section, as shown in the general schematic. (Fig. 2b). It also helps to have an Outlet Diameter \(D_o\) approximately twice the inlet Diameter \(D_i\); this way, the particle-laden outflow can freely exit the seeder without seeds clumping together. This is only an approximation; the only constraint is that Outlet Diameter be appreciably greater than Inlet Diameter.

3.3 Inlet Shape:
The Inlet is defined in terms of four important parameters – inlet height (w.r.t. base), inlet cross-section, inlet position (w.r.t. seeder axis) and inlet angle (w.r.t. base) – out of which the first has been discussed. (see 3.2 Inlet Height & Outlet Height)

The shape of the inlet, for obvious reasons, is almost always chosen to be circular. This provides for minimum wall shear stress. Additionally, circular inlets result in uniform spread upon entry into the seed chamber, which is favorable, considering the helical trajectory of the jet.

Square-section inlets and elliptical-section inlets (not shown) were tested out numerically, and were not found to have any desirable advantage. Additionally, from a fabrication point of view, circular inlets can be attached to cylindrical seed chambers with considerable ease as compared to other inlet shapes.

3.4 Inlet Orientation:
Inlet orientation refers to the inclination of the inlet pipe (w.r.t. the base) as well as its position relative to the seeder axis.

3.4.1 Inlet Angle
Inlet angle defines the helix pitch and the distance travelled by the jet before reaching the particle bed. Inlet angle, through numerical testing, has been found to favorably influence particle entrainment when kept between 30° and 45°. However, under non-ideal conditions, the downward flow of the jet is influenced by gravity. Therefore, it is advisable to have inlet angles within the range of 30° and 40°. Having inlet angles greater than 45° can lead to the particle bed being eroded non-uniformly by the incoming jet. At higher inlet angles (~45° or greater), the jet scoops particles from the bed directly with minimal or zero helical motion. This results in two disadvantages: on-uniform seed distribution within the jet and non-uniform erosion of the particle bed, particularly in the center. (Fig. 1).

3.4.2 Inlet Position
With respect to the seeder axis (i.e. the axis of the cylindrical seed chamber), the position of the inlet can be one of three configurations: tangential, radial or in between these two. (see top view Fig. 3). Tangential inlets are most common for many reasons: ease of fabrication, uniformity of flow helix, and ease of angular adjustment (see Section 4). Radial, semi-radial (i.e. positioned between radial and tangential) and other non-tangential configurations give rise to counter-rotating helices that intersect...
at multiple points in the trajectory. This effect is pronounced in inlets positioned very close to the seed chamber axis. This causes disturbance throughout the flow and a helix breakdown.

**Figure 3.** Top View, semi-radial inlet configuration; offers no advantages (Generated on ANSYS 13.0)

**4 MODEL DESIGN OF CYCLONE SEEDER**

A Sample schematic is illustrated in (Fig. 4). The Height/Diameter ratio is 20/3 (without considering the hemispherical ceiling) or 23/3 (considering the spherical ceiling), neither of which affects the results appreciably. The dimensions are as indicated in the Figure.

**Figure 4.** Model Design, with dimensions as specified; outlet sunk below inlet
The inlet is positioned at 30° w.r.t. the base (i.e. ∠ABC = 30°). It is tangentially positioned, at the specified height. As shown (in dark), the outlet is sunk below the inlet (in this case, by a depth of 3.6Dₚ) to avoid direct fluid exit.

Simulations were carried out using Standard k-ε model, using approximate Boundary Conditions. Among these boundary conditions, important would be an inlet velocity of 50 m/s and outlet pressure of 1.5199×10⁵ N/m² (i.e. 1.5atm).

Conforming to the predictions in the previous sections, the seeder functions to agreeable standards. The jet flow is shown to re-circulate at the base (particle bed). The velocity at this region is close to 25 m/s, which is sufficient for entrainment of standard PIV test particles (usually Aluminum Oxide of 0.5 micron to 5 micron diameter, with Stokes’ Settling Velocities between 1.25×10⁻⁴ m/s and 1.11×10⁻³ m/s).

As can be seen from the path of the inner helix, the fluid exits the seed chamber at a height lower than that of the inlet. Also, any upward flow is redirected downward and incorporated into the outer helix (Fig. 5a). It should also be noted for analytical purposes that the flow toward the particle bed is velocity-driven externally, whereas the flow from the bed to the outlet is driven by pressure.

**Figure 5a and Figure 5b.** Isometric View of Seed Chamber (left), with upward spread directed downward; Side View of Seed Chamber (right), showing inner helix exit through sunk outlet; velocity at particle bed (base) ≈ 25 m/s (Generated on ANSYS Fluent 13.0)

The inlet angle can be adjusted by using a variable-orientation pipe that can be bent freely in any direction (commonly seen in flexible straws used for soft-drinks and fruit juices).

**5 CONCLUSION**

Cyclone Seeding is an effective medium of introducing seeds into fluid flows for
optical testing. The method has minimal particle agglomeration, flow slugging [5] and is simple to use, as compared to other methods [1]. General Design Parameters that need to be followed have been described with a model design. Numerical Simulations using the commercial CFD Software Fluent have shown the stability of the design in conforming to the desired output, with minimum agglomeration (and consequent elimination of external agitation mechanisms). Settling of undesirably heavier particles within the ballast volume (by ejection from helix due to high centrifugal velocities) is also an added advantage. Thus, a low-cost seeding mechanism can be constructed for use with most Optical Flow Visualization techniques.

6 REFERENCES