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SCHLIEREN IMAGING FOR FLOW VISUALISATION OF GAS JET IN VACUUM FOR ACCELERATOR APPLICATIONS

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Abstract

Schlieren imaging was explored for flow visualising of a gas jet in vacuum for beam profile monitor application. In supersonic gas jet based beam profile monitors, the high density jet flows through various differentially pumped skimmer stages before being shaped into a sheet. Schlieren imaging is a well known technique used in aerodynamic studies to visualise gas flow. This technique is explained in the paper along with a gist of other flow visualisation techniques. A Z-type schlieren imaging setup used to view the high density flow features of a pulsed supersonic gas jet inside vacuum is described in detail. Flow around a Pitot probe in supersonic flow was simulated and the resultant density profile obtained was compared with the image obtained using schlieren imaging. The flow features including a detached shock around the tip of the probe was observable at medium and high vacuum after processing the image. Image processing algorithms and tools useful for this application are also discussed.

INTRODUCTION

Various particle accelerator instruments require introducing and controlling gas flow in vacuum. For non-invasive beam profile measurement in high intensity particle accelerators gas sheets are useful tools. At Low Energy High Intensity Proton Accelerator (LEHIPA) Facility [1] in Bhabha Atomic Research Centre, we explored methods to characterise gas flow in vacuum. These experiments would be useful to characterise the gas sheet generators for beam profile measurement application.

Gas sheet can be generated by shaping supersonic free jets [2]. Nozzle pressure ratio (NPR) is the ratio between the pressure at the nozzle exit to nozzle entry. A high NPR produces supersonic free jets and these can be shaped using one or more skimmers and finally a rectangular slit is used to form a gas sheet in the beam line.

Another method uses molecular beaming effect [3]. Gas flowing enter vacuum after flowing through a long thin rectangular slit. Due to the molecular beaming effect in rarefied flow conditions, the gas continues to flow in the same direction expanding slowly. Number of such slits can be placed around the beam to produce uniform density gas sheet.

When particle beam interacts with the gas sheet placed at an angle to the beam, say 45 degrees, the image created by the photon emitted by the beam excited gas molecules can be captured and processed to obtain the beam profile.

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For reconstruction it is important to characterise the sheet. Pressure probes have been carried out in the post interaction region for supersonic sheet generators [4]. Probe beam based excitation imaging also have been carried out [4, 5]. Pitot probe response to supersonic free jets in vacuum was studied as these are compact [6].

Probing the Flow

Flow measurement can be done using pitot-static probes or hot wire based anemometers [7]. The gas may be ionised locally and the ion current can be measured to know the density at the location. Mass spectrometers can identify the concentration in gas mixtures.

Flow Visualisation

Gases such as nitrogen, oxygen, argon used for this application are not visible to the eye. Shadowgraphy and Schlieren imaging are two traditional methods used to visualise flows in aeronautics wind tunnels. Interferometers are also useful to precisely measure small density variations. In Planar Laser Induced Fluorescence (PLIF), trace gases that can be excited using high power lasers are mixed to visualise the flow. Particle Image velocimeter (PIV) use seed particles to track the flow. Light scattering methods can work without seeding particles and trace gases. Gases can also be excited using electric discharges and probe electron or ion beams to visualise

Performance of these methods in high to very high vacuum ambient conditions needs exploration. Sensitivity and calibration methods need to be analysed.

SHADOWGRAPHY

Invisible gases can create shadows. Variation in refractive index deflects the light by refraction causing density variation in the image as shown in Fig. 1.

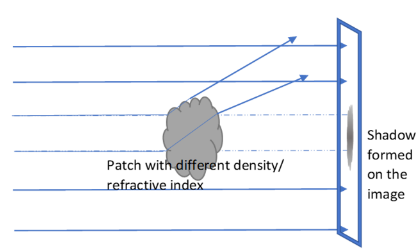

Figure 1: Formation of shadow image of gas flow.

The intensity variation in shadowgraph is proportional to the second derivative of the refractive index [8]. It is useful for visualising flow with very high gradients in refractive index. The setup is simple can be done with only a

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light source and an image plane. However, reconstruction of the image for quantitative measurements is complex as the intensity at any point in the image could be the resultant of number of light paths reaching the point.

SCHLIEREN IMAGING

In schlieren imaging, a lens or mirror is used to focus the image and the light is blocked by a knife edge kept at the focus as shown in Fig. 2. Change in refractive index in the light path leads to deflection. The deflected light that passes without focusing at the knife edge produces intensity variations in the image.

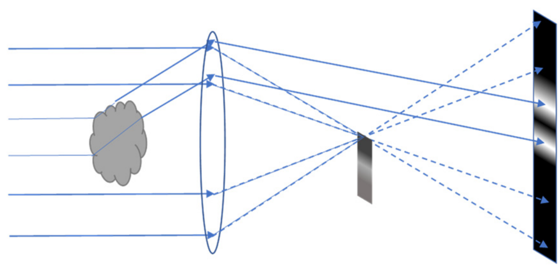

Figure 2: Formation of schlieren image of gas flow.

This method is also not suitable for quantitative analysis. Variations such as laser schlieren and schlieren interferometers have been explored for this purpose [9].

The intensity variation is proportional to the first derivative of the refractive index variation. It is more sensitive to refractive index variations than shadowgraphy and includes a focused image. However, shadowgraphs have produced sharp images of shockwaves in high density flows [10].

INTERFEROMETER

Interferometers measure the difference in path length of the light passing through the test section with respect to the reference path as shown in Fig. 3. The fringe pattern produced by the interference of two light paths is directly proportional to the cumulative refractive index variation in both the paths. The deflection of light is neglected in this technique. Hence, it is most suitable for low gradients of refractive indexes where deflection would be less.

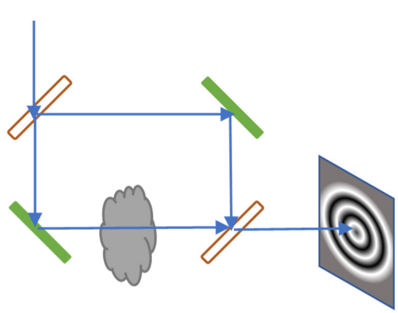

Figure 3: Formation of interference image of gas flow.

SETUP FOR STUDYING SCHLIEREN IMAGING IN VACUUM

A setup as shown in Fig. 4 was developed to study schlieren imaging in vacuum.

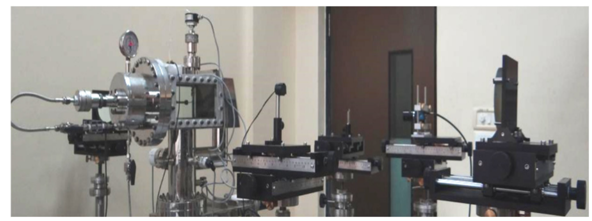

Figure 4: Setup for schlieren image of gas flow in vacuum.

This setup uses a bright LED with a pin hole opening as light source. The concave mirror reflects the light through the setup to another concave mirror behind the test section. The second concave mirror focuses the light. A vertical knife edge was placed carefully at the focus to allow some part of the light to pass through and be captured by the camera behind it.

The test section is in vacuum between 1000 to 10^{-4} Pa was measured by the vacuum gauges at various pumping stages. Gas was inlet from a nitrogen cylinder to the settling chamber until 3 bar pressure was attained. This gas was allowed to flow into the vacuum through an orifice nozzle to generate an underexpanded gas jet. Axial pitot probe measurements were carried out to compare with computed values and matching pressure ratio trend was obtained. The shock structures generally have width corresponding to the mean free path. In vacuum, the mean free path is large and shocks tend to have smaller density gradients compared to high density flows.

Analysis

Inside the test section the light passes through various regions of density variations. The path of a single ray of light entering perpendicular to the glass window is depicted in Fig. 5.

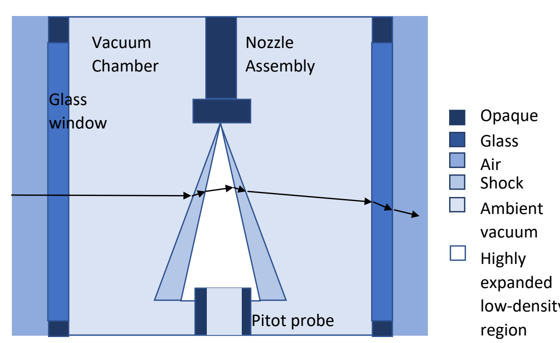

Figure 5: The deflection of a single light ray (Top view).

If the light is deflected in the direction of the knife edge it will be blocked whereas the light deflected away from the knife edge will fully pass through. High density regions deflect the light away from the centre whereas low density regions deflect like towards the centre. Figure 6 shows

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likely light paths when passing through the cross section of the flow followed by a converging lens and knife edge.

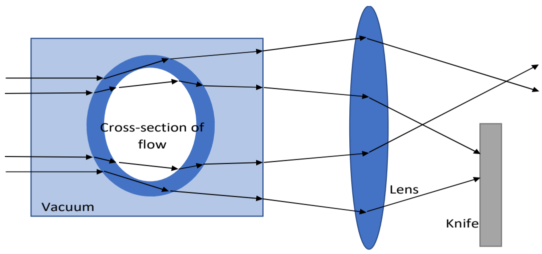

Figure 6: Deflection of light in the schlieren setup by the cross section of the flow.

For viewing the deflection introduced by the flow the image can be subtracted by the image before the flow is started. The solenoid valve that controls the injection of gas through the nozzle was controlled to obtain few frames at the beginning of each recorded video before the flow is started.

Results

A schlieren video was recorded which started before opening the solenoid valve. The flow was not visible in the raw image obtained at various time intervals. The video was exported to ImageJ software for processing it. The virtual stack created was subtracted by the image of the first frame and result was stores 32-bit float. The resultant video showed a black and white video with some features of the flow visible. The histogram of the image revealed that gray values were ranging between +/-20. The contrast enhancement tool was useful to obtain better images. Saturation percentage was optimised to obtain the resultant image shown in Fig. 7. This image was obtained at 1000 Pa ambient vacuum measured by the gauge. At higher vacuum, the visibility of the flow features deteriorated. Only dark spot was visible at the nozzle exit at 10^{-4} Pa along with large amount of noise.

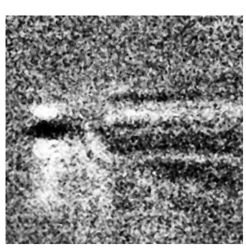

Figure 7: Image of flow with pitot probe obtained after subtraction and image enhancement.

The upper portion of the raw image was brighter and the flow feature were less clear in this region after image processing. Reduction of ambient light and reflections by constructing a dark room could be explored for better results.

While observing the processed schlieren videos the air flow around the vacuum chamber was visible and was introducing significant noise. The rotary pump below the setup was the reason for this flow. Placing the rotary pump at a distance could help reduce this noise. Reduction of vibrations in the setup due to the pumps could also improve effectiveness of image subtraction for noise removal.

In the present setup, the first concave mirror is at a distance from the test setup as the light source was on the same side. The second mirror was close to the setup. Ideally, the deflection by the flow would have been prominent if the second concave mirror was kept at longer distance from the test setup. Thus, rearranging the setup needs to be explored to obtain less noisy results.

CONCLUSION

Shadowgraphy and Schlieren imaging are the simplest traditional methods of non-invasive flow visualisation. Schlieren imaging is suitable for moderate gradients in refractive index and it is formed along with a focused image thus making it easier to see where the flow features are appearing. This technique was explored to study the gas flow visualisation of a free jet in various levels of vacuum. Simple image processing algorithms were explored for reduction of noise and image enhancement. It was observed that in medium vacuum the flow features were visible. At higher vacuum the images were very noisy and the flow was barely visible. Number of methods to be explored to reduce these noises were discussed here.

For gas sheet application, the theory specific to this flow structure needs to be studied. Typical reconstruction algorithms utilise the Abel Inversion for quantifying the density distribution from the intensity variation in the images obtained by various flow visualisation techniques which assumes axial symmetry in the flow. For thin sheet like flow the measurement of density variation and finding the dimensions of the sheet would require further investigation.

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