Calibration of SuperSonic Wind Tunnel

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OBJECTIVE

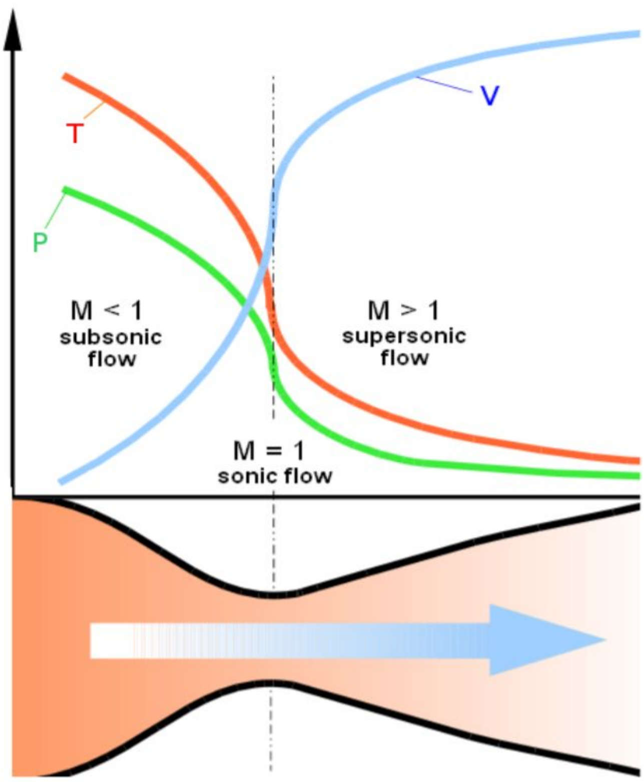
1. To calibrate the supersonic wind tunnel.
2. To compare and study the actual and Isentropic Mach number distribution along the length of the contour provided.

INTRODUCTION THEORY

Wind Tunnel

Wind Tunnels are large tube through which air flows. They are used to replicate original conditions while cruising an airplane. Objects are kept in Wind Tunnel and is held stationary so it does move. Researchers can observe many objects like small-scaled aircraft or even a ball using Wind Tunnels like range of Lift or Drag produced, yielding properties or aerodynamics (using smoke or dye in air).

SuperSonic Wind Tunnel



SuperSonic Wind Tunnel produced air flow of supersonic range ($1.2 < M < 1.5$). It can be simply said as a convergent divergent duct where the velocity increases from subsonic to supersonic speeds. Unlike in subsonic flow, in SuperSonic Flow Region the velocity increases in a divergent duct and decreases in the convergent duct where the cross-sectional area decreases.

Shock Waves are involved in the SuperSonic Region. Shocks are thin layer of disturbances across which the flow properties change significantly like pressure, temperature, entropy, etc. There are mainly two types of shocks: Normal Shocks and Oblique Shocks.

As the velocity of air is reduced when passed through a shock, the inlet is designed such that there will be a lot of shock interactions which can reduce the flow velocity. In designing the supersonic section of the wind tunnel, we have to make sure that these shock interactions do not have a negative effect on the flow velocity and the speed should further increase downstream with the increase in the cross sectional area.

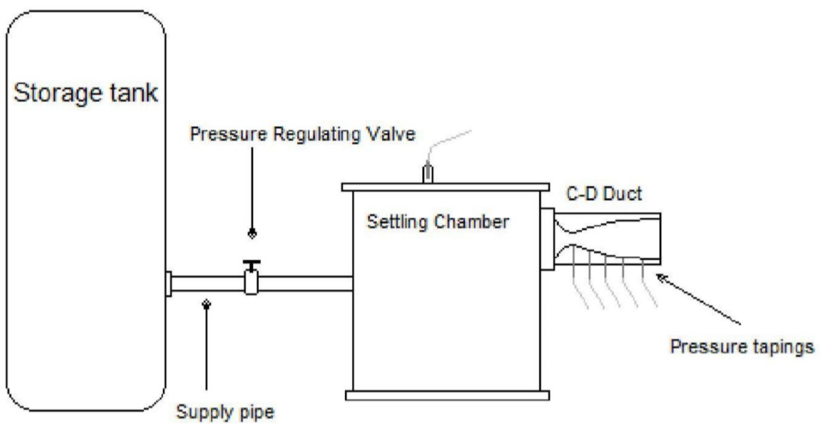
The supersonic wind tunnel can be divided into different sections. These sections are the Convergent Section having the SubSonic Region where the velocity of the flow increases as the cross-section of the duct decreases. Next is the Throat Section, which has to be designed with the help of Area Mach relations to get the cross-sectional area of the throat. In the SuperSonic Region, the duct must be subdivided into two regions, in the first section, the cross-sectional area increases and the slope of the duct increases downstream. In the latter stages of the SuperSonic Flow Region, the cross sectional area increases and the slope of the duct decreases making the curve parallel to the flow. This helps obtain uniform direction of flow at the end of this section so that the models that are tested in the wind tunnel experience a uniform flow in the test section which follow the supersonic expansion region.

To obtain SuperSonic Flow, we have to increase the ambient pressure. Initially, flow will be SubSonic and as ambient pressure is further increased Mach Number will increase. Once Mach number equals “1” at Throat Section, flow “chokes” at the throat and if ambient pressure is further increased flow properties will remain same behind throat and will be SuperSonic downstream. A Normal Shock will be formed after throat because more pressure difference is required to obtain Full SuperSonic Flow. As ambient pressure is increased to the required value, normal shock will move towards the end of the duct and disappear giving full SuperSonic Flow.

ASSUMPTIONS

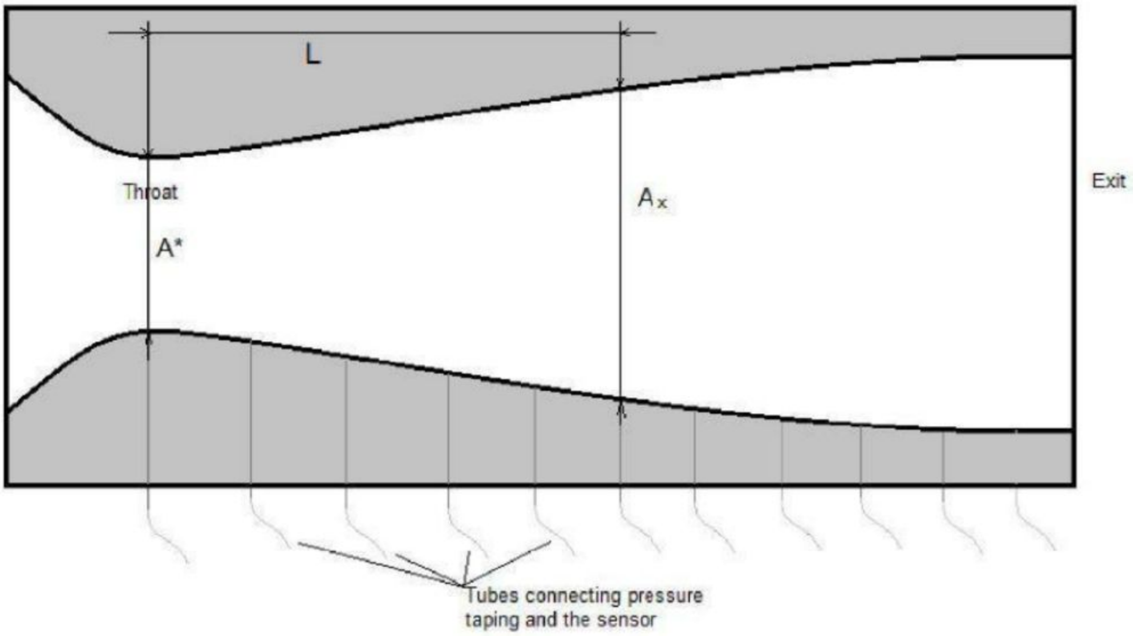
1. The gas follows ideal gas behaviour.
2. The flow is isentropic, i.e., reversible and adiabatic.
3. The flow is steady after exiting from the settling chamber.
4. The flow properties remains same in plane perpendicular to the flow.

EXPERIMENTAL SETUP



STORAGE TANK: It is high pressure tank used to store and provide high pressure air. Our storage tank can pressurized upto 200 psi.
SUPPLY PIPE: It supplies air from storage tank to the settling chamber. It should be able to provide required mass flow rate with least pressure lose.
PRESSURE REGULATING VALVE:

SETTLING CHAMBER: It is used to remove any fluctuations or perturbations and ensure steady flow. In our facility, settling chamber operate within safe pressure of 60 psi.
CONVERGENT-DIVERGENT DUCT: As discussed above it a duct of varying cross sectional area which converts subsonic flow to supersonic flow.



PRESSURE PORTS: There is a pressure port at settling chamber to measure total pressure P_O and there are 18 pressure ports at different location in C-D duct to measure pressure at various points. (We used 14 pressure ports to measure the pressure.)
PRESSURE SENSOR: The pressure sensor used in our experiment (Pressure scanner 9016) can measure up to 100 psi from 16 ports simultaneously at the rate of 1000 Samples per second. The sensor is connected to a computer, via ethernet cable, where a LabView program analyses and stores the measured pressures.

PROCEDURE

We start the experiment by connecting the pressure ports to the pressure sensor. One pressure of settling chamber and 14 pressure ports of C-D duct (One port was not working). We note down the pressure ports and their corresponding sensor ports. We then start increasing the ambient pressure and consequently store data through LabView.

MEASUREMENTS

1st Measurement

SP1/SC	**33.9393**
SP2/PP1	3.0251
SS3/PP2	-6.8070

2nd Measurement

SP1/SC	**55.2214**
SP2/PP1	10.4582
SS3/PP2	-2.9294

3rd Measurement

SP1/SC	**89.3707**
SP2/PP1	23.0741
SS3/PP2	2.8265

SP4/PP3	-8.1393	SP4/PP3	-5.1996	SP4/PP3	-0.6956
SP5/PP4	-8.2236	SP5/PP4	-5.5418	SP5/PP4	-0.7190
SP6/PP6	-7.6053	SP6/PP6	-9.4133	SP6/PP6	-6.6265
SP7/PP8	-4.9669	SP7/PP8	-4.2751	SP7/PP8	-8.2811
SP9/PP10	-1.3237	SP9/PP10	-4.6418	SP9/PP10	-6.8013
SP10/PP11	-2.6777	SP10/PP11	-6.9556	SP10/PP11	-9.2855
SP11/PP13	-0.7500	SP11/PP13	-6.7283	SP11/PP13	-9.4159
SP16/PP14	-0.3975	SP16/PP14	-4.7115	SP16/PP14	-9.3631
SP12/PP15	-1.1077	SP12/PP15	-2.5879	SP12/PP15	-9.6175
SP13/PP16	-0.6019	SP13/PP16	-1.1099	SP13/PP16	-9.0135
SP14/PP17	-0.4210	SP14/PP17	-0.7432	SP14/PP17	-7.9507
SP15/PP18	-0.0010	SP15/PP18	-1.2825	SP15/PP18	-6.3104

(All readings are Gauge Pressure in PSI)

SC: Settling Chamber
SP: Sensor Ports
PP: Pressure Ports (on the duct)

PP	Dist (cm)	Height (cm)	PP	Dist	Height (cm)
1	0	2.8	10	18.1	8.9
2	2.2	4.5	11	19.1	8.9
3	4.4	6.1	12	19.8	9
4	6.4	7	13	20.5	9
5	8.6	7.8	14	21.2	9
6	10.9	8.3	15	21.9	9
7	12.9	8.6	16	22.5	9
8	14.9	8.7	17	23.5	9
9	17.6	8.9	18	24	9

Derivation:

$$(\mathrm{I}) \qquad c_p = \frac{\gamma R}{\gamma - 1}$$

Consider the energy equation relating two points in a flow. One point has conditions T_1 and V_1 and the other is at the stagnation point, with temperature T_0 and zero velocity. The energy equation then becomes:

Energy Equation $$c_p T_1 + \frac{1}{2}V_1^2 = c_p T_0$$

Rearranged: $$\frac{T_0}{T_1} = 1 + \frac{V_1^2}{2c_p T_1}$$

Substitute (**I**) *into the last equation:* $$\frac{T_0}{T_1} = 1 + \frac{V_1^2}{2[\gamma R/(\gamma-1)]T_1} = 1 + \frac{\gamma-1}{2}\frac{V_1^2}{\gamma R T_1}$$

Definition of the speed of sound: $$a_1^2 = \gamma R T_1$$

Simplify: $$\frac{T_0}{T_1} = 1 + \frac{\gamma-1}{2}\frac{V_1^2}{a_1^2}$$

Definition of Mach number: $$M_1 = V_1 / a_1$$

Simplify: $$\frac{T_0}{T_1} = 1 + \frac{\gamma-1}{2}M_1^2$$

$$\frac{T_0}{T_1} = \left(1 + \frac{\gamma-1}{2}M_1^2\right)$$

Compressible Flow Relations: $$\frac{p_0}{p_1} = \left(1 + \frac{\gamma-1}{2}M_1^2\right)^{\gamma/(\gamma-1)}$$

$$\frac{\rho_0}{\rho_1} = \left(1 + \frac{\gamma-1}{2}M_1^2\right)^{1/(\gamma-1)}$$

Area-Velocity Relation

For an isentropic streamline: $$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 = const$$

Alternatively: $$\ln\rho + \ln A + \ln V = \ln(const)$$

Differentiate: $$\frac{d\rho}{\rho} + \frac{dA}{A} + \frac{dV}{V} = 0$$

Recall Euler's Equation: $$dp = -\rho V dV$$

Rearranged: $$\rho = -\frac{dp}{VdV}$$

Substitute for ρ: $$-\frac{d\rho V dV}{dp} + \frac{dA}{A} + \frac{dV}{V} = 0$$

Since the flow is isentropic, we can define: $$\frac{d\rho}{dp} = \frac{1}{dp/d\rho} = \frac{1}{a^2}$$

Substitute: $$-\frac{VdV}{a^2} + \frac{dA}{A} + \frac{dV}{V} = 0$$

Rearrange: $$\frac{dA}{A} = \frac{VdV}{a^2} - \frac{dV}{V} = \left(\frac{V^2}{a^2} - 1\right)\frac{dV}{V}$$

Area-Velocity Relation: $$\frac{dA}{A} = \left(M^2 - 1\right)\frac{dV}{V}$$

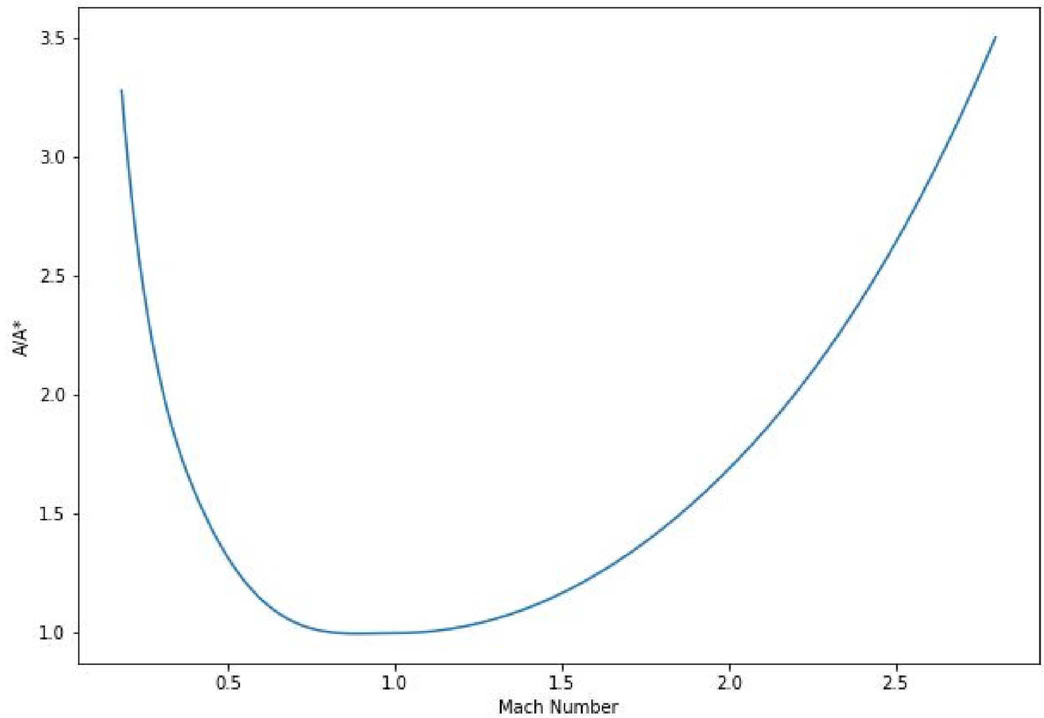
$$\frac{A}{A^*} = \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M}$$

ISENTROPIC MACH NO RELATION

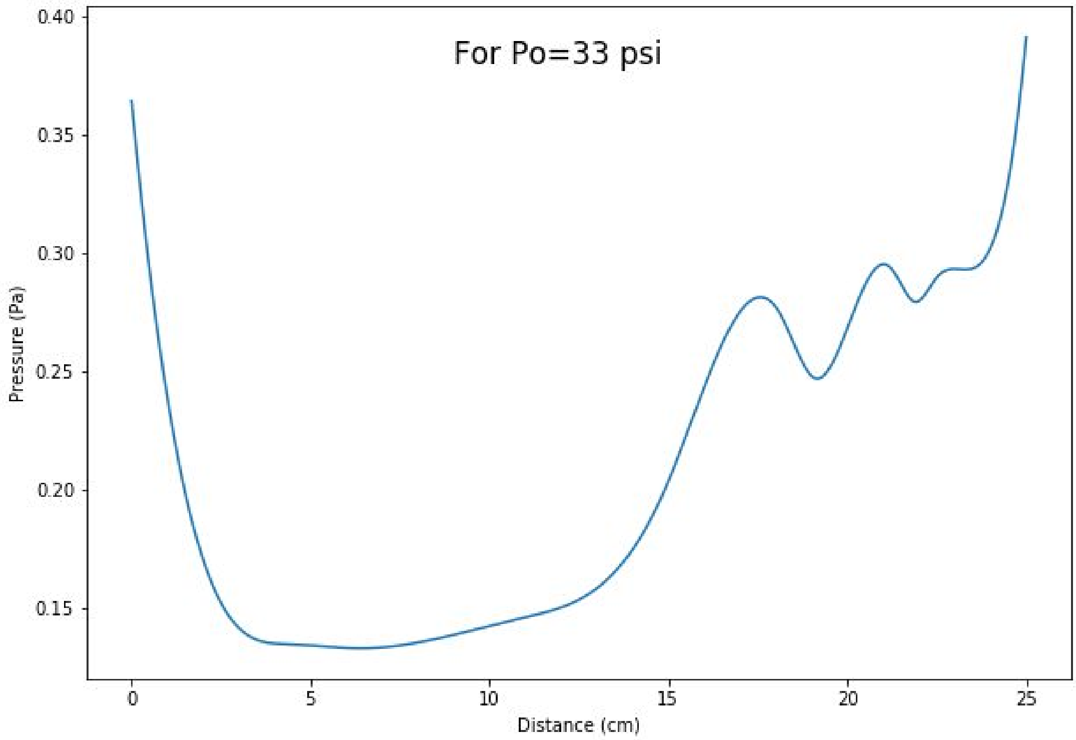
$$\frac{p}{p_t} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma}{\gamma-1}}$$

REAL MACH NO RELATION

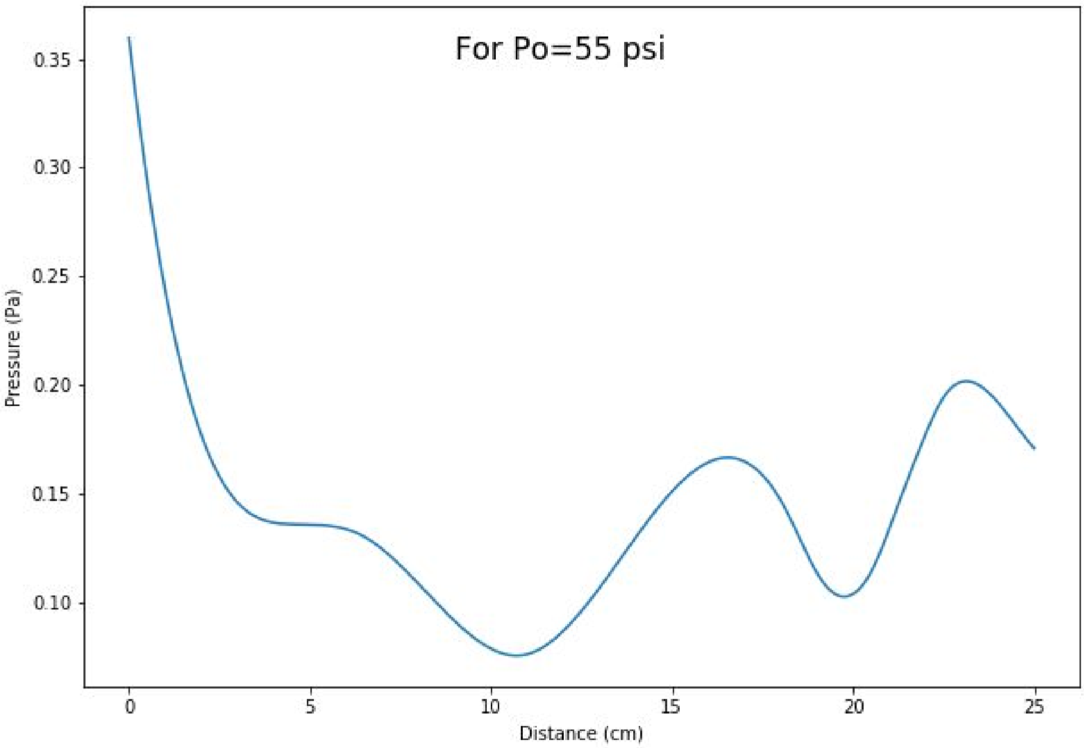
RESULTS

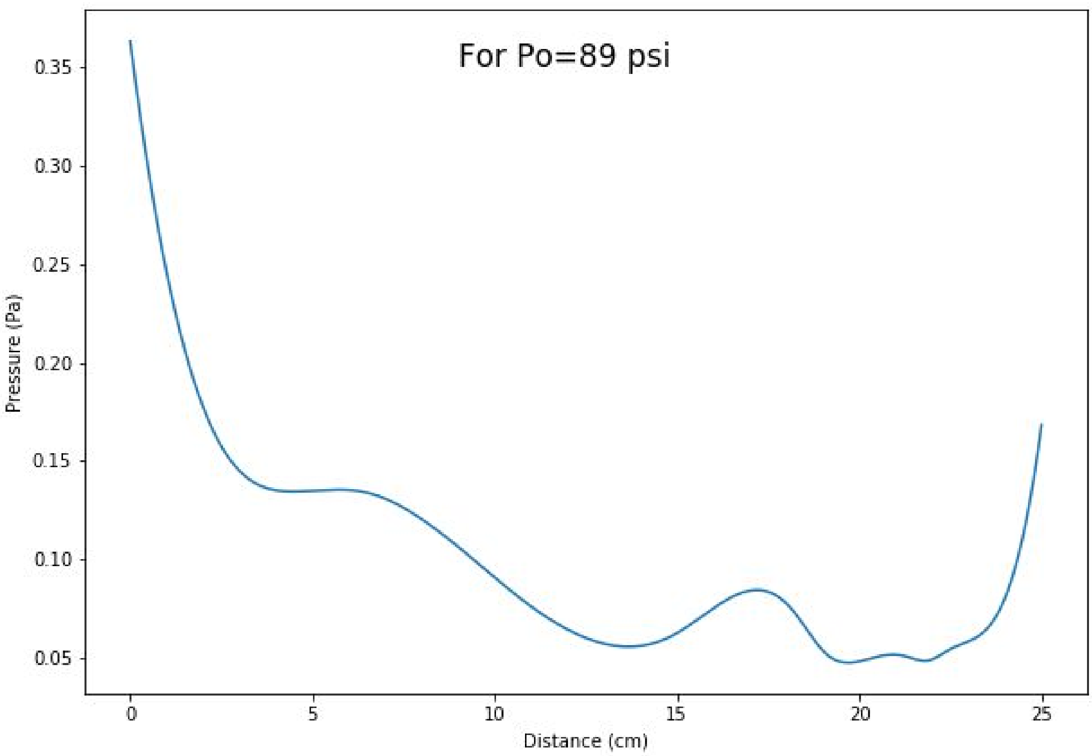


3.5
3.0
2.5
2.0
1.5
1.0
A/A*
0.5
1.0
1.5
2.0
2.5
Mach Number

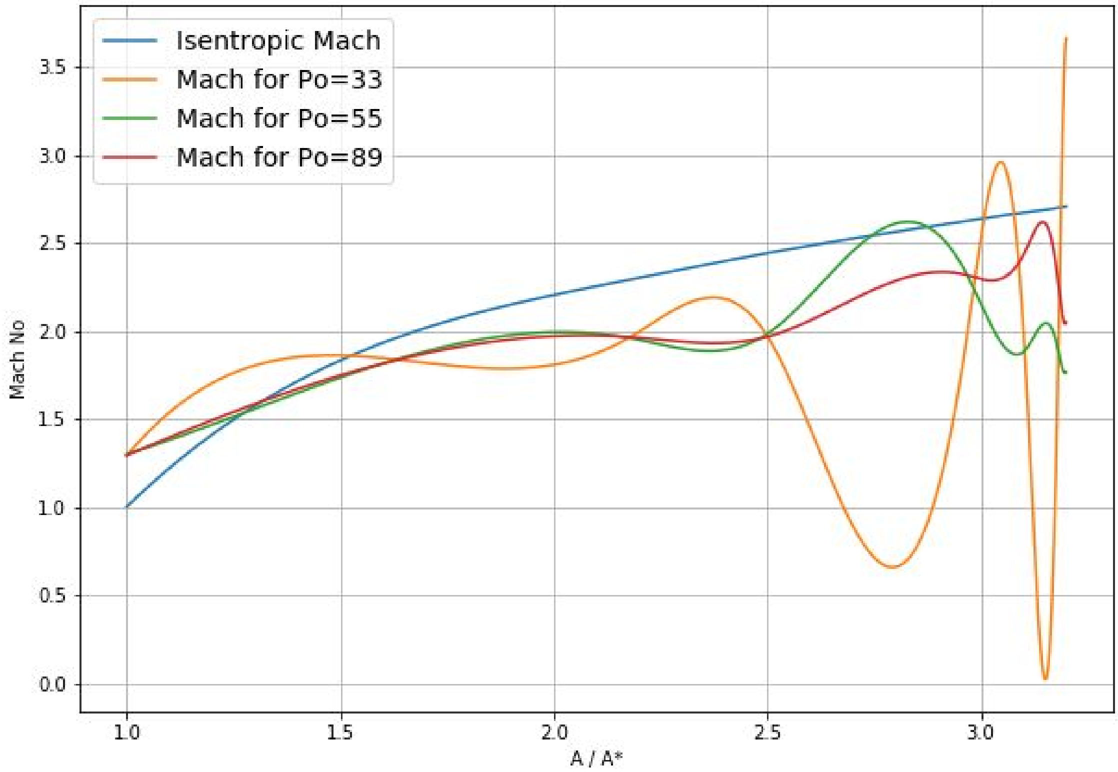


For Po=33 psi
0.40
0.35
0.30
0.25
0.20
0.15
Pressure (Pa)
0
5
10
15
20
25
Distance (cm)


For Po=55 psi
0.35
0.30
0.25
0.20
0.15
0.10
Pressure (Pa)
0
5
10
15
20
25
Distance (cm)


For Po=89 psi
0.35
0.30
0.25
0.20
0.15
0.10
0.05
Pressure (Pa)
0
5
10
15
20
25
Distance (cm)

DISCUSSION AND ERROR ANALYSIS



1. Since the back pressure interferes with the incoming flow, isentropic Mach Number cannot be achieved.
2. There is a sudden drop in Mach Number at A/A*= 2.4, which indicates an oblique shock for P_O = 33 psi.
3. There is a sudden drop in Mach Number at A/A*= 2.7, which indicates an oblique shock for P_O = 55 psi.
4. There is a sudden drop in Mach Number at A/A*= 3.2, which indicates an oblique shock for P_O = 89 psi.
5. As we can see, oblique shock shifts towards right as P_O (stagnation pressure) is increased.
6. Also due to friction in the duct and settling chamber, flow is not entirely Isentropic.

CONCLUSION

Through this experiment, we learned how does a convergent-divergent nozzle works, how why readings differ from those calculated theoretically and some ways to make our result more similar to isentropic results.

PRECAUTIONS

1. Do not exceed pressure limits of settling chamber.
2. Connect the port with pipes tightly.
3. Wear the protective headphones during the experiment.
4. Don’t cross the exit flow area, it can hurt you.