# Visualizing the flow through a supersonic gaseous ejector using Planar Laser Mie Scattering

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**Abstract** Supersonic Ejectors are a typical gas-dynamic devises used in various industries. Mixing inside an ejector is highly three dimensional and complex. Precise measurement of mixing length using conventional pressure measurements is difficult. Non-intrusive optical diagnostics help in better understanding of the flow physics. Planar Laser Mie Scattering (PLMS) is used to achieve the non-mixed length variation with respect to the primary flow Mach number and primary flow stagnation pressure in an air-air two dimensional supersonic ejector. Seeding separately the primary and secondary flow helps in visualizing the flow field better. The variation in the non-mixed length between successive images under same condition reveals the influence of flow turbulence. In-house image processing codes help in observing the variations quantitatively. Effects on the observation of the non-mixed length due to the three dimensional effects (3D) are also addressed. **Keywords:** Mie Scattering, Supersonic Ejector, Confined Jet, Non-mixed Length, 3D effects

## **1** Introduction

A supersonic ejector is a gas-dynamic device which uses the high kinetic energy of a primary flow to pump a secondary flow [1]. It has various industrial applications. The flow process through a supersonic ejector is dominated by the interaction between the secondary stream and primary stream, which happens through a supersonic mixing layer. The gas-dynamics of this mixing process is complex, three dimensional and unsteady. A typical time averaged flow field encountered in the supersonic ejector is illustrated in Fig. 1.



Fig.1 Schematic of the typical time averaged flow field encountered in the supersonic ejector

Much of the flow details inside a supersonic ejector are still being investigated, particularly the characterization of mixing. High quality flow visualizations are essential to investigate these flows. Conventional density based flow visualization tools like Schlieren and Shadowgraphs yield line of sight integrated images. Discerning the three dimensional aspects of the flow from these images are difficult. Thus, it becomes necessary to use laser based visualization techniques which highlight a very thin slice within the flow volume, and multiple planes through the flow volume builds up the three dimensional flow picture [2]. Further, the laser pulse width which is in the order of nanoseconds ensures that instantaneous flow features are frozen in the image. With the advancement of high speed laser, tracking the flow development in both space and time is possible. The flow images capture the trajectories of particles seeded in the flow that scatter light from the laser sheet. Sufficient caution has to be exercised when seeding the flow, since essential requirements are that the seeding particles are small enough to faithfully follow the flow, but their concentration are not large to disturb the flow itself [3]. The objective of this paper is to utilize such scattering methods to probe into the flow details.

## 2 Experimental Setup

The experiments are conducted in a two dimensional supersonic ejector test rig which is established at LHSR [4]. Details regarding the experimental facility, optical arrangements to perform laser scattering and the flow conditions are discussed in detail in this section.

## a. Supersonic Ejector Facility

The experimental facility consists of 8 m<sup>3</sup> storage tank that can be charged maximum to 11 bar from the atmosphere through a 30 HP Screw Compressor which operates at 95 CFM. The compressed air is dried through the refrigerant type dryer that is present in between the storage tank and the compressor unit in order to remove the moisture content so that the air upon expansion through the supersonic nozzle will not condensate and precipitate the optical window. A variable frequency control drive will monitor the storage tank pressure and accordingly load the compressor unit. A pneumatic rotary actuator valve is used to start the flow through the tunnel by the press of a hand held switch and a pilot operated pressure regulating valve ahead of it will help in regulating the required primary flow stagnation chamber pressure. Flow is passed through the stagnation chamber and the primary flow. A typical layout of the experimental facility is shown in the Fig. 1.



Fig. 2 Layout of the Supersonic Ejector Facility

At the end of the stagnation chamber, a primary flow CD nozzle of design Mach number  $(M_{p-d})$  2.0 is kept. The supersonic nozzle has a throat height of 3.4 mm and exit height of 6 mm such that the exit Mach number is 2.0. The primary flow nozzle is enclosed in the ejector passage and the secondary flow enters through the intake-duct that is arranged as shown in Fig. 2. Venturimeter is used to measure the secondary flow rate and the net flow rate in the in-take and exhaust. The ejector passage has three sections: convergent portion, constant area mixing duct and diffuser. The detailed dimensions of the flow passage is given in the Fig. 3. The mixed primary and secondary flow leaves through the ejector exhaust.



Fig. 3 Dimensions of the supersonic ejector passage

## b. Planar Laser Mie Scattering (PLMS) Setup

The scattering of incident light by the particles that are larger than the wavelength of the illuminating light source will be in the Mie scattering range, hence this flow visualization technique is named Planar Laser Mie Scattering (PLMS) [5]. This type of scattering provides information regarding the flow features. Thin laser light sheet of thickness less than 1mm is used to see the seeded flow. The ejector has two BK-7 glass plates fixed to either side. Light enters through the Quartz window near the exit of the diffuser. These optical windows are in right angles which help in visualizing the flow field. The laser sheet is passed through one window and the images are captured through other window. For this kind of imaging, the seeded particles should be mono-dispersive in nature with the size less than a micrometer. Particles are produced through the in-house seeder unit to meet the mass flow rate conditions and their size ranging from 0.8 to 1.0 micrometer. The seeder unit is designed based upon the modified Laskin Nozzle [6] arrangement. The unit has 9 struts with each strut having 11 nozzles (each of 1 mm in diameter). The nozzles are drilled on the periphery of the cylindrical struts and are dipped inside the fluid to be atomized. The seeder unit should be operated at a differential pressure of 2 bar, between the seeder input and the output, for the production and transportation of sufficient amount of particles. The sketch of the seeder unit and the particle size distribution chart for different fluids are given in the Fig. 3.



Fig. 4 (a) Sketch of the in-house seeder unit (b) Particle size distribution for various fluids used in the seeder unit

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The primary and secondary flow are individually seeded, but in separate experiments at the same operating conditions. Di-Ethyl Glycol compound (Smoke Fluid 'P') is used as the working fluid in the particle generator. An Nd-YLF laser is used as the illuminating light source at a wavelength of 527 nm (100 ns pulse width) at 1 kHz repetition rate with 24 mJ energy. A laser guiding arm is used to transport the laser light to the ejector facility and an appropriate collimated sheet optics is used to produce laser sheet, having a thickness of 0.5 mm. LaVision's Davis 8.2.1 software is used for image acquiring and processing along with their High Speed Controller. Phantom Miro 110 camera, having 1280 X 800 pixels at 20 micrometer/pixel is used for capturing the image. Instantaneous images capture the details of the turbulent flow field. To get the mean flow field, 800 instantaneous images are averaged.

#### c. Flow Conditions

The ejector is operated at a  $P_{op}$  of 5-10 bar using a primary flow nozzle of  $M_{p-d}$  2.0, while the secondary flow is sucked in from the ambience. The tunnel can be operated for 2-3 minutes. Secondary duct and the exit duct will be fully opened and the ejector will be operated in the mixed regime. Typical runtime observed by measuring the pressure at the exit of the diffuser is shown in Fig. 4.



Fig. 5 Typical pressure signal observed at the exit of the diffuser during the operation of the supersonic ejector

## **3** Results and Discussions

For the primary flow  $M_{p-d}$  of 2.0,  $P_{op}$  is varied and the imaging is done. The first section discusses the observed non-mixed length by seeding the primary and secondary flow individually, whereas the variations found in such observed non-mixed length is reasoned out in the second section. In the third section, influence of the three dimensional (3D) effects on the non-mixed length is shown in detail.

#### a. Observations of Non-Mixed Length (NML)

A simple image processing code [7] is used to define the non-mixed length portion, as the length from the exit of the nozzle to the point where the distinct features of the primary or secondary flow is maintained [8]. Flow seeding is done separately in the primary flow line and the secondary flow line for individual studies. A typical imaging done by seeding the primary and secondary flow is given in Fig. 6(a) and Fig. 6(b). Presence of large scale structures and potential core instabilities can be seen there. Fig. 6(c) is arranged by overlaying the artificially colored, time averaged flow field of the primary and secondary flow seeding individually with pale pink and light green respectively to emphasize the process of mixing happening. Presence of shock cells is also observed along with the formation of mixing layer.

#### **Primary Flow Seeding**

Particles are produced in the seeder unit by having a differential pressure of 2 bar between the stagnation chamber of the primary flow and the seeder unit. Particles are introduced in to the entrance region of the primary flow stagnation chamber and mixes well with the air. The seeded flow expands through the primary

flow supersonic nozzle. Shock structures are immediately seen at the exit of the nozzle. Flow instabilities propagate further downstream which leads to the mixing of the primary flow with the entrained secondary flow.



Fig. 6 (a) Instantaneous PLMS image of the seeded primary flow (b) Instantaneous PLMS image of the secondary flow (c) Time averaged, superimposed image of primary (pale pink) and secondary (light green) flow (different color scales are used for the sake of clarity). Flow is from left to right at an operating total pressure of 5.89 bar with a design Mach number of 2.0 in the primary flow nozzle.

The instabilities result in the formation of large scale structures which eventually breakdown and fill the entire duct. The distance between the primary flow nozzle exit and the above said location defines the nonmixed length in this case. The instantaneous and the time averaged images during the primary flow seeding at different  $P_{op}$  are given in Fig. 7. The size of the produced large scale structures increases with  $P_{op}$  which can be clearly seen in the instantaneous image. In the time averaged image, variations in the shock cell sizes are considerably seen with changes in  $P_{op}$ . At higher values they stretch whereas at lower values they are positioned tightly.



Fig. 7 (a) Instantaneous and (b) Time averaged images of primary flow seeding at three different primary flow total pressure conditions

#### **Secondary Flow Seeding**

Secondary flow seeding is done near the entry portion of the secondary air in-take. A differential pressure of 2 bar is maintained, just like the previous case but between the seeder unit and the ambient. When the ambient air is seeded, upon suction, air mixed with the seeded particles, enter in to the ejector section. The secondary flow is stagnated before the ejector passage. Flow enters in to the constant area portion of the ejector through the rounded convergent section. Since the primary flow is not seeded here, the termination of the primary flow potential core can be seen clearly. The instabilities observed in the terminal region of the potential core can be observed much better than the earlier case. The distance from the primary flow nozzle exit to the end of the primary flow potential core defines the non-mixed length in this case. The instantaneous and the time averaged images during the secondary flow seeding are given in Fig. 8.



Fig. 8 (a) Instantaneous and (b) Time averaged images of primary flow seeding at three different primary flow total pressure conditions

The variations in the observed non-mixed length to the primary flow stagnation chamber pressure during the individual seeding of primary and secondary is given in Fig. 9. As it can be observed from the image, the potential core length is small compared with the distance at which the primary flow interacts with the wall and the structure breaks off. But though values have large difference at smaller primary flow stagnation chamber pressure, at higher values, the distance seems to come close. It might be due to the large kinetic energy present in the primary flow. The variation in the non-mixed length during primary flow seeding is gradual. Especially during the initial pressure changes it almost remain constant.



Fig. 9 Variation of non-mixed length with total pressure of the primary flow observed during the seeding of primary flow and secondary flow individually

At higher pressure regions the variations seem to be significant. Whereas in the secondary flow seeding, values seems to vary almost linearly. Around the total pressure of 7 bar in the primary flow, a rapid increment is observed in both the cases. It might be due to the primary flow nozzle operating in the perfect expansion condition. The instabilities involved during this mode of operation is not as vigorous as in the other conditions.

## b. Variations in the Non-Mixed Length (NML)

The observed non-mixed length varies between every single image acquired for the same conditions. The variations seems to be very large. The plot shown in Fig. 10 (a) gives the variation of the obtained non-mixed length for each image that is analyzed, out of the 800 images acquired. This is also the reason behind the larger error bound that is found in Fig. 9. These characteristics are due to the inherent turbulent nature of the primary and secondary flow. Because of the variations in the non-mixed length, on time averaging, there exists a definite mixing zone which can be observed by plotting the intensity variation in the centerline of the flow field as shown in Fig. 10 (b). The moment secondary flow diffuses into the primary flow intensity starts to increase and it linearly rises to a certain value and remains almost constant. The smaller peaks observed in the intensity increment inside the potential core shows the presence of the shock cell. Due to the density variation inside the shock cell, the intensity also varies.



Fig. 10 (a) Observed variations in the non-mixed length for the same case throughout the acquired 800 images (b) Centerline normalized intensity variation along the ejector length on the time averaged image of the secondary flow operating at a primary flow total pressure of 7.89 bar

## c. Influence of three-dimensional (3D) effects on the Non-Mixed Length (NML)

Though the aspect ratio at the exit of the primary flow nozzle is large, the three dimensional effect grows stronger downstream and it influences the calculated non-mixed length. A typical transverse visualization of the primary flow seeding in Fig. 11 shows the presence of vortices coming through the sides of the nozzle exit. Those vortices are produced due to the boundary layer formation in the side plates of the nozzle. But they seem to persist as individual entities longer. It could be due to the side walls of the ejector. Seeding the secondary flow effectively shows that those formed vortices indeed affect the fluid entrainment into the primary flow.



Fig. 11 Transverse imaging inside the supersonic ejector flow during primary flow seeding at different sections in the stream-wise direction at a primary flow total pressure of 6.89 bar

Also the secondary seeding in Fig. 12 reveals that the eyes of the vortices are still devoid with the particles. Existence of such primary flow pockets even after the observed non-mixed length can also be evidently seen.

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Fig. 12 Transverse imaging inside the supersonic ejector flow during secondary flow seeding at different sections in the stream-wise direction at a primary flow total pressure of 6.89 bar

#### **4** Conclusions

Studies of non-mixed length using planar laser Mie scattering reveals better information about the flow quality, shock cell formation, instabilities in the primary flow potential core and large scale structures formation. Typical variation of non-mixed length by seeding the primary flow and the secondary flow individually for various primary flow stagnation chamber pressures at the design primary flow Mach number of 2 has been studied. Secondary seeding reveals the linear variation of the potential core length with primary flow total pressure. Increment in the non-mixed length is seen in both the cases. The variation in the non-mixed length between each image for the same conditions shows the influence of turbulent flow field and shock oscillations. Despite the large aspect ratio of the primary flow nozzle, propagating three dimensional effects from it influences the observed non-mixed length. Transverse scanning is also found to be important to properly quantify the non-mixed length.

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