Design Of An Automated Jet Flow Characterisation Setup

End-term Project Report

Submitted by

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OVERVIEW OF THE PROJECT

Motivation for the problem:

To explore the area of flow measurement systems and to develop a robust, cost effective system to identify characteristics of a jet flow for experimental purposes. The setup can be used to study the velocity profile of the jet produced and the entrainment of air near the jet with the variation of temperature and jet flow velocity.

Description:

Parts of the setup:

- Centrifugal air blower (the velocity of air can be changed to alter the flow rate)
- Ceramic heating element and variac to vary the temperature of the jet by heating the flowing air
- To achieve different flow rates at the exit, two ball valves were installed on the setup. One is installed before the heater, and the other after
- Pitot tube to measure the air velocity
- Automated frame arrangement to move the Pitot tube to the desired test location where the data must be collected. This can be achieved using a stepper motor with linear actuators to provide the horizontal planar motion to the Pitot tube.
- Differential Pressure sensor to measure the pressure drop to determine the flow velocity
- Data Acquisition system for entering the input and control the parts to obtain the desired output
- Arduino Uno to control the stepper motor
- Nozzle and Duct

Variables: Temperature and velocity of the jet

The temperature of the air jet can be controlled using the ceramic heating element and variac setup. The velocity of the jet can be controlled by adjusting the air intake into the air blower as well as the air flow through the ball valve.
Using this setup, the velocity profile of the air jet can be determined and it is expected to be a Gaussian profile.

Expected deliverable at the end of the OELP:

We expect to produce a low-cost automated jet flow characterisation system. The schematic diagram of the system is shown in figure 1. This setup can also be used to study the jet impingement cooling/ heating employed in the equipment like gas turbines, printed circuit boards, battery packs, dryers etc.

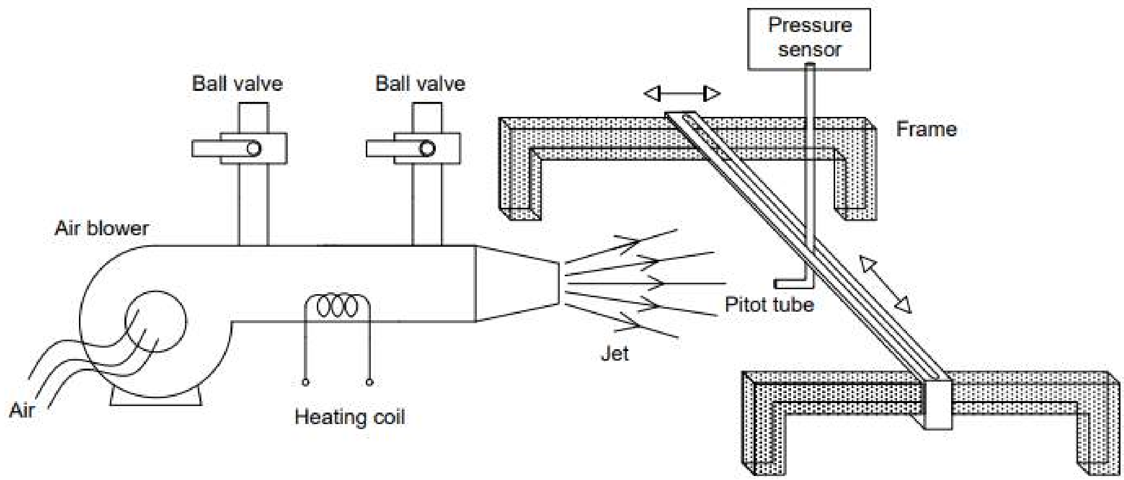


Fig. 1 Automated jet flow characterisation setup

LITERATURE REVIEW

When a jet enters a surrounding medium, entrainment occurs in the jet and the surrounding fluid starts mixing with the jet and the jet spreads out laterally as it moves. The average velocity of the jet continuously decreases as it imparts momentum to the surrounding fluid that is entrained. There are no contour walls because the jet spreads at constant pressure. The momentum flux remains constant at any cross section (at any given distance along the jet axis). As a result, the cross-section of the jet increases, the velocity profile becomes non-uniform, and a portion of the surrounding fluid is entrained in the main flow.

Assume $\dot{m}_1$, $\dot{m}_2$ and $\dot{m}_3$ are the mass flow rates at three different axial locations as shown in the Fig. 2.

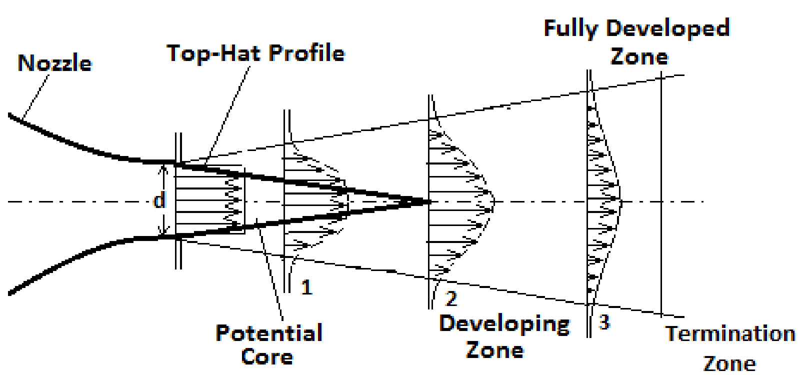


Fig.2 : Jet flow with the various zones of the subsonic air jet.

Source: http://article.sapub.org/image/10.5923.s.ajfd.201501.01_001.gif

Theoretically, $\dot{m}_1 = \dot{m}_2 = \dot{m}_3$. But experimentally, $\dot{m}_3 > \dot{m}_2 > \dot{m}_1$

The mass flow rate is not constant because entrainment occurs in a jet. Hence, the mass flow rate of the entrainment is given by

$\dot{m}_{entrainment,1} = \dot{m}_1 - \dot{m}_2$ (between locations 1 and 2) and

$\dot{m}_{entrainment,2} = \dot{m}_2 - \dot{m}_3$ (between locations 2 and 3)

The expected velocity profile will be a Gaussian function $v(r)$ where r is the radial distance from the axis of the jet.

The equations are as follows:

i) Discharge is given by

$Q = \int_0^R 2\pi r u dr$, r is the radial distance from the axis of the duct/nozzle and R is the radius of the duct/nozzle.

ii) Momentum which remains constant in the absence of external forces is given by

$M = \int_0^R 2\pi r \rho u^2 dr$, ρ is the density of the air and u is the flow velocity of air.

iii) Energy which may drop due to losses due to the entrainment action is given by

$$E = \int_0^R 2\pi r \rho u^3 dr$$

Different zones in a subsonic air jet

An air jet is a circular jet of diameter d that emerges from a round nozzle with uniform velocity into a large stagnant volume of fluid. The Pitot tube downstream of the jet measures the time mean average velocity at various jet cross sections and is a Gaussian profile. The jet flow is primarily divided into four regimes.

1. *Potential core*: The core fluid forms a cone with constant flow velocity; this zone typically extends from 4d to 6d (where d is the exit diameter of the nozzle).

2. *Transition zone*: This zone occurs immediately after the potential core. The velocity decay along the central line begins. This zone is also referred to as the flow development region. The velocity decay in this region is proportional to the square root of the axial distance from the nozzle. This area ranges from 6d to 20d.

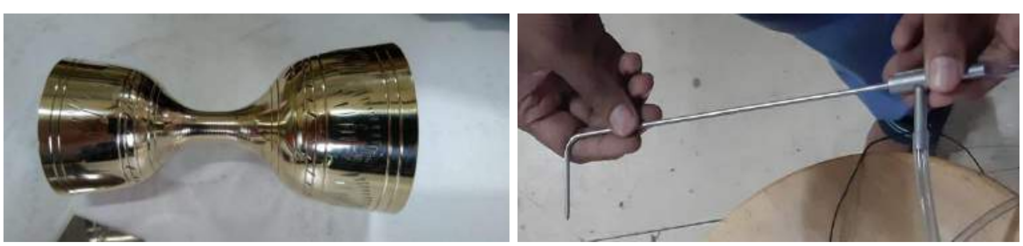
3. *Profile similarity zone*: Located away from the potential core. The transverse velocity profiles of the jet at different cross sections are similar. This zone is also known as the fully developed regime. The axial distance is inversely proportional to the decay in center-line velocity.

4. *Termination zone*: This zone is distinguished by the rapid decay of the centerline velocity.

SPECIFICATIONS OF COMPONENTS USED

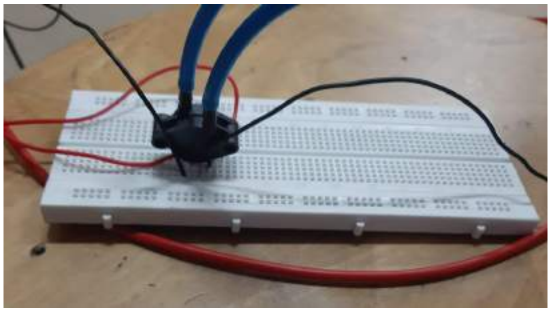
(a) **(b)** **©**

Fig.3: (a) Air blower - Bosch GBL, 620W power and airflow rate = 3.5 $\frac{m^3}{min}$
(b) Ball valve - 3/4 inch nipple joint with 3/4 inch ball valve (c) GP Pipe/ Duct - Galvanized pipe of length~1.56 m, Inner Diameter~43 mm, Outer Diameter ~47mm



(a) **(b)**

Fig.4: (a) Nozzle - Brass, Inlet diameter ~ 40 mm, Outlet diameter ~ 8 mm (b) Pitot tube




(a) **(b)**

Fig.5: (a) Differential Pressure Sensor - 0.5 bar (on breadboard) (b) Traversing mechanism frame

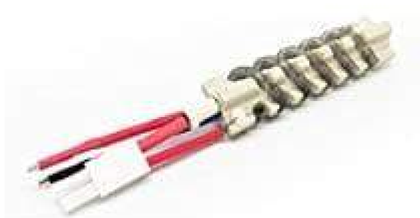


Fig.6: Ceramic Heating Element - 110 V , Heater resistance value ~ 80 Ω

WORK DONE

The air jet is created by connecting a blower to a pipe and attaching a nozzle to the end of the pipe. We installed two ball valves (brass ball valves) to achieve the desired air flow. One valve is installed near the blower outlet and the other after the heater. A blower used for household cleaning is adequate for our setup. The manufacturer has set the flow rate of these blowers at $3.5 m^3/min$. So we assumed this as our maximum flow rate and set the blower's minimum flow rate to $0.5 m^3/min$ because we need some range while controlling the flow.

Maximum discharge, $Q_{max} = 3.5\frac{m^3}{min}$, Minimum discharge, $Q_{min} = 0.5\frac{m^3}{min}$

Discharge, $Q = Av$

Where, A : Cross-section area of the jet = πr^2
v : Velocity

$A = \pi r^2 = 3.14159 \times (0.004)^2 = 0.0000502655\, m^2$

For $Q_{max} = 3.5 \frac{m^3}{min}$, velocity at the exit of the nozzle is 1160.5 $\frac{m}{s}$

For $Q_{min} = 0.5 \frac{m^3}{min}$, velocity at the exit of the nozzle is 165.7 $\frac{m}{s}$

Note: The values for discharge calculated are theoretical values. To get the actual values of discharge we have to multiply the theoretical values of Q with the Coefficient of discharge (C_d). We will consider $C_d \simeq 0.61$.

To find the minimum ΔP measured by the Pitot tube, we consider the minimum discharge from the air blower which is $Q_{min} = 0.5 \frac{m^3}{min}$. The corresponding velocity at the nozzle exit is $v_0 = 165.7 \frac{m}{s}$.

We know, $\Delta P = \frac{\rho v^2}{2}$.

$$\text{Hence, } \Delta P_{min} = \frac{\rho v_0^2}{2} = \frac{1.165 \times (165.7)^2}{2} = 15993.405\, Pa = 0.15993\, bar$$

To find the maximum ΔP measured by the Pitot tube, we consider the maximum discharge from the air blower which is $Q_{max} = 3.5 \frac{m^3}{min}$. The corresponding velocity at the nozzle exit is $v_0 = 1160.5 \frac{m}{s}$.

$$\Delta P_{max} = \frac{\rho v_0^2}{2} = \frac{1.165 \times (1160.5)^2}{2} \simeq 784487.845\, Pa \simeq 7.84487\, bar$$

For 30 ℃, we get the range of ΔP as 0.15993 bar to 7.84487 bar.

We used a Galvanized pipe of approximately 1.56 m length. The nozzle has been attached to the end of the pipe using flanges. The reason for using two ball valves is to gain better control over the jet flow rate.

To obtain the velocity profile of the ejecting jet at various axial and radial locations, we use a Pitot tube connected to the pressure sensor. The pressure sensor was powered by two 1.5 V DC power supplies connected in series. A multimeter was connected to the pressure sensor to display the voltage difference across the sensor. For a fluid with known density and measured difference between stagnation pressure and static pressure (ΔP), as measured with a pitot tube, the fluid velocity can be calculated with the equation: $v = \sqrt{\frac{2\Delta P}{\rho}}$.

The traversing mechanism allows the Pitot tube to move in both axial and radial directions with respect to the nozzle exit. Since the traversing mechanism part is still under assembly, we took the reading manually.

Because it is a table top configuration, we assumed the maximum dimensions of the traversing mechanism to be 25 times the jet diameter(d) along the axial direction, or 500 mm, and 20 times the jet diameter(d) along the radial direction, or 400 mm.

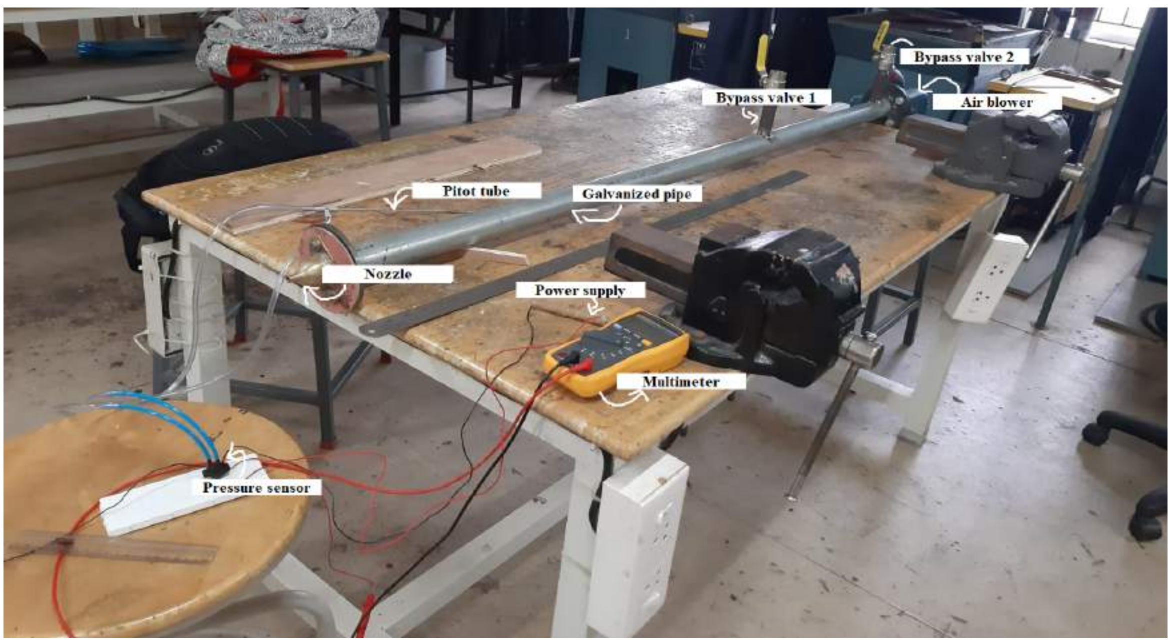


Fig.7: Actual image of the prototype

We can use a ceramic heating element to vary the temperature of the air jet. The change in temperature will result in a change in the density of the air jet which in turn results in a change in the velocity of the air jet. So, by varying the temperature, we vary the velocity and this enables us to obtain the velocity profile of jet flows at different temperatures. Also, if we work at different temperatures, the pressure range for the pitot tube changes anyway as the velocity and density of the air jet depend on the temperature.
As the ceramic heating element is yet to be fixed, the readings were taken at room temperature using the prototype to demonstrate its working.

OBSERVATIONS

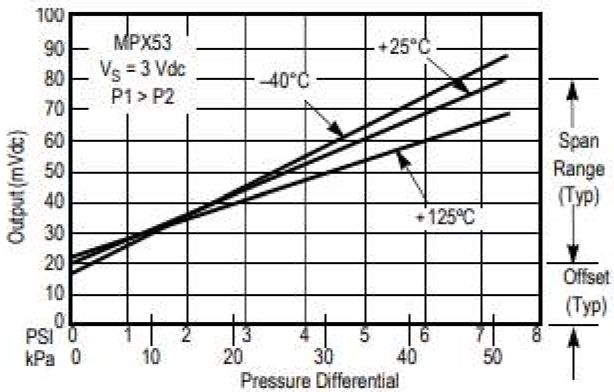


Fig.8 : Output vs. pressure differential

Relationship between differential pressure sensor output (mV$_{DC}$) and pressure differential:

At 25℃,

$$y - y_1 = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(x - x_1)$$

$$y - 24.2 = \left(\frac{30 - 24.2}{10 - 0}\right)(x - 0)$$

$$y = (0.58)x + 24.2$$

$$V_{DC} = (0.58)\Delta P + 24.2$$

$$\Delta P = \frac{V - 24.2}{0.58}$$

In this way we can know the pressure difference which is displayed in the Differential Pressure sensor and then velocity can be calculated using the equation when measured using a pitot tube.

$$\Delta P = \frac{1}{2}\rho v^2 \quad \text{(Differential pressure)}$$

$$v = \sqrt{\frac{2\Delta P}{\rho}} \quad \text{(jet velocity)}$$

i)Variation in velocity as a function of axial distance:

a: Axial Distance
V_{DC}: DC Voltage
ΔP: Pressure Differential
v: The exit velocity of air jet at different axial locations

a (cm)	0	1	2	3	4	5	6	7	8	9	10	11	12
V_{DC} (mV)	29	28.8	28.9	28.9	28.5	27.7	27.2	26.2	25.5	25.2	25.3	24.7	24.8
ΔP (kPa)	8.27	7.93	8.10	8.10	7.41	6.03	5.17	3.45	2.24	1.72	1.89	0.86	1.03
v ($\frac{m}{s}$)	119.15	116.67	117.92	117.92	112.78	101.74	94.21	76.95	62.01	54.34	56.96	38.42	42.05

a (cm)	13	14	15	16	17	18	19	20	21	22	23	24
V_{DC} (mV)	24.8	24.6	24.5	24.4	24.5	24.5	24.4	24.4	24.3	24.3	24.2	24.2
ΔP (kPa)	1.03	0.68	0.52	0.34	0.52	0.52	0.34	0.34	0.17	0.17	0	0
v ($\frac{m}{s}$)	42.05	34.16	29.87	24.15	29.87	29.87	24.15	24.15	17.08	17.08	0	0

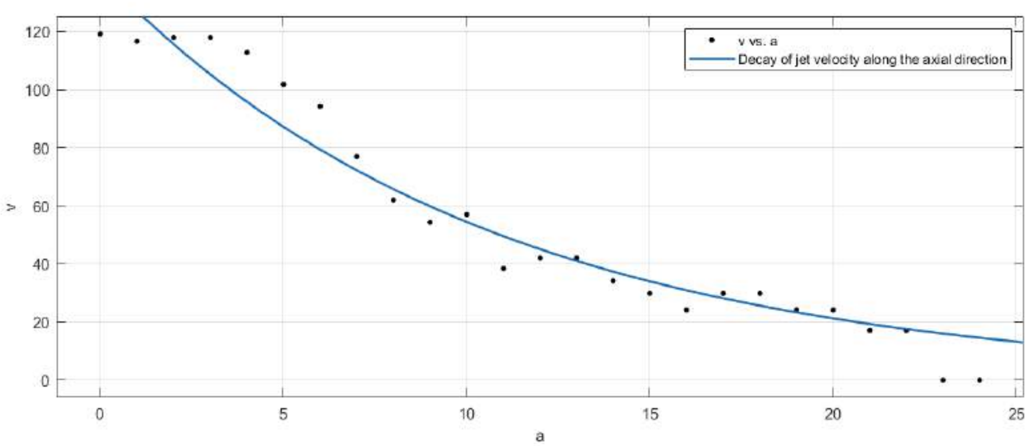


Fig.9 : This graph shows the decay of jet velocity at various points along the axial direction. The graph was obtained by fitting an exponential curve using the curve-fit tool on MATLAB.

ii)Variation in velocity as a function of radial distance:

r: Radial Distance
V_{DC}: DC Voltage
ΔP: Pressure Differential
v: The exit velocity of air jet at different radial locations

The axial distance is set at 2cm.

r (cm)	-2	-1	-0.5	0	0.5	1	2
V_{DC} (mV)	24.3	24.5	25.2	25.6	25.2	24.5	24.3
ΔP (kPa)	0.17	0.52	1.72	2.41	1.72	0.52	0.17
v ($\frac{m}{s}$)	17.08	29.87	54.34	64.32	54.34	29.87	17.08

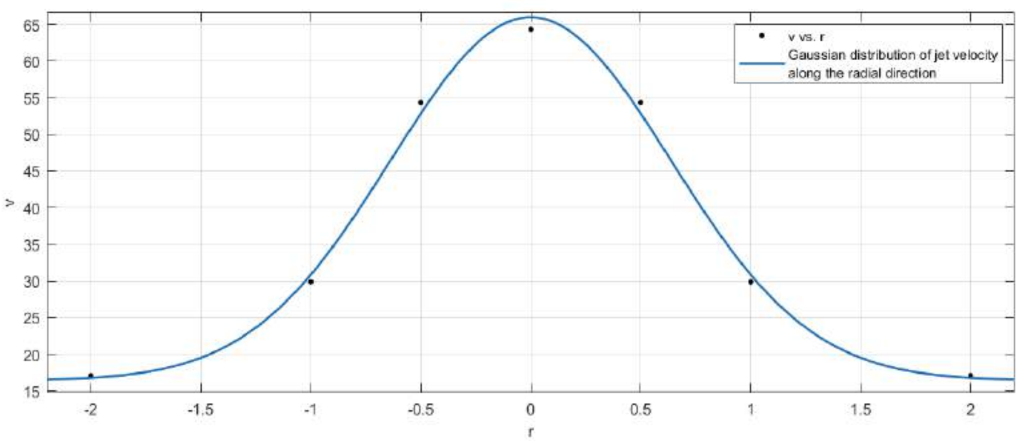


Fig.10 : This graph shows the distribution of jet velocity at a fixed axial distance from the nozzle exit but at different radial locations. The graph was obtained by fitting the data to a Gaussian distribution using the curve-fit tool on MATLAB.

Curve fit equation obtained: $f(r) = \left(49.55 \times e^{-\left(\frac{r-(4.75\times10^{-7})}{0.6806}\right)} + 16.43 \times e^{-\left(\frac{r+204.1}{1.229\times10^{-4}}\right)}\right)$

We know that the cross section area at the exit of the nozzle is 0.0000502655 m^2 and that the velocity at the exit of the nozzle is 119.15 $\frac{m}{s}$. Volume flow rate is given by,

$$Q_1 = A \text{ x } v = 0.0059891343 \frac{m^3}{s}$$

Mass flow rate is given by

$$\dot{m}_1 = \rho \text{ x } Q = 1.165 \text{ x } 0.0059891343 = 0.0069773415 \frac{kg}{s}.$$

The flow rate along the axial direction at a distance of 2 cm is given by

$$Q_2 = \int_{-\infty}^{\infty} 2\pi r \left(49.55 \times e^{-\left(\frac{r - (4.75 \times 10^{-7})}{0.6806}\right)} + 16.43 \times e^{-\left(\frac{r + 204.1}{1.229 \times 10^{-4}}\right)} \right) dr = 0.000178396 \frac{m^3}{s}$$

Now, mass flow rate is given by

$$\dot{m}_2 = \rho \text{ x } Q = 1.165 \text{ x } 0.000178396 = 0.0002078 \frac{kg}{s}$$

Mass flow rate of entrainment is given by,

$$\dot{m}_{entrainment} = \dot{m}_1 - \dot{m}_2$$

$$\dot{m}_{entrainment} = 0.0067695415 \frac{kg}{s}$$

RESULTS

Potential core region is from the nozzle exit to approximately 3 cm in front of the nozzle along its axis. The jet flow velocity is approximately 117.915 $\frac{m}{s}$ (taking the average of the first of the first 4 readings from 0 cm to 3 cm).

We can observe that the jet flow velocity decays in the axial direction as we move away from the nozzle.

From the velocities measured in the radial direction at a fixed axial distance of 2 cm from the nozzle, we get a Gaussian distribution.

Using the velocities calculated, we were able to find the mass flow rate of the jet flow at the nozzle exit and at an axial distance of 2 cm from the nozzle. Subtracting these 2 values, we get the mass flow rate of entrainment at 2 cm along the axis of the nozzle as

$$\dot{m}_{entrainment} = 0.0067695415 \frac{kg}{s}$$

ERRORS

As the traversing mechanism for the pitot tube and pressure sensor is not ready, we proceeded to take the readings manually by holding the pitot tube by hand at the required locations. But due to the high flow velocity, the pitot tube kept moving from the location we wanted to measure the velocity. Also, sometimes the pitot tube was not kept steady due to manual handling. These are the main reasons for errors to occur while taking readings.

WORK IN PROGRESS

1. Building the traversing mechanism

   We have not yet received all of the necessary equipment for the automated traversing mechanism. They can be constructed once they arrive.
2. Designing and understanding the working of the 2D traversing mechanism

   We are planning to use a stepper motor to provide motion to the Pitot tube arrangement. We have to fix the RPM of the stepper motor and the minimum traversing distance of the Pitot tube. The traversing mechanism can be made using a lead screw arrangement or a gear-belt arrangement. In case of the lead screw, the minimum traversing distance is related to the pitch of the lead screw and in case of the gear-belt arrangement, the minimum traversing distance is related to the pitch of the gear.
3. Fixing the ceramic heating element

   The ceramic heating element has to be placed inside the pipe between the two ball valves. As the size of the heating element is smaller than the diameter of the pipe, sufficient packing needs to be provided while placing the element inside the pipe. Also, insulation using mica sheets must be done to prevent electric shock if a short circuit occurs.

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