LAB 5 - Calibration of Pressure sensor and its application in Flow Measurement
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AE351
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- **OBJECTIVE:**

To study different types of pressure sensors and flow meters, and to
1. Calibrate the Differential Pressure sensor.
2. Characterize the different flow meters (Orifice, Nozzle, and Venturi).

- **INTRODUCTION AND THEORY:**

- Flow rate (volume and mass) **is measured using flow meters**.
Flow measuring devices can be broadly classified as
1. Variable area type
2. Drag effect type
3. Positive displacement type.

- *Principle of operation variable area flowmeters*:

In the variable area flowmeter we deliberately create a change in the area of the duct through which the fluid is flowing. Because of the change in the area, the velocity of the fluid changes, and because of the change in the velocity, there will be a change in the static pressure and we measure the static pressure and relate it to the flow rate which is being measured.

Basic equations which describe the variable area flowmeters.
Assumptions:
1. Flow is a set of an ideal fluid and incompressible flow
2. Flow is one-dimensional and steady.
3. Velocity across the cross is uniform.

Since we are assuming one-dimensional flow, the velocity is a function only of coordinate x so, u is a function of x only. We will introduce a correction for viscous effect, velocity variation across a section later.

Continuity equation: $A_1 . U_1 = A_2 . U_2$

Equation of Momentum: $\frac{P_1}{\rho} + \frac{U_1^{\ 2}}{2} = \frac{P_2}{\rho} + \frac{U_2^{\ 2}}{2}$

Mass flow rate at any section: $\dot{m} = \rho A v$

$\dot{m}_{theoretical} = \sqrt{\frac{2\rho\Delta P}{\{\frac{1}{A_2^{\ 2}} - \frac{1}{A_1^{\ 2}}\}}}$ where $\Delta P = P_1 - P_2$

Flow velocity, $V = \sqrt{\frac{2(P_0 - P_{static})}{\rho}}$

In order to make above equation valid for real fluid flowing through the periphery of the device we can introduce a dimensionless constant known as the coefficient of discharge (C_d).

$$C_d = \frac{\dot{m}_{actual}}{\dot{m}_{theoretical}}$$

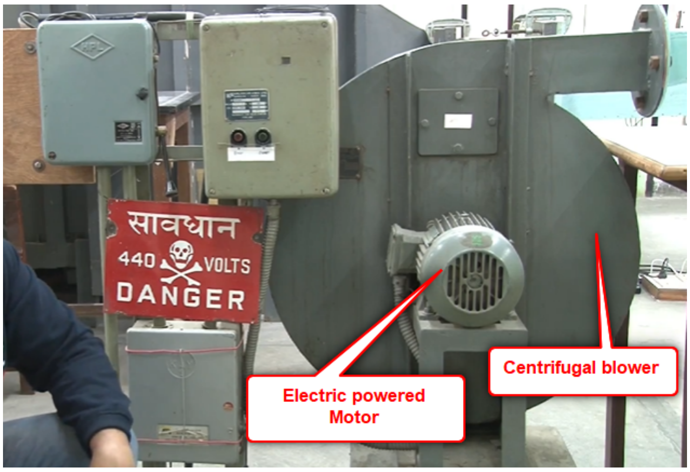
The pressure measured at the wall is equal to the pressure just outside the boundary layer which is formed next to the boundary. Therefore the pressure measured here is exactly the same as the pressure in the bulk of the fluid.

<u>NOTE :</u> A detailed discussion on the Orifice, Nozzle, venturi meter, and Pitot tube is there in the "Result and Discussion" section.

- **EQUIPMENT AND OPERATING CONDITIONS:**

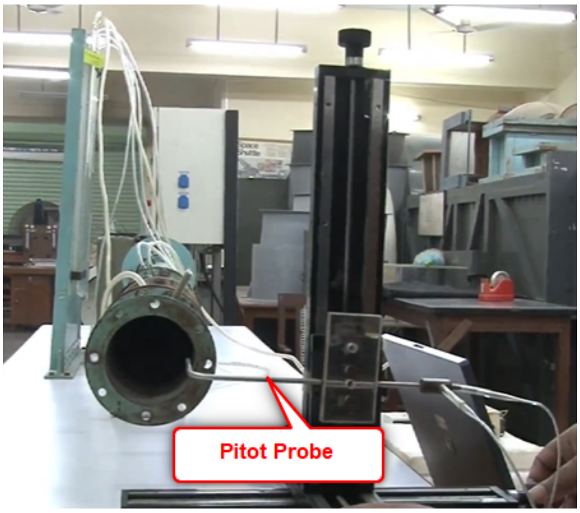
The experimental setup includes:

1. The open-circuit low-speed wind tunnel consists of a ***centrifugal blower*** driven by an electric motor (rpm around 2800). The blower draws in air from the atmosphere and discharges through the pipe. The butterfly valve located downstream of the blower is used to control the mass flow rate. The flow meters are fixed downstream of the valve in the order as shown in the figure. The velocity profile is determined at the exit, which is used for calculating the mass flow rate.



2. ***Differential Pressure sensor***:
An electronic differential pressure sensor is used to determine the pressure drop across flow meters and is connected to a DAQ system. The pressure sensor consists of a transducer that converts the pressure difference between the two ports connected to it, into an electrical signal and sends the electronic signal (DC voltage) based on the pressure.
For the present experiment, we will be using 4 differential pressure sensors:
- 1 sensor of 0 to 7.25psi range
- 3 sensors of 0 to 14.5psi range.

3. ***Pitot Probe***:
it measures the stagnation pressure and the static pressure. We will connect the Pitot tube at the exit of the venturi meter. So it will measure the pressure difference between the stagnation pressure and the static pressure. Will move the pitot tube from one wall to the next wall to measure the pressure difference at a different location of the cross-section at the exit of the venturi. At the outlet, we connect a pitot probe. The horizontal port measures the total pressure or the stagnation pressure and the perpendicular to the flow port measure the static pressure



4. ***Flow meters***: connected in the tube

- 1st is the **orifice meter** whose two ports are connected to the **differential manometer**.
- 2nd is the **Nozzle meter** whose ports are connected to the second **differential manometer**
- 3rd is the **venturi meter** whose ports are connected to the third **differential manometer**.

The differential manometer basically measures the pressure difference between the two ports.

5. ***Butterfly wall*** is used to control the mass flow rate of the air. It is initially set at 0. As we go ahead Mass flow rate will increase in the tube.

- Important Dimensions:

	Orifice	Nozzle	Venturi	
			Outer Dia	Throat Dia
Diameter	50mm	48mm	82.61 mm	43.4 mm

- **PROCEDURE:**

1. Understand the basic principles of Data Acquisition.
2. Note down the ambient temperature and pressure.

3. Calibration of Pressure sensor:

a) Connect the high-pressure port of the pressure sensor to the calibrator via T-joint and leave the other port of the pressure sensor open to the atmosphere.
b) Obtain the output voltage from the sensor for different pressures applied using the hand pump.
c) Repeat it 4 to 5 times.
d) Using the acquired data, find the best fit curve (linear fit), which defines the calibration equation for the sensor.

4. Calibration of Flowmeter:

a) Connect the pressure taps of flow meters to the pressure sensors using rubber tubes.
b) Switch on the tunnel and set the mass flow rate using the butterfly valve.
c) After a steady state is reached, obtain the pressure data from the sensors.
d) Traverse the pitot probe vertically, to determine the velocity profile across the cross-section of the pipe. Use this profile to determine the mass flow rate of air in the pipe.
e) Repeat the above two steps for different flow rates.

Experimental Data for Flow meters:

- **Sensor Calibration:**

Pressure (in an inch of H_2O)	**Voltage from Multimeter (in mV)**
0	0
0.5	5.1
1	10.3

1.6	16.1
2.1	21.1
2.5	24.9
3.2	32.1
3.6	36
4	39.6
3.7	36.8
3.3	33.1
2.7	26.9
2.2	21.8
1.8	18.6
1.4	14.4
0.9	10.4
0.3	3.1

- **Flow meter reading (Differential Pressure) :**

valve opening	Orifice Δh (in cm of Hg)	Nozzle flow Δh (in cm of Hg)	Venturi Δh (in cm of Hg)
5	1.5	1.2	1.8
6	2.3	1.4	2.3
7	2.8	1.6	2.6
8	3.1	1.8	2.8
9	3.2	1.8	2.9
10	3.2	1.8	2.9

- **Differential Pressure readings for Pitot tube**

Pitot location (in cm)	Voltage (in mV) for Valve opening 5	Voltage (in mV) for Valve opening 6	Voltage (in mV) for Valve opening 7	Voltage (in mV) for Valve opening 8	Voltage (in mV) for Valve opening 9	Voltage (in mV) for Valve opening 10
4	**5.4**	**7.2**	**8.2**	**8.8**	**8.8**	**8.8**
3.5	**6.6**	**8.7**	**10.2**	**10.9**	**10.7**	**10.4**

3	**7.5**	**10.2**	**11.9**	**12.1**	**13**	**12.4**
2.5	**8.9**	**11.9**	**13.4**	**13.9**	**14**	**13.8**
2	**9.8**	**13.1**	**15.6**	**15.5**	**15.6**	**15.6**
1.5	**11.2**	**14.4**	**16.4**	**16.9**	**17**	**17.2**
1	**12**	**15.6**	**17.6**	**18.4**	**18.7**	**18.4**
0.5	**12.3**	**16.3**	**18.4**	**19**	**19.2**	**19.2**
0	**12.4**	**16.3**	**18.7**	**19.6**	**19.6**	**19.6**
0.5	**12.3**	**15.9**	**18.4**	**18.9**	**19.1**	**19.2**
1	**11.4**	**15.2**	**17.4**	**18.2**	**18.2**	**18.4**
1.5	**10.5**	**14.4**	**16.4**	**16.6**	**16.9**	**17.2**
2	**9.4**	**12.8**	**14.8**	**15.3**	**15.6**	**15.5**
2.5	**8.4**	**11.4**	**13.1**	**13.9**	**13.4**	**13.4**
3	**7.1**	**9.9**	**11.4**	**11.7**	**11.7**	**11.5**
3.5	**6.2**	**8.7**	**9.8**	**10.2**	**10.3**	**10.2**
4	**4.2**	**6**	**7.8**	**7.4**	**7.3**	**7.1**

- **RESULTS AND DISCUSSION :**

(a) Calculations and Plots

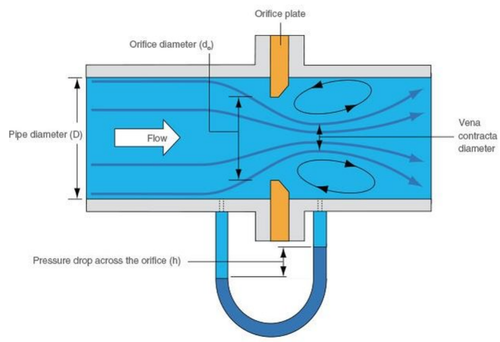
1. Explain the difference between Absolute Pressure, Gauge Pressure, and Differential Pressure.

- *Absolute pressure, Gauge Pressure, and Differential pressure* are different ways of measuring the pressure using pressure sensors (they vary on the references used for measuring the pressure):
- *Absolute Pressure* uses perfect Vaccum as its reference. Using an absolute pressure sensor eliminates the reference to varying atmospheric pressure or any dependence on a specific pressure range for reference.
- *Gauge Pressure* uses a reference to the atmosphere around the sensor. One common reason for using gauge pressure is to ensure that with any location throughout the world, the sensor will always reference the location in which it is installed.
- *Differential pressure* is essentially the difference in pressure between two given points. A true differential pressure sensor is used to identify the difference between the two separate physical areas of the same flow.

2. Explain the difference between Piezoresistive strain, Capacitive, Electromagnetic, Piezoelectric, Optical pressure sensing technology.

- *Piezoresistive strain*: They use the change in electrical resistance of a material when stretched to measure the pressure. The basic principle of the piezoresistive pressure sensor is to use a strain gauge made from a conductive material that changes its electrical resistance when it is stretched. The strain gauge can be attached to a diaphragm that recognizes a change in resistance when the sensor element is deformed. The change in resistance is converted to an output signal

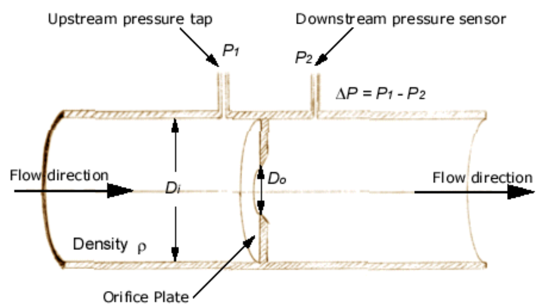
- *Capacitive:* Capacitive pressure sensors measure pressure by detecting changes in electrical capacitance caused by the movement of a diaphragm (this changes the spacing and hence the capacitance).
- *Electromagnetic*: Electromagnetic pressure sensor is the general name of a variety of sensors using electromagnetic principles, mainly including an inductive pressure sensor, Hall pressure sensor, eddy current pressure sensor, and so on.
- *Piezoelectric:* Piezoelectricity is defined as the production of an electric potential due to pressure on certain crystalline substances such as quartz. The nature of the piezoelectric device is the production of electric potential as it is deformed or stressed.
- *Optical:* Optical pressure sensors detect a change in pressure through an effect on light. In the simplest case, this can be a mechanical system that blocks the light as the pressure increases. In more advanced sensors, the measurement of phase difference allows very accurate measurement of small pressure changes.



3. Explain in brief about the Orifice meter, Nozzle meter, Venturi meter, Pitot probe.

- *Orifice meter* :

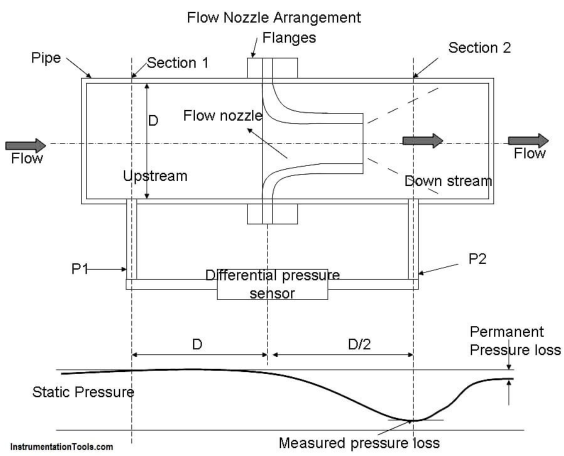
An orifice meter is **a device with an orifice that measures how fast a fluid is flowing, by recording the pressure decrease across the orifice**. The two most important factors that influence the reading of an orifice meter are the size of the orifice and the diameter of the pipe which it is fitted into.



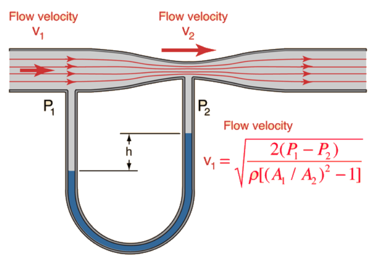
$$Q_a = \frac{C_d A_2}{\sqrt{1-(\frac{A_2}{A_1})^2}} \sqrt{\frac{2(p_1-p_2)}{\rho}}$$

C_d -- Discharge Coefficient
A_2 -- Cross-section Area of the Orifice
A_1 -- Cross-section Area of the Pipe
ρ -- Density of the liquid flowing

- *Nozzle meter or Flow Nozzle* :

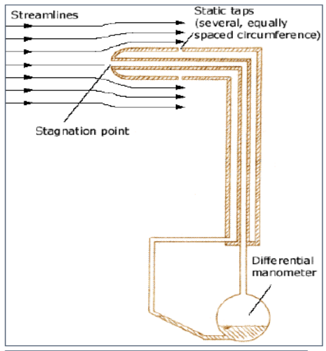


The Flow Nozzle is a flow tube consisting of a smooth convergent section leading to a cylindrical throat area. The throat is the smallest section of the nozzle. Pressure taps are located on the upstream side of the nozzle plate and on the downstream side of the nozzle outlet. They may be in the form of an annular ring, i.e. equally spaced holes connected together which open into the pipeline, or in the form of single holes drilled into the pipeline.



- *Venturi meter* :
  Venturi meters are flow measurement instruments that use a converging section of pipe to give an increase in the flow velocity and a corresponding pressure drop from which the flow rate can be deduced. They have been in common use for many years, especially in the water supply industry.

- *Pitot tube* :
  An open-ended right-angled tube pointing in opposition to the flow of a fluid and used to measure pressure. A device consisting of a pitot tube inside or adjacent to a parallel tube closed at the end but with holes along its length, the pressure difference between them is a measure of the relative velocity of the fluid or the airspeed of an aircraft.

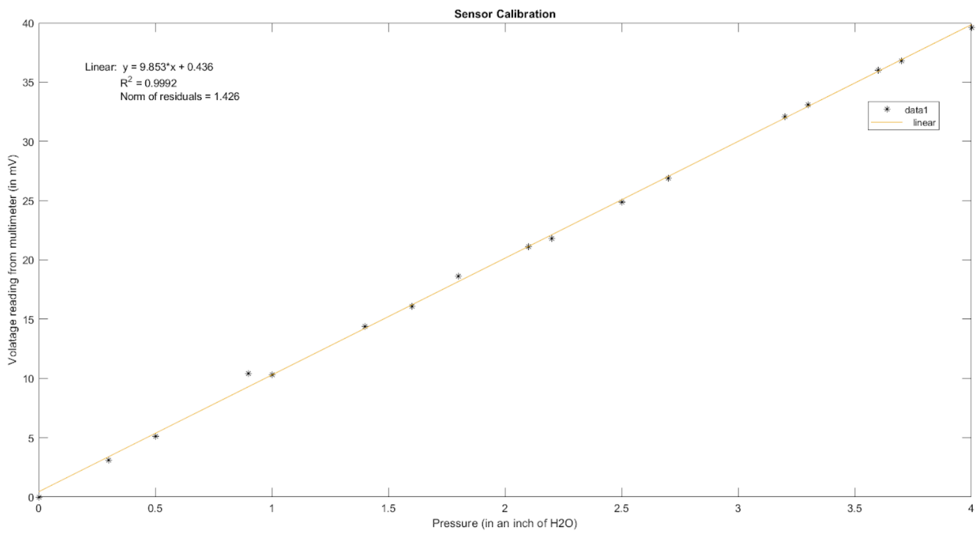


$$p_0 = p_{stat} + \frac{1}{2}\rho V^2, (Bernoulli)$$
$$V = \sqrt{2(p_0 - p_{stat})/\rho}$$
$$V = C\sqrt{2(p_0 - p_{stat})/\rho}$$

P_0 = stagnation pressure
P_{stat} = static pressure

4. Plot the data points and the calibration equation for all the sensors indicating the equations representing them.

Calibration of the pressure sensor:



Calibration equation of the differential pressure sensor = equation of the linear fit curve
$\Rightarrow y = 9.853x + 0.436$

Here y → Voltage (in mV) and x → Pressure (in an inch of H_2O)

5. Plot the variation of Cd with $\dot{m}$ and pressure drop, across flow meter in the same plot. Use different plots for the different flow meters.

$A_1 = \frac{\pi}{4}D_1^{\ 2} = \frac{\pi}{4}(8.261)^2 cm^2$ = 53.599 cm^2

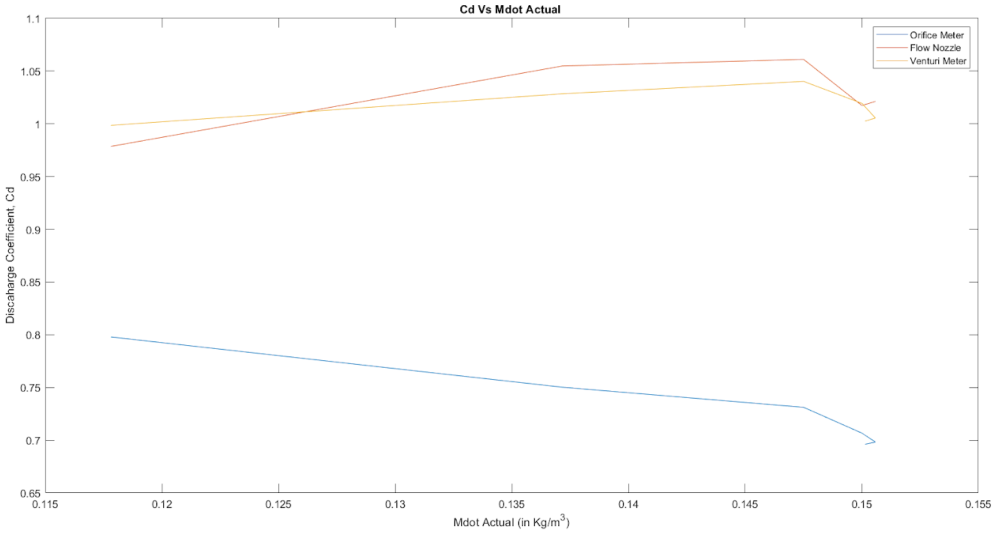
$A_2 = \frac{\pi}{4}D_2^{\ 2}$

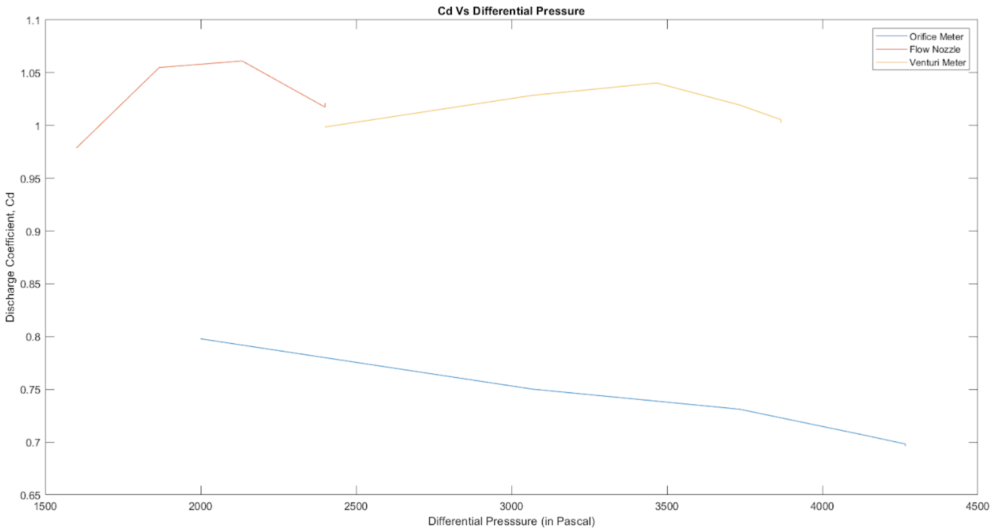
$$A_{2\_Orifice} = \frac{\pi}{4}(D_{2,Orifice})^2 = 19.63\ cm^2$$

$$A_{2\_Nozzle} = \frac{\pi}{4}(D_{2,Nozzle})^2 = 18.10\ cm^2$$

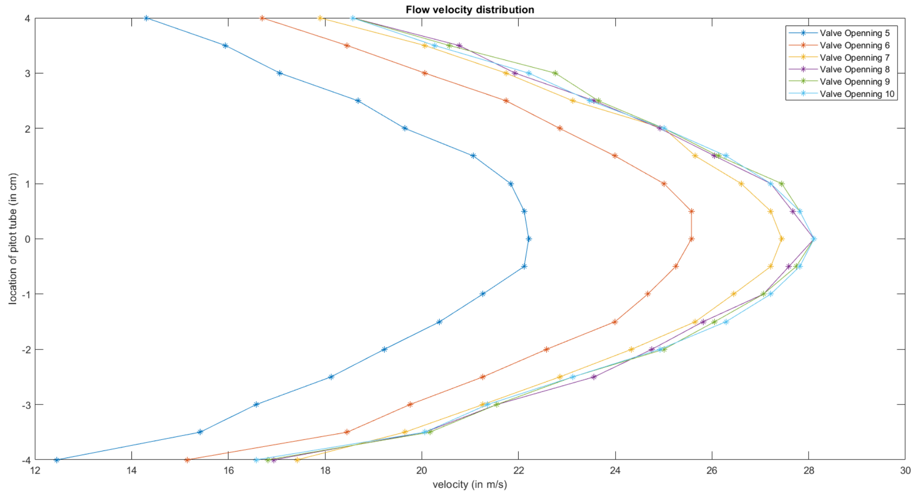
$$A_{2\_venturi} = \frac{\pi}{4}(D_{2,venturi})^2 = 14.79\ cm^2$$

$$\dot{m}_{theoretical} = \sqrt{\frac{2\rho\Delta P}{\frac{1}{A_2^2} - \frac{1}{A_1^2}}} \text{ where } \Delta P = P_1 - P_2$$





6. Plot the velocity profile at the exit of the Pipe.



A Sample Calculation:

Consider the Orifice meter with valve opening 5,

1 cm of Hg = 1333.22 Pascal

Therefore 1.5cm of Hg = 1999.84 Pascal

Orifice: diameter, d_2=50mm → $A_2 = \frac{\pi d_2^{\,2}}{4}$ =19.635 * 10^{-4} m^2

Outer diameter, d_1 = 82.61mm → $A_1 = \frac{\pi d_1^{\,2}}{4}$=53.5989 * 10^{-4} m^2

To calculate $V_{avg} = \frac{\int_{x=-4}^{x=+4} v_{calculated\ from\ Pitot\ Tube\ Pressure}\,dx}{4-(-4)} \approx \frac{trapz(v_{calculated\ from\ Pitot\ Tube\ Pressure})}{17}$

[trapz function of MATLAB]

V_{avg} = 17.94 m/s

$\dot{m}_{actual} = \rho A_1 V_{avg}$ = 0.118 kg/s

$\dot{m}_{theoretical} = \sqrt{\frac{2\rho\Delta P}{\{\frac{1}{A_2^{\,2}} - \frac{1}{A_1^{\,2}}\}}}$ = 0.148 kg/s

Cd = $\frac{\dot{m}_{actual}}{\dot{m}_{theoretical}}$ ***= 0.798***

7. Comment on the nature of the results and explain inconsistencies, if any.

As the Actual Mass flow rate, $\dot{m}_{actual}$ increases Discharge Coefficient Cd

- Of orifice meter **Decreases**
- Of Flow Nozzle and venturi meter **Increases**

A major reason for this behavior is the separation of flow. Also, the data suggest that the ***venturi meter*** is the most efficient and the ***Orifice meter*** is the least efficient in terms of discharge coefficient.

The pressure sensor calibrated in this experiment can be used to find pressure easily at any point.

(b) Error Analysis:

Possible sources of Systematic error: (in this experiment)

1. The pressure applied to the sensor should be within the range specified on the sensor.
2. Do not block the flow at the exit, during data acquisition.
3. Align the pitot probe parallel to the flow.
4. Make sure that, there are no blockages in the pipes.
5. Ensure sufficient time for the pressure to stabilize after repositioning the probe at each point.

The random error can be estimated by statistical analysis only.

Statistical analysis of the data:

Consider the Differential Pressure reading for Pitot Tube, in mV:

Valve Opening	5	6	7	8	9	10
Sample Mean	9.153	12.235	14.088	14.547	14.625	14.582
Sample SD	2.639	3.323	3.678	3.832	3.894	3.991
Sample Variance	6.964	11.041	13.526	14.685	15.161	15.934

- **Conclusion :**

Valve Opening	5	6	7	8	9	10
$Cd_{Orifice\ Meter}$	**0.798**	**0.750**	**0.731**	**0.707**	**0.698**	**0.696**
$Cd_{Flow\ Nozzle}$	**0.979**	**1.055**	**1.061**	**1.017**	**1.021**	**1.018**
$Cd_{Venturi\ Meter}$	**0.998**	**1.028**	**1.040**	**1.019**	**1.005**	**1.003**

- **Reference:**
    - Pictures from Google, Lectures and Lecture Notes of AE351 (Lab5)
- **Appendix :**

The Matlab code used:

```
%% calibration of the pressure sensor

Pressure_InchOfH2O = [0;0.5;1;1.6;2.1;2.5;3.2;3.6;4;3.7;3.3;2.7;2.2;1.8;1.4;0.9;0.3];
Voltage_mV = [0;5.1;10.3;16.1;21.1;24.9;32.1;36;39.6;36.8;33.1;26.9;21.8;18.6;14.4;10.4;3.1];

plot(Pressure_InchOfH2O,Voltage_mV,'*k');
xlabel("Pressure (in an inch of H2O)");
ylabel("Volatage reading from multimeter (in mV)");
title("Sensor Calibration");



%% Flow Meter Reading (Differential Pressure)
% orifice Nozzle Venturi
% Valve opening 5 6 7 8 9 10
% Mdot_Theoretical contains the Mdot Theoretical value

Differential_Pressure_cmofHg = [1.5,1.2,1.8;
    2.3,1.4,2.3;
    2.8,1.6,2.6;
```

```
    3.1,1.8,2.8;
    3.2,1.8,2.9;
    3.2,1.8,2.9 ];

Differential_Pressure_Pascal = (Differential_Pressure_cmofHg.*1333.29); % pressure in Pa

Area1 = 53.599 * 10^-4;
Area2 = [19.63, 18.10, 14.79].* 10^-4;

Mdot_Theoretical = zeros(6,3);

for j = 1:1:3
    Mdot_Theoretical(:,j) = (Differential_Pressure_Pascal(:,j) * (2*1.225/(1/Area2(1,j)^2 - 1/Area1^2))).^0.5;
end


%% calculation of MDot actual and the Discharge Coeff.

% differential Pressure Reading for Pitot tube

% it is in mV
Diff_Pressure_mv = [5.4,7.2,8.2,8.8,8.8,8.8;
    6.6,8.7,10.2,10.9,10.7,10.4;
    7.5,10.2,11.9,12.1,13,12.4;
    8.9,11.9,13.4,13.9,14,13.8;
    9.8,13.1,15.6,15.5,15.6,15.6;
    11.2,14.4,16.4,16.9,17,17.2;
    12,15.6,17.6,18.4,18.7,18.4;
    12.3,16.3,18.4,19,19.2,19.2;
    12.4,16.3,18.7,19.6,19.6,19.6;
    12.3,15.9,18.4,18.9,19.1,19.2;
    11.4,15.2,17.4,18.2,18.2,18.4;
    10.5,14.4,16.4,16.6,16.9,17.2;
    9.4,12.8,14.8,15.3,15.6,15.5;
    8.4,11.4,13.1,13.9,13.4,13.4;
    7.1,9.9,11.4,11.7,11.7,11.5;
    6.2,8.7,9.8,10.2,10.3,10.2;
    4.2,6,7.8,7.4,7.3,7.1;
    ];

Diff_Pressure_Pascal = (Diff_Pressure_mv-0.436).*(248.84/9.853); % Pressure in Pascal

% velocity in m/s
velocity = (Diff_Pressure_Pascal.*(2/1.225)).^0.5;

test=(4:-0.5:-4);
%% Velocity plot
plot(velocity(:,1),test,'-*');
hold on;
plot(velocity(:,2),test,'-*');
hold on;
plot(velocity(:,3),test,'-*');
hold on;
plot(velocity(:,4),test,'-*');
hold on;
plot(velocity(:,5),test,'-*');
hold on;
plot(velocity(:,6),test,'-*');
hold on;
xlabel("velocity (in m/s)");
ylabel("location of pitot tube (in cm)");
title("Flow velocity distribution");

%% Average Velocity calculation
Velocity_avg=zeros(1,6);

for j =1:1:6
    Velocity_avg(1,j) = trapz(velocity(:,j))/17;
end
%% Actual Mass Flow Rate
mdot_Actual=Velocity_avg.*1.225*Area1;

%% Cd calculation
Cd_Orifice = mdot_Actual./transpose(Mdot_Theoretical(:,1));
Cd_Nozzle  = mdot_Actual./transpose(Mdot_Theoretical(:,2));
Cd_Venturi = mdot_Actual./transpose(Mdot_Theoretical(:,3));

%% Mdot_Actual vs Cd plot
plot(mdot_Actual,[Cd_Orifice;Cd_Nozzle;Cd_Venturi]);
title("Cd Vs Mdot Actual ");
```

```
xlabel("Mdot Actual (in Kg/m^3)");
ylabel("Discaharge Coefficient, Cd");

%% Differential Pressure Vs Cd plot
plot(Differential_Pressure_Pascal(:,1),Cd_Orifice);
hold on;
plot(Differential_Pressure_Pascal(:,2),Cd_Nozzle);
hold on;
plot(Differential_Pressure_Pascal(:,3),Cd_Venturi);
hold on;
title("Cd Vs Differential Pressure");
xlabel("Differential Presssure (in Pascal)");
ylabel("Discharge Coefficient, Cd");
```

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