CHAPTER 4

EXPERIMENTATION

4.1 WIND TUNNEL

For the conduct of the aerodynamics experiment of present studies, an open circuit subsonic table top wind tunnel as shown Figure 4.1 was used. The table top wind tunnel used for the aerodynamic experiments is available in CAP laboratories (Hanger II), Department of Aerospace Engineering, Madras institute of technology campus, Anna University, Chennai, India. Isometric view of different components and dimensions of different components of wind tunnel is presented in Figure 4.2 and 4.3 respectively. A brief detail of the major subsystem of the wind tunnel is presented in the following sections.

Figure 4.1 Photographic view of table top wind tunnel
4.1.1 Wind tunnel inlet

Inlet section is the largest part in the wind tunnel through which the working fluid (air) enters into the circuit and passes through different points of wind tunnel. The inlet section hosts three different components with it.

Figure 4.2 Isometric view of different parts of table top wind tunnel

Figure 4.3 Dimensions of the table-top wind tunnel.
4.1.1.1 Honeycomb section

A honeycomb section is placed perpendicular to the flow direction at the beginning of inlet section as shown in Figure 4.4. The intended function is to reduce the non-uniform components of the flow. The cross-sectional size of the honeycomb section is 550 mm height and 720 mm breadth with 100 mm length as shown in Figure 4.4. The honeycomb has 29 and 22 holes of square shape of side 23 mm in horizontal and vertical direction respectively. Open area percentage of the honeycomb section is calculated as 85%.

![Figure 4.4 Dimensions and photographic view of honeycomb section](image)

4.1.1.2 Screen

Two wire mesh screens of square cell of 1mm side were used inside the inlet section. The screens are located just downstream (150 mm) of honeycomb to reduce the turbulence present in the working fluid. The second screen is placed at 310 mm downstream of the honeycomb in the inlet section.

4.1.1.3 Settling chamber

It is the longest section available in the inlet section. This section serves as the reservoir to the tunnel nozzle section with condition of working
fluid at the downstream of honeycomb and screen. Cross section size of the settling chamber is same as that of inlet (550mm × 720mm) of the tunnel.

4.1.2 Contraction Section (Effuser)

The function of contraction section is to uniformly accelerate the working fluid by contracting the duct opening from the large inlet area (720mm × 550mm) down to the smaller outlet area (240mm × 180mm) (Figure 4.5).

![Figure 4.5 Dimensions of the side and top view of the contraction section](image)

The contraction coefficient of the nozzle section is calculated as

\[
\text{Contraction Coefficient} = \frac{\text{Area of the inlet}}{\text{Area of the outlet}}
\]

\[
= \frac{0.396 \text{ m}^2}{0.0432^2}
\]

**Contraction Coefficient = 9.17**

Contraction coefficient of 6 to 10 is adequate for low speed wind tunnel with test section velocity less than 40 m/s. From the above simple
calculation, the contraction coefficient for the contraction section is found to be 9.17.

4.1.3 Static Pressure Housing

A short straight duct section immediately downstream of contraction section allows more uniform flow of air into the test section. This section is used to minimize impact on the test section flow from the contraction effect at its inlet due to the contraction section outlet. This section holds the static pressure probe that measures the static pressure at the entrance of the test section.

4.1.4 Test Section

Test section is the main focus of the wind tunnel, where in the test models are mounted and oriented for analysis, data collection and observation. The test section is placed between static pressure housing and diffuser section in the wind tunnel assembly. It is desirable to obtain uniform steady flow velocity along the test section length and a minimum variation of the axial velocity across the test section. The test section is rectangle in cross section with 240 mm breadth and 180 mm height. Total length of the test section is 660 mm as shown in Figure 4.6. The test section should be easily accessible as well as provide viewing access to the model being tested. Hence the base plate of the test section is detachable to access inner area of the test section. Two sides of the test section (Front and rear) are made up of transparent acrylic sheet (6 mm thickness) to enhance the viewing access to the test model.
4.1.5 Diffuser

Main function of the diffuser section is to gradually decelerate the fluid flow to facilitate smooth pressure recovery. Inlet of the diffuser is a rectangle of size 180mm × 240mm, and the outlet is a circular in shape with 610mm diameter. Total length of the diffuser is 2660 mm. The apex angle of the diffuser cone is 4°.

4.1.6 Tunnel Propeller

At the exit of the diffuser, a four blade teak wood propeller is attached. Diameter of the propeller is 600 mm, which is co-axially mounted at the exit of the diffuser with the help of propeller shaft. The propeller shaft is made of heat treated steel of diameter 20mm and length 600mm. The propeller shaft is supported by a tripod like structure made of steel. A platform on the tripod houses the propeller shaft with the help of five self-lubricating bearings. Power required to rotate the propeller is given by a
timing belt connected between gear box and the propeller shaft as shown in figure.

4.1.7 Tunnel Drive Section

Freestream velocity in the test section can be varied by changing the propeller speed. Propeller speed can be changed by using a mechanical gear box. The gear box and driving motor are connected by means of three jaw coupling with electrically non-conducting bush. By shifting the timing belt to different gear assembly available in the gear box, four different output (propeller) speeds (500, 1000, 1500 and 3000 RPM) can be achieved.

Technical specification of the drive motor used in the wind tunnel is given below:

Make : Everest
Type : 24154
Phase : 3
Power : 15 HP
RPM : 3000
Voltage : 400 / 450
Frequency : 50 Hz
Amps : 21

Typically freestream velocity which can be achieved in the test section at different propeller speed is shown in Figure 4.7. The drive motor will be co-axially coupled with the propeller shaft for a conventional wind tunnel. The air ejected by the propeller will be blocked by the drive motor, when it is arranged co-axially near to the exit of the diffuser. Due to blocking
of air there may be some disturbance to the working fluid within the diffuser and test section. To avoid such a blocking of outlet air by the drive motor, drive unit (motor and gear box) is rigidly (on concrete) mounted on the ground as shown in Figure 4.8. Output of the gear box is connected with the propeller shaft by using a timing belt to reduce the speed loss due to the belt friction.

Figure 4.7 Test section freestream velocities at different propeller speed

Figure 4.8 View of wind tunnel propeller drive unit
4.1.9 Traverse Mechanism

In the present study, measurement of static pressure and mean velocity along the wake axis of circular and elliptic cone is major objective. To collect pressure and velocity data at specified locations along the wake axis, a traverse mechanism is required to move the sensors along the wake axis. A two dimensional traverse mechanism was designed and fabricated (Figure 4.9) for mounting the probe during the pressure and velocity measurement experiments. Image of the traverse mechanism attached on the side wall of the test section is shown in the Figure 4.10.

**Figure 4.9 Dimensions of traverse mechanism**

**Figure 4.10 View of traverse mechanism attached to the test section**
On the two ends of traverse two rotatable knobs are available; between the knobs a flexible Teflon sheet of 1mm thickness is connected. By rotating the one side knob the excess Teflon sheet available on the other knob will be released. Due to the displacement of Teflon sheet between two knobs, a probe holder attached with it also travels along the same direction. At middle of the side wall of test section, a slot of width 6mm is removed for a length 300mm. When the knobs are operated, a probe placed inside the test section can move along the wake axis due to the displacement of probe holder along with the Teflon sheet. Due care was taken to avoid the intrusion of surrounding air into the test section via the slot provided for the probe movement.

Maximum displacement along the flow direction is 250mm and transverse direction is 7 cm. On the front side of the traverse a measuring scale is pasted along with a pointing needle. While probe is operated the corresponding displacement of the probe can be observed from the scale. Along the flow direction the sensor can be displaced in steps of 1mm. To hold the sensor probes two adjustable screws are provided on the top of the probe support.

**4.1.10 Base-Jet Injection Setup**

In the second part of the experiments, mean velocity distributions along the wake axis of circular and elliptic cones were measured. Velocity distribution was measured for both with and without base-jet injection. Effects of base-jet injection velocity (IR), base-jet size (AR) and base-jet shape on the wake axis parameters (L_{ij}, MRV and PASP) are the objective of the present study. Compressed air at normal temperature was used as the base-jet injection fluid during the velocity measurement experiments. Compressed air required for the injection was supplied by an electrically operated two stage reciprocating compressor. Maximum storage pressure of
the compressor is 14 kgf/cm$^2$. Before allowing the air for injection, the compressed air is stored in the local setting chamber as a temporary storage. Before compressed air reaches the local storage, it passes through two oil filters to avoid the intrusion of oil particle and moisture into the injection fluid.

The air stored in the local reservoir is maintained at constant pressure of 10 kgf /cm$^2$ during the base-jet injection experiments. The mean velocity distribution along the wake axis was measured using a Constant Temperature hot-wire Anemometer (CTA). Sensor of the CTA is very small (5µ, 1.25m long) and sensitive to the foreign particles like oil, dust and moisture presents in the compressed air. Intrusion of foreign particles into the injected air may cause severe damage to the CTA sensor.

To avoid such a service damage of CTA sensor, four filters are used before the injection air reaches the exit of the base-jet orifice. Two oil filters are used one at near to the exit of the compressor reservoir and another near to the inlet of the local reservoir. Third, a moisture filter is used near to the exit of local reservoir as shown in Figure 4.11. Fourth filter is a dual purpose filter, because it acts both as the moisture filter as well as the Pressure Regulating Valve (PRV) to control the flow rate through the base-jet. Since the local reservoir pressure is high (10kgf /cm$^2$), an integrated moisture separator and PRV controls the mass flow rate of base jet air through the base jet orifice. By operating a control valve available on the top of the PRV (Figure 4.12) downstream pressure can be controlled and hence the exit velocity of the base-jet also.
Figure 4.11 Layout of base-jet air supply system

Figure 4.12 View of Local reservoir and filters and PRV of base-jet
4.2 TEST MODELS CONFIGURATION STUDY

4.2.1 Design of Test Models

Static pressure and mean velocity distribution behind the circular and elliptic cone were measured during the experiments. To compare the effect of change of geometrical shape from circular to elliptic it is necessary to maintain base area and cone length constant. The different dimensions of circular and elliptic cone are derived as follow.

**Base diameter of the cone:**

Wind tunnel test section size (W×H×L) = 240 × 180 × 660 (mm)

Test section cross section area (W×H) = 240 × 180 mm²

= 43200 mm²

Blockage area of the cone is considered as low as 3% of the test section cross section area

Hence 3% of inlet area = \( \frac{3 \times 43200}{100} \)

= 1296 mm²

Area of the cone base = \( \frac{\pi}{4} (d^2) \) = 1296 mm²

\( d^2 = 1650.11 \text{ mm}^2 \)

\( d = 40.62 \text{ mm} = 40.5 \text{ mm} \)

**Axial length of the cone**

Semi apex angle of circular cone is considered as 10°. Hence the length of the cone is
\[ \tan 10^\circ = \frac{20.25}{L} \]

\[ L = 110.08 \text{ mm} \sim 110 \text{ mm} \]

From the calculated value of diameter and length of the cone, the finesse ratio \((L/d)\) can be calculated as

\[ \frac{L}{d} = \frac{110}{40.5} = 2.75 \]

**Base dimensions of elliptic cone:**

Base area of the circular cone = Base area of the elliptic cone = 1296 mm²

Area of the ellipse = \(\pi \times a \times b = 1296 \text{ mm}^2\)

Ellipticity ratio of the cone = 3

\[ \frac{a}{b} = 3 \]

\[ a = 3b \]

\[ \pi \times 3b \times b = 1296 \]

Length of semi minor axis \(b\) = 11.7 mm

Length of semi major axis \(a\) = 35.2 mm

Since it is very difficult to fabricate a cone with pointed tip at the leading edge, hence a blunt leading edge of 2mm diameter was used during the experiments. Similarly at the leading edge of the elliptic cone also the blunt end of elliptic shape was used \((a_l = 1.73\text{ mm} \text{ and } b_l = 0.57\text{ mm})\).
4.2.2 Fabrication of Cones

The circular and elliptic cones were fabricated from the brass to get better surface finish of the cone. Circular and elliptic cone were fabricated using CNC milling machine. The test models are hollow with detachable base as shown in Figure 4.13. The cone is mounted on the detachable base plate of the test section (Figure 4.14). A double convex column of width 30mm and thickness 5mm was used as the support to the cones. To connect the base-jet injections tube to the base-jet adapter the support of the cone also a hollow one. To conveniently drawn the base jet supply tube, cone and its supports were fabricated as hollow. Since the cone support is a double convex shape of sufficient length, its disturbance on the downstream is insignificant (computationally verified). The detachable base plate of the cone houses the base jet adapter and hence base jet nozzle also.

Figure 4.13 Circular and elliptic cone (with and without base plate)
4.2.3 BASE JET CONFIGURATION

4.2.3.1 Base jet design

Mean velocity distribution along the wake axis of circular and elliptic cone was measure with different configuration of base-jets. Effect of base-jet shape (circular, square and hexagonal), base-jet injection velocity (IR = U_j / U_o) and base-jet size (AR = A_j / A_b) on the important wake axis parameters like Ljp, MRV and PASP was studied. For each shape of base-jet three different sized jets are used during the experiment. For example size of the base-jet with respect to the area of the cone base, 0.5% of base area (AR = 0.005), 1% of base area (AR = 0.01) and 1.5% of base area (AR = 0.015). During the course of experiments it is very difficult to attach the separate base for every size of the base-jet; hence a special design was adapted to change the base-jets instantly.
Design of base-jet size

(i) Base area of the cone = 1296 mm\(^2\)

\[
0.5\% \text{ of the base area} = 0.005 \times 1296 = 6.48 \text{ mm}^2
\]

\[
\frac{\pi}{4} \times d_j^2 = 6.48
\]

\[
d_j = 3 \text{ mm}
\]

(ii) 1% of the base area = 0.01 \times 1296 = 12.96 mm\(^2\)

\[
\frac{\pi}{4} \times d_j^2 = 12.96
\]

\[
d_j = 4 \text{ mm}
\]

(iii) 1.5% of the base area = 0.015 \times 1296 = 19.44 mm\(^2\)

\[
\frac{\pi}{4} \times d_j^2 = 19.44
\]

\[
d_j = 5 \text{ mm}
\]

Similarly dimensions of the square shape and hexagonal shape base-jet are designed and fabricated. The different size of circular, square and hexagonal shape jets are listed Table 4.1. The Figure 4.15 shows the different shape and size of base-jet nozzles used during the experiments. Figure 4.16 shows the dimensional details of different size of circular base-jet nozzles.

Table 4.1 Exit dimensions of different shape base-jet

<table>
<thead>
<tr>
<th>% of base area</th>
<th>Area mm(^2)</th>
<th>Circular jet dia. (d) mm</th>
<th>Square jet side (s) mm</th>
<th>Hexagonal jet side (t) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>6.48</td>
<td>3.0</td>
<td>2.6</td>
<td>1.6</td>
</tr>
<tr>
<td>1.0</td>
<td>12.96</td>
<td>4.0</td>
<td>3.6</td>
<td>2.2</td>
</tr>
<tr>
<td>1.5</td>
<td>19.44</td>
<td>5.0</td>
<td>4.4</td>
<td>2.7</td>
</tr>
</tbody>
</table>
4.2.3.2 Base - jet assembly

The base-jet assembly consists of three different components as (i) base plate, (ii) base-jet adapter and (iii) base-jet nozzle. For circular and elliptic cone two separate base plates were fabricated with exact dimensions of closing side of the base. Base-jet adapter will be fixed by tight fit with the
base plate as shown in Figure 4.17. Inlet size of the base-jet adapter is equal to the outer diameter of the base-jet delivery hose. Base-jet delivery hose is a flexible high pressure hose connected between outlet of PRV and base-jet adapter. Internal thread provided on the outlet side of the jet adapter can hold any base-jet as shown in Figure 4.18. The Figures 4.19 show the rear view of test model with and without base-jet nozzle.

Figure 4.17 View of base plate and base-jet adapter of elliptic cone

![Base Plate and Base-Jet Adapter](image)

Figure 4.18 Dimensions of base-jet assembly of circular cone

![Dimensions of Base-Jet Assembly](image)
4.3 TEST CONDITIONS

All the aerodynamics experiments are conducted at the CAP laboratory in the department of Aerospace Engineering, Madras Institute of Technology. During the experiment the pressure and temperature inside the lab is as $P_a = 101210$ Pa [average barometric pressure at Chennai, from metrological survey of India database during period of conduct of experiment]. Temperature at laboratory is considered as 302 K (29°C). These standard values are used during the computation of the experiment.

4.4 INSTRUMENTATION

In this section different instruments used for the acquisition of pressure, velocity and flow visualization are presented along with their important specifications.

4.4.1 Pressure Scanner (DSA)

Static Pressure along the wake axis of the circular and elliptic cones was measured using Digital Sensor Array - DSA, Scanivalve Corporation (DSA 3217 / 16 Px), USA (Figure 4.20). The scanner is capable of measuring one PSI differential pressure (Range +/- 1 PSI). The full scale accuracy of the DSA is 0.12%. DSA Link V4.03 software was used to interface DSA module and the computer during data acquisition. The pressure was measured at 25
different locations (up to 3 times base diameter) with 5mm distance between points along the wake axis. For all the experiments the data was acquired at 30 FPS (Frames per Scan) with 100 samples per frame. Raw DSA data at every location was reduced into average static pressure and plotted using MATLAB program given in Appendix 1.

Figure 4.20 View of Digital Sensor Array (DSA) - Pressure scanner

**Working Principle:** DSA 3217 incorporates 16 temperature compensated piezoresistive pressure sensors with pneumatic calibration valve, microprocessor, RAM and 16 bit A/D converter. The amount of resistance of these piezoresistive elements to stress or load at any time indicates the pressure acting on the sensor. However the resistance exhibited by these elements and its sensitivity to stress or load depends on the temperature which is compensated by the inbuilt microprocessor. These microprocessors also control the actuation of internal calibration valve to perform online zero or multi point calibration. In addition to the microprocessor does the engineering unit conversion where the pressure data output is interfaced via Ethernet using TCP/IP protocol.
DSA 3217 has thermally compensated silicon pressure sensors with its own individual calibration valve for each sensor which has four modes of operation, as 1. Operate, 2. Calibrate, 3. Purge, 4. Isolate. These modes are selected by applying the control pressures in the pre-determined logical order. DSA 3217 calibration valve is of “Normally Px” logic according to which the valve sets to operate mode when no control pressures provided. When 90psi control pressure is given, the valve sets to either Purge or Calibrate or Isolate mode. Hence the sensors are calibrated online automatically either with zero calibration or multipoint calibration by theses valves.

For quick zero calibration a separate internal solenoid valve is used instead of pressure calibrator. When actuated, the +ve side of the sensors get shorted pneumatically to reference manifold thereby creating a zero differential pressure. The calibrated data of transducers with full temperature and pressure ranges are stored in a 60 plane temperature/pressure look up table in EEPROM. Hence when sensed sensor bridge temperature varies the microprocessor selects the appropriate temperature plane or interpolates between the planes to correct the pressure reading.

DSA 3217 module can be directly interfaced to PC, Host computer or Ethernet port using the software.

**Technical Specifications of DSA 3217**

- **Inputs (Px):** Standard: 16 each .063 inch (1.6mm) O.D. tabulations.
- **Differential:** ±10 inch H2O, 1psid
- **Resolution:** 16 bit
- **Scan Rate:** 500 Hz/Channel EU
- **Communication:** Ethernet 10baseT
Communication Protocol: TCP/IP or UDP

Operating Temperature: 0°C to 60°C

Power Requirements: 28VDC nominal @ 400 mA (20-36VDC)

External Trigger: 6 mA at 4 V DC minimum edge sensing

Overpressure Capability: 10 inch H2O = 2 psi (13.79kPa)

Maximum Reference Pressure: 250 psi (1724kPa)

Media Compatibility: Gases compatible with silicon, silicone, Aluminium, and Buna-N.

Weight: 6.4 lbs. (2.9 kg)

Advantages of DSA

- The temperature compensated pressure sensors made used are more than ten times less sensitive to temperature variation than normal piezoresistive pressure sensors. Hence these sensors can be made used in measuring the pressures where ambient temperatures vary greatly.

- These are independent of attitude hence it can be placed near the zones where pressure needs to be measured.

- Multiple pressure range available.

- Field replaceable pressure sensors thereby reducing the down time.

- With the online temperature correction and quick zero calibration techniques, ±0.05%FS full scale long term accuracy is achieved for nearly 6 months.
Limitation:

- DSA 3217 cannot be used for temperature ranges below 0°C and above 60°C where DSA 3218 has to be used.

### 4.4.2 Hot-Wire Anemometer

**Basic principle of hot-wire filaments**: The important component in a hot-wire anemometer system is hot-wire filaments (sensor wire). The hot-wire filament may be regarded as an infinitely long, straight cylinder in cross flow. A number of heat transfer relations have been proposed for this kind of problem. The following Equation (4.1) is one such empirical relation proposed by Kramer, which gives satisfactory results for many gases and liquids.

\[
Nu = 0.42 Pr^{0.2} + 0.57 Pr^{0.33} Re^{0.5} \tag{4.1}
\]

\[
Nu = \frac{h d_w}{k} = \text{Nusselt number}
\]

\[
Pr = \frac{\mu c_p}{k} = \text{Prandtl number}
\]

\[
Re = \frac{\rho \mu d_w}{\mu} = \text{Reynolds number}
\]

where,  
- **h** - Film coefficient (heat flux leaving the wire surface per unit temperature difference between the wire and freestream)
- **d_w** - The hot-wire sensor diameter.
- **k** - Thermal conductivity of the gas
- **μ** - Dynamic viscosity of the gas.
- **ρ** - Density of the gas,
- **β** - Coefficient of expansion of the gas.
\( C_P \) - Specific heat of the gas at constant pressure.

\( U \) - Velocity of the flow past the wire.

The heat transformed per unit time to the ambient gas from a wire as length ‘l’ at an uniform temperature of \( T_w \) is given by

\[
h \pi d_w l (T_w - T_g)
\]

This can expressed as \((h \, d_w / k) \times k \pi l (T_w - T_g)\)

\[
Nu \, k \pi l (T_w - T_g)
\] (4.2)

Substituting Equation (4.1) in Equation (4.2)

\[
k \pi l (T_w - T_g) [0.42 Pr^{0.2} + 0.57 Pr^{0.33} Re^{0.5}]\] (4.3)

For thermal equilibrium, heat transfer per unit time from the wire must be equal to the heat generated per unit time by the electric current through the hot-wire. (i.e) For thermal equilibrium of wire

\[
I^2 R_w = k \pi l (T_w - T_g) [0.42 Pr^{0.2} + 0.57 Pr^{0.33} Re^{0.5}]\] (4.4)

where \( I \) - current through the wire

\( R_w \) - Total electric resistance of the wire at temperature \( T_w \)

The important property of a wire is the temperature coefficient of resistivity. The temperature dependence of resistance of wire may be expressed as

\[
R_w = R_o [ 1 + C ( T_w - T_o) + C_1( T_w - T_o)^2 + \ldots ]
\]

\[
\frac{R_w - R_o}{R_o C} = T_w - T_o = \Delta T
\] (4.5)
where \( R_o \) - wire resistance at reference temperature \( T_o \).

\( C, C1 \ldots \) - Temperature coefficient of electrical resistivity.

For Tungsten typical value of \( C \) and \( C1 \) are

\[ C = 5.2 \times 10^{-3} \text{ (K}^{-1} \text{)}, \ C1 = 7 \times 10^{-7} \text{ (K}^{-1} \text{)} \]

Substituting Equation (4.5) into Equation (4.4)

\[ I^2 R_w = k \pi d \frac{R_w - R_o}{R_w} [0.42 Pr^{0.2} + 0.57 Pr^{0.33} Re^{0.5}] \quad (4.6) \]

For hot-wire anemometer applications the Equation (4.6) may be written in the form as

\[ \frac{f \times R_w}{R_w - R_o} = A_1 + B_1 U^{0.5} \quad (4.7) \]

where \( A_1 = 0.42 \times \left( \frac{\pi k_l}{C R_0} \right) \times Pr^{0.2} \)

\[ B_1 = 0.57 \times \left( \frac{\pi k_l}{C R_0} \right) \times Pr^{0.3} \times Re^{0.5} \]

Hence the Equation (4.7) can be written as

\[ l^2 R_w = (R_w - R_o)(A_1 + B_1 \sqrt{U}) \quad (4.8) \]

This Equation (4.8) popularly known as King’s relation.

Resistance ratio is given by the equation

\[ R = (R_w / R_o) \]

The Equation (4.8) becomes
\[ I^2 = \frac{R_w - R_0}{R_w} \times [A_1 + B_1 \sqrt{U}] \]

\[ I^2 = \frac{R - 1}{R} \times [A_1 + B_1 \sqrt{U}] \]

For a fixed value of \( R \)

\[ I^2 = [A_1 + B_1 \sqrt{U}] \quad (4.9) \]

For a hot-wire probe with a finite-length active wire element, the conductive end losses must be taken into account. In practice this is often derived by modifying Equation (4.9) as

\[ I^2 = [A_1 + B_1 U^n] \quad (4.10) \]

For any hot-wire anemometer sensor, the value of \( A_1, B_1 \) and exponent \( n \) can be determined by a suitable calibration procedure.

In general two modes of operations are followed in hot-wire anemometry.

I. Constant current mode (CCA): In this mode the current flow through the sensor wire is kept constant and variations in the wire resistance caused by the fluid flow are measured by monitoring the voltage drop variations across the filament.

II. Constant Temperature mode (CTA): In constant temperature hot-wire anemometer system, the wire resistance \( R_w \) is always maintained constant and not allowed to fluctuate. The current passing through the hot-wire made to decrease or increase as soon as a changes in resistance of hot-wire due to flow velocity variations. The current adjustment is automatically done by employing a servo amplifier which
has a feedback capacity for a frequency range from 0 to many kHz. A typical schematic diagram of constant-temperature hot-wire anemometer circuit is show in Figure 4.21. Basically it has a wheat-stone bridge, a feedback servo amplifier, a high-gain amplifier and RMS voltmeter.

![Figure 4.21  A circuit diagram hot-wire anemometer](image)

**Advantages of CTA.**

- Since the feedback takes place almost instantaneously keeping the wire temperature and hence its resistance at a predetermined value, no compensator is needed.

- The compensation for the thermal inertia of the filament is continuously adjusted automatically as its operating point varies. Thus, when taking traverse of a jet, wake with a CTA, there is no need for a special calibration and compensator setting for each mean velocity.
The advantages of CTA than CCA

- The CCA is calibrated at constant temperature, and then used in a pseudo-constant current mode.
- The CCA calibration has to be a static one because to obtain a constant temperature calibration, each operating point of the bridge has to be adjusted manually.
- The CTA can be used in the same way as it is calibrated.
- The temperature of the wire is maintained approximately constant automatically by feedback circuit and this makes it possible to calibrate the system dynamically.

Relation Between flow Velocity and Output Voltage: In a constant temperature hot-wire anemometer system, the flow velocity and the output voltage of the servo amplifiers are related as follow,

From Equation (4.8) we know that

\[ E = I \, R_w \quad \Rightarrow \quad I = \frac{E}{R_w} \]

\[ \frac{E^2}{R_w} = \frac{R_w - R_0}{\bar{R}_w} \times (A_1 + B_1 \sqrt{U}) \]

\[ E^2 = A + B \sqrt{U} \]

where, \[ A = A_1 \, (R_w \, (R_w - R_0)) \]

\[ B = B_1 \, (R_w \, (R_w - R_0)) \]

For a finite length hot-wire the characteristic equation is

\[ E^2 = A + BU^n \quad (4.11) \]
A Constant Temperature Hot-wire Anemometer (Figure 4.22) available in the CAP Laboratory, department of Aerospace Engineering, MIT campus, Anna University is used for the measurement of mean velocity and velocity fluctuation during the experiments. Important specification of the hot-Wire frame, Module, Probe (sensor), probe support, cable are presented below.

![Figure 4.22 View of Hot-wire anemometer frame with modules](image)

**Specifications:**

I) Probe (From dantec dynamics website)

Model - 55P11 (1 dimensional wire/straight wire probe)

- Medium: Air
- Sensor material: Platinum-plated tungsten
- Sensor dimensions: 5µm diameter, 1.25mm long
- Sensor body material: Ceramic tube
- Sensor body dimension: 1.9mm diameter, 30mm length
Sensor resistance $R_{20}$ (approximately) - 3.5 $\Omega$

Temperature coefficient of resistance - 0.36% / °C

Maximum sensor temperature - 300°C

Maximum ambient temperature - 150°C

Minimum velocity - 0.05 m/s

Maximum velocity - 500 m/s

Frequency limit $F_{\text{max}}$ - 400kHz.

ii) Probe support

Model - 55H22 – (1D -90° support)

Diameter - 4mm

Overall length - 235mm

Cable length - 750mm

Connector - BNC

iii) Frame

Model - 90N10 frame

Frame dimension - 447 × 440 × 192.5 mm (W × L × H)

iv) Cable

Model - 9055A1864 BNC/BNC probe cable

Length - 4m

Internal resistance and impedance - 0.2 $\Omega$

Cable compensation circuit - 5 meters

Module - 55C90 CTA module.
4.4.3 Shadowgraph flow visualization setup

The optical flow visualization system form an important part of this experimental setup. Such systems provide vital information which helps in qualitative analysis of subsonic and supersonic flow field characteristics. Types of optical flow visualization system are Interferometer, Schlieren and shadowgraph.

**Working principle of flow visualization:** Fluid flow is visible either by observing the motion of suitable selected foreign particles added to the flowing fluid or by using an optical pattern resulting from the variation of the optical properties of the fluid, such as the refractive index, due to the variation of the properties of the flowing fluid itself.

**Shadowgraph Technique:** The shadowgraph technique is used for flow field with rapidly varying density gradients. In this technique the screen is placed close to test section, the effect of light ray deflection is visible as shadow on screen. Typical shadowgraph setup consists of a light source, a collimating lens and screen. The test section has stagnation air in it and that illumination on screen is of uniform intensity. If the flow flowing in test section the light beam will be refracted due to change in density gradient. The density gradient is constant in test section; light ray will be deflected by same amount everywhere, so the illumination of the picture is same on the screen. The shadowgraph method has advantages over other optical methods because of simplicity and wider application in fluid dynamics research.

In shadowgraph, Schlieren and interferometer flow visualization methods are used to visualize the supersonic flow field when the density gradient exists due to the flow itself (Due to the formation of shock and expansion wave). But in the present study both outer flow (primary air) and
base-Jet (secondary air) are in subsonic velocity only. Hence, it is difficult to use any of the above said optical flow visualization methods.

Since the velocity of both the jets are subsonic, it is very important to create an artificial density gradient between the primary and secondary jets. To create an artificial density gradient the jet inject from the base is of helium gas, whose density is 7.2 times small than that of normal air. The primary objective of the flow visualization study is to study the flow pattern and penetration characteristics of base-jet; hence the base-jet is of helium gas.

(All the dimensions are in mm; Test section: 240 x 180 mm for 660mm length with glass side walls) 1- Wind tunnel, 2- Light source, 3- Condenser lenses, 4- Slit, 5- Beam cutter, 6- Reflecting mirror (concave), 7- Folding mirror (plain mirror), 8- Screen, 9- Camera, 10- Test model.

**Figure 4.23 Layout of shadowgraph flow visualization setup**

The schematic arrangement of the shadowgraph flow visualization setup is presented in Figure 4.23. Flow visualization setup consisting of different components as source lamp power supply unit, source lamp,
condenser lenses, slit assembly, reflective mirror, beam cutter, folding mirror, screen, digital camera.

Specifications of different component of the shadowgraph flow visualization setup is given below,

I. Source lamp with power supply: 24 Volts AC/DC Power supply can be provided to the source lamp to operate 24 V, 150W halogen Light Source.

Input Power: 230V, 50Hz AC

- Output voltage: AC: 0 to 24 volts variable
  DC: 0 to 24 volts variable.
- Output current: 6.5 Amps.
- Output Mode: Constant Current limit.
- Output Display: 200v, DC DPM with 0.1V resolution
- Input Fuse: 5 amps, Fast blow
- Temperature: 0-40 C with forced air cooling.

II. Condenser Lens: A condenser lens assembly is used to efficiently collect the light emitted from the source lamp and also to focus the collected Light at a point on slit assembly. One end of the condenser lens is fully open, on the other side, an iris diaphragm is provided, which can be used to adjust the (increase or decrease) diameter of the outlet of the condenser lens. By operating iris diaphragm, contrast of the light which falling on the slit can be controlled. To get a clear final image it is recommended to open the diaphragm to the diameter from 5mm to 7mm.
Material of lens : High optical quality Boro-silicate & flint
Size : 80mm Focal length, F/1.6 with Iris Diaphragm.

III. Slit Assembly: The slit assembly was positioned exactly at the focal point of the condenser lens. One end of the slit is fully open circular ring like structure, on the other side an adjustable jaw like plate will be there to adjust the opening of the slit. Opening of the slit can control by operating knurled hand screw which is available on it. To get an effective image, slit opening should be exactly positioned at the focal point of the condenser lens. Also, opening of slit must be maintained minimum (recommend 1mm).

IV. Baffle Assembly: The purpose of using the baffle assembly is to stop the unwanted light before falling on the reflecting mirror. It is in the form of a hole in a flat path mounted on an adjustable assembly. Position of the baffle assembly, decides the improvement of contrast of the image. Optimum location of the baffle assembly for the present experiment is show in Figure 4.23.

V. Reflecting Mirror: A High sensitive, circular reflecting mirror is placed at one side of the test section to reflect the light coming from the baffle assembly. The light reflects from the mirror will be a collimating one, hence the location and alignment of the mirror is very important in the flow visualization. Light source, condenser lens, slit, baffle assembly and reflecting mirror must be arranged in an optical axis, which is aligned with the high of the axis of the tunnel. Any miss alignment in location of slit and reflecting mirror leads to elliptic shape image instead of a perfect circular image.

Specifications:

Material : High optical quality Boro-silicate crown glass.
Diameter : 150 mm
VI. Folding Mirror: Once the collimating light passes through the test section, due to the existence of density gradient, refractive index of the light varies hence a shadowgraph image can be recorded on the other side of the test section. But in the present experiment, due to lack of space on the other side of the test section, the light coming from the test section is folded by a high quality plain mirror to change it direction. The folded image can be received on the screen and record by a digital camera.

VII. Screen: It is the important component of the flow visualization. Any defect in the screen causes serious damage in the final image. Selection of the screen material also is important task. In the present experiment, a nice cloth of sandal colour (finalized by trial and error) was used as a screen to get comparatively good image on the camera.

VIII. Camera: A Digital camera with 8 mega pixel quality was used to record the shadowgraph image form the screen. For every experiment, both video and still images records for reference purpose. The camera is place in an optimum in between screen and folding mirror to record the image without disturbing the optical axis. The camera is positioned in a fixed location, the images record in the camera is transfer to a personal computer by using a data transferring card already connected with it, without disturbing the camera position.

Specification:

Make : Cannon
Model : PowerShot A590 IS
Camera effective pixels : Approximately 8.3 million
Image sensor: 1/2.5 inch, type CCD

Lens: W-5.8mm, T-23.2mm (f/2.6(W)- f/5.5 (T)

Shutter: Mechanical shutter and electronic shutter

Shutter speed: 1 /60 – 1 / 2000 sec,
15 – 1 / 2000sec. (shutter speed range throughout all shooting modes)

Recording media: SD memory card

Number of recording pixels (still image): 3264×2448 pixels (large)
Number of recording pixels (movies): 640 × 480 pixels (20 frames / sec)

Interface: Hi-speed USB (mini-B) audio/video output

Power source: 2AA size batteries or AC adapter kit ACK800

Dimension: 94.3 × 64.7 × 40.8 mm, weight – 175g

4.5 DATA ACQUISITION AND PROCESSING

Effect of change in geometrical shape of a bluff body from circular cross section to elliptic cross section on the parameters along the wake axis (L_{jp}, MRV and PASP) is analysed in this study. Experiments are conducted at both with and without base-jet injection behind both the cones. In the course of experimentation, static pressure, velocity measurements are carried out in addition with flow visualization at low subsonic velocity. In this section different methods involved to collect the experimental data and post processing of acquired data are presented.
4.5.1 Pressure Measurement

Static pressure distribution along the wake axis of circular and elliptic cone without any base-jet injection was measured using a static pressure probe and DSA. The static pressure probe used for the measurement is designed and fabricated based on the guidelines given in the literatures. A pressure hose is connected between outlet of static probe and input port of the DSA.

The static pressure probe is placed on the probe support of the 2D traversing mechanism. With the help of traverse, at 25 different locations along the wake axis of both the cones static pressure was measured. The different location of pressure data observed is presented in Figure 4.24. At every 5mm distance the static pressure was measured along the wake axis of circular and elliptic cone at 6m/s, 15m/s and 25m/s without any base-jet injection.

Figure 4.24 Locations of pressure measurement along the wake axis
At every selected location along the wake axis, the static pressure data was acquired and stored using the DSA module and DSA Link interface software according to the operating procedure. Before starting of every experiment, a particular location (folder/file) where the acquired data has to be stored was created. During the data acquisition, data file pertaining particular measured location along the wake axis also named correspondingly. For example, if static pressure measured at 15 mm from the base then the file name entered as 15 mm. log. Careful selection of destination folder and file name can reduce the error during data processing.

During the static pressure measurement, differential pressure was measured at every selected location. For the analysis of effect of freestream velocity and change in geometrical shape on the static pressure distribution, the raw differential pressure has to be reduced as absolute pressure (p) and coefficient of process ($C_p$). A dedicated MATLAB program was developed to read the raw pressure data from individual file and reduce it to the required parameters like $P$ and $C_p$ (Appendix 1).

As the output of the post processing, a plot of coefficient of pressure distribution with respect to the non-dimensional axial distance ($x/d$) as show in Figure 4.25 can be obtained. Computationally (using CFX) obtained pressure coefficient and available literature (Calvert (1967)) pressure coefficients are also presented in the same figure for the reference. Good agreement between experimental, computational and literature data can be observed. Processed numerical data of absolute pressure and $C_p$ also saved in a file at the destination folder. Similarly the created plots also stored in the destination folder.
4.5.2  Velocity Measurement

4.5.2.1  Calibration of hot-wire sensor

For the measurement of velocity distribution along the wake axes of circular and elliptic cone a constant temperature hot-wire anemometer (CTA, DANTEC make) was used. Based on the working principle of the CTA, it is known that the output from hot-wire anemometer is in the form of voltage. In general the output voltage of the CTA module will be collected with the help of A/D board (which is installed in a personal computer) and streamline software. The purpose of streamline software is to create an interface between the users and hot-wire modules. The stream line software also does the reduction of raw voltage data in to mean velocity, velocity fluctuation and turbulence intensity. CTA was operated manually and the raw data output from CTA was collected by a data acquisition system (yokogawa-DL750) as shown Figure 4.26. Data reduction was done by a dedicated MATLAB program to get the required velocity and velocity fluctuation plots.
Figure 4.26 Layout of data acquisition and processing of velocity measurement

Data reduction either by streamline software or a MATLAB program, to get effective results it is very important to calibration the CTA sensor perfectly. From the calibration process only the coefficients A, B and n can be obtained. In this section calibration procedure of hot wire sensor used during the experiment is explained.

A typical hot–wire sensor calibrated is shown in Figure 4.27 and 4.28. Total height and diameter of the calibrate assembly is 170mm and 106mm respectively. Near to the exit of the calibrator, a constant area tube of diameter 14mm and height 10mm is placed. The calibrator is designed as per the standard dimension of a calibration unit. The air required for the calibrator is supplied by an air compressor via local reservoir and pressure regulating valve (PRV – 0 to 10 kg/cm²). Exit velocity of the calibrator, is controlled by PRV.
Using a pitot static tube, exit velocity of the calibrator was measured for the selected PRV set pressure using DSA module. A typical plot of PRV set pressure versus calibrator exit velocity is shown in Figure 4.29.
Repeatability of the exit velocity of the calibrator also verified with respect to the PRV set pressure (Figure 4.30). Raw pressure data observed from the calibrator exit using DSA was reduced into velocity by a MATLAB program given in Appendix 2.

![Figure 4.29 Calibrator exit velocity for different PRV set pressures](image1)

![Figure 4.30 Repeatability of calibrator exit velocity for different PRV set pressures](image2)

After a mathematical relation developed between PRV set pressure and calibrator exit velocity, the pitot static tube is replaced by a hotwire sensor. Using the hotwire-module and data acquisition system, output voltage
for pre-defined PRV set pressure (24 points) was measured and recorded. A typical output voltage plot for different PRV set pressure is presented in Figure 4.31. By using the king’s law, between the hot-wire output voltage and calibrator exit velocity, the value of ‘n’ can be obtained by trial and error method. To find out the optimum ‘n’ value with minimum error, a dedicated MATLAB program was developed (Appendix 3). The Figure 4.32 shows the Sum of Squared Error (SSE) for different value as ‘n’.

Figure 4.31 Hot-wire output voltage for different PRV set pressure

Figure 4.32 Determination of exponent value of ‘n’ with minimum SSE

From the Figure 4.32 it can be noted that the exponent value of the probe used during the experiment is 0.4466. The value of determined ‘n’ is very close to
the recommended value by the manufacturer (0.45 to 0.5). Once the value of ‘n’ is available, it is important to find out the values of the coefficients A and B. Using the value of CTA output voltage (E) and calibrator exit velocity (U) a linear correlation was developed as show in Figure 4.33.

![Figure 4.33 Determination of constants ‘A’ and ‘B’ using King’s law](image)

The value of ‘n’ is essentially obtained from the previous step. As the result of linear fit, between $E^2$ and $U^n$, the value of coefficients A and B can be obtained.

\[
A = 1.661 \\
B = 0.8352 \\
n = 0.4466
\]

During the calibration, effect of number of calibration points, effect of upstream pressure of the PRV and effect of data acquisition time also studied. Based on the analysis it was found that 24 point calibration with 10kgf/cm² Pressure in the local storage cylinder are the parameters finalized for the calibration. A typical value PRV set pressure, calibrator output velocity and, hot-wire output voltage is presented in the Table 4.2.
<table>
<thead>
<tr>
<th>S. No</th>
<th>PRV set pressure (kgf/cm(^2))</th>
<th>Calibrator exit velocity (m/s)</th>
<th>CTA output voltage (Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1.315747</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>5.036648</td>
<td>1.83751</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>7.353333</td>
<td>1.900875</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>9.17473</td>
<td>1.966625</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>11.28374</td>
<td>2.021503</td>
</tr>
<tr>
<td>6</td>
<td>0.7</td>
<td>13.11418</td>
<td>2.066978</td>
</tr>
<tr>
<td>7</td>
<td>0.8</td>
<td>14.60777</td>
<td>2.090784</td>
</tr>
<tr>
<td>8</td>
<td>0.9</td>
<td>15.56799</td>
<td>2.130788</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>17.15291</td>
<td>2.155664</td>
</tr>
<tr>
<td>10</td>
<td>1.2</td>
<td>19.74343</td>
<td>2.208315</td>
</tr>
<tr>
<td>11</td>
<td>1.4</td>
<td>22.62258</td>
<td>2.243541</td>
</tr>
<tr>
<td>12</td>
<td>1.6</td>
<td>24.99771</td>
<td>2.273834</td>
</tr>
<tr>
<td>13</td>
<td>1.8</td>
<td>27.42571</td>
<td>2.302558</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>29.13159</td>
<td>2.339582</td>
</tr>
<tr>
<td>15</td>
<td>2.2</td>
<td>31.69033</td>
<td>2.358264</td>
</tr>
<tr>
<td>16</td>
<td>2.4</td>
<td>33.31768</td>
<td>2.385381</td>
</tr>
<tr>
<td>17</td>
<td>2.6</td>
<td>36.10754</td>
<td>2.407674</td>
</tr>
<tr>
<td>18</td>
<td>2.8</td>
<td>38.69885</td>
<td>2.438909</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>40.42214</td>
<td>2.45713</td>
</tr>
<tr>
<td>20</td>
<td>3.2</td>
<td>43.24335</td>
<td>2.477695</td>
</tr>
<tr>
<td>21</td>
<td>3.4</td>
<td>45.7096</td>
<td>2.499995</td>
</tr>
<tr>
<td>22</td>
<td>3.6</td>
<td>47.51351</td>
<td>2.519347</td>
</tr>
<tr>
<td>23</td>
<td>3.8</td>
<td>50.04207</td>
<td>2.539881</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>52.35229</td>
<td>2.555373</td>
</tr>
</tbody>
</table>
4.5.2.2 Data reduction of CTA output voltage

Effect of geometrical shape of the cones on the wake axis velocity distribution and velocity fluctuation was measured using constant temperature hot-wire anemometer. Along the wake axis (a line perpendicular to the base and collinear with axis of cone), at 56 different locations velocity was measured. Locations of the velocity measurement point are present in the Figure 4.34.

![Figure 4.34 Locations of velocity measurement along the wake axis](image)

Since the change occurs in the reverse flow region due to base jet injection is primary interest in this study, a large number of observations was made within that region ($\Delta x=2m$, 40 point). At every location along the wake axis output voltage obtained from the CTA module was stored in a personal computer with the help of a data acquisition system (yakogawa-DL 750). The raw output voltage form the CTA (Figure 4.35) was converted in to the velocity by a dedicated MATLAB program as given in Appendix 4.
At all the 56 locations along the wake axis, the CTA voltage was observed for 10 seconds with 1000 sample/second (1kilo sample per second). At every location 10,000 voltage data was acquired and stored by the data acquisition system. The reduced data of time averaged mean velocity ($U_m$) and velocity fluctuation ($u'_{rms}$) will be stored as a numerical data in a separate file in the working directory. Finally the program will plot the non-dimensionalized velocity and RMS value of velocity fluctuation against the non-dimensionalized axial distance (x/d) and save it in the working directory. A typical reduced data of mean reduction and velocity fluctuation is shown in Figure 4.36 and 4.37 respectively.
4.5.3 Processing of Shadowgraph Image

The flow visualization image obtained from the shadowgraph method is of poor quality due to the experimental limitations. It required to improve the quality of flow visualization image. Different processes involved during the image processing are present in this section.
A dedicated MATLAB program was developed to enhance the quality of the flow visualization image (Appendix 5). Image processing is done in five different stages as

- Conversion of tricolour raw image into gray scale image.
- Removal of unwanted black pixels from the image (trimming).
- Treatment (Enhancement) of intensity of individual pixels.
- Filtering of enhanced image
- Plotting of pixel intensity value along the wake axis.

### 4.5.3.1 Conversion of RGB image into gray scale image

In this stage the raw tricolour image as shown in Figure 4.38 will be converted into a grayscale image (Figure 4.39). Intensity values of entire pixels in the grayscale image will be 1 to 256 (1 – perfect black and 256 – perfect white). Whereas for tricolour image every for pixel have three different intensity value (Red, Green, Blue), hence the enhancement of individual pixel is very difficult for tricolour image than that of grayscale image.

![Figure 4.38 Raw tricolour (RGB) flow visualization image of circular cone with helium base-jet injection](image-url)
4.5.3.2 Trimming

During this process, the converted grayscale image undergoes a trimming operation. That is the process of removal of black pixel present outside the visualization circle. A typical trimmed image is shown in Figure 4.40.

4.5.3.3 Enhancement of pixel intensity

The trimmed image undergoes a pixel integrity enhancement operation based on a mathematical relationship as shown in MATLAB
program (Appendix 5, Process 3). The ultimate aim of this process is to clearly distinguish the helium jet (relatively black colour—low pixel intensity value) and separation layers (Relatively white – higher intensity value). During the enhancement, two marginal values of pixel intensity will be selected, one lower limit and the other is higher limit. Every pixel of the image will be considered for its current intensity value. If the intensity of the pixel is lower than lower margin than its intensity will be still reduced (darkening). When the intensity of pixel is greater than the maximum marginal value, then its intensity will be increased (whitening). A typical pixel intensity enhanced image is presented in Figure 4.41.

![Output image of pixel intensity enhancement operation](image)

**Figure 4.41 Output image of pixel intensity enhancement operation**

### 4.5.3.4 Image filtering

Output image of the image enhancement process will be of irregular in quality; hence it is necessary to filter the image. In the present study average filtering method was selected. The size of the matrix for the filtering operation was taken as 7x7. Number of iterations for the filtering operation also is very important; hence in the present study 30 iterations was done during filtering operation. The parameters like average filtering, matrix
size and number of iteration are decided based on the trial and error method. A typical filtered image of flow visualization is present in the Figure 4.42.

Figure 4.42 Output image of filtering operation

4.5.3.5 Pixel intensity plot

One of the important objectives of the present study is to get the penetration length of different base jets injected from circular and elliptic cones. By using flow visualization image, very accurately length of base-jet penetration can be obtained.

In the filtered image every pixel has an intensity value. At exit of the base-jet, since the intensity of helium is more, very low pixel intensity value can be observed. Similarly, at the stagnation point of base-jet also due to the accumulation of helium gas intensity of pixels will be low. By capturing the low pixel intensity value along the wake axis except the exit of the jet, length of penetration of different velocity base-jet can be determined. Distances equal to two time base diameter, intensity values of pixels were extracted. Extra care was taken to select the starting and end point of the axial
line along the wake. The extracted pixel intensity value will be plotted against the non-dimensionalized distance (x/d) as shown in Figure 4.43.

![Figure 4.43 Output plot of pixel intensity distribution along the wake axis of flow visualization image](image)

**4.5.4 Calibration of Base-Jet Exit Velocity**

Base-jet air was injected at different velocity as 12.5 m/s, 18.8 m/s, 25 m/s, 31.3 m/s and 37.5 m/s to achieve the base-jet injection ratio (IR) of 0.5, 0.75, 1.0, 1.25 and 1.5. To maintain the correct exit velocity through the base-jet some pre-processing is required. Before start of the experiments base-jet nozzle is attached to the base-jet adapter of the cone. Since the local reservoir pressure is maintain at 10kgf/cm², an integrated moisture separator and PRV controls the mass flow rate of base jet air through the base jet orifice. By operating a control valve available on the top of the PRV (Figure 4.12) downstream pressure can be controlled to a predefine value. By using the CTA, exit velocity of the base-jet is measured for different PRV set pressure. After getting the velocity data for different PRV set pressure, a mathematical correlation is derived between them. Then from the correlation, PRV set pressure required to attain the designed base-jet velocity (IR) can be obtained.
A typical base jet calibration curve of a circular base jet of AR=0.005 is presented in Figure 4.44. From the figure a mathematical correlation can be derived as shown. Using the correlation correspond PRV set pressure required to achieve the base-jet velocity can be obtained as shown in Table 4.3. Before starting any base-jet injection experiment, exit velocity of the base-jet will be verified (Using CTA) without tunnel flow to increase the level of confidence.

![Figure 4.44. Exit velocity of base-jet nozzle for different PRV set pressure](image)

**Table 4.3 PRV set pressure required to achieve different base-jet injection ratios**

<table>
<thead>
<tr>
<th>Base-jet injection ratio (IR)</th>
<th>Exit velocity (m/s)</th>
<th>Required PRV set Pressure (Kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>12.5</td>
<td>1.3</td>
</tr>
<tr>
<td>0.75</td>
<td>18.8</td>
<td>2.2</td>
</tr>
<tr>
<td>1.0</td>
<td>25</td>
<td>3.0</td>
</tr>
<tr>
<td>1.25</td>
<td>31.3</td>
<td>3.8</td>
</tr>
<tr>
<td>1.5</td>
<td>37.5</td>
<td>4.4</td>
</tr>
</tbody>
</table>