Engineering Fluid Mechanics

Venturi Tube Experimentation Report

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Introduction

In this laboratory session, we examined the flow through a Venturi tube to verify Bernoulli's principle and to characterize the device for use as a flowmeter. A Venturi tube consists of a converging section leading to a throat and then a diverging section. As the cross-sectional area decreases, the fluid velocity increases, causing a corresponding decrease in static pressure. Downstream, as the area increases, some of the kinetic energy is recovered as static pressure, though not all, due to viscous and frictional losses. By measuring the static pressure at various points along the Venturi and using a Pitot tube at the throat, we can determine the flow characteristics and calibrate the Venturi as a flow measuring device.

Theory and Derivations

Bernoulli's Equation and Continuity

For a steady, incompressible, and inviscid flow along a streamline, Bernoulli's equation states:

$$p + \rho g z + \frac{\rho v^2}{2} = \text{constant},$$

where p is the static pressure, ρ is the fluid density, g is gravitational acceleration, z is the vertical coordinate, and v is the flow velocity.

If we consider two sections along the Venturi, for example the inlet (section 1) and the throat (section 3), and assume the Venturi is horizontal ($z_1 = z_3$), the gravitational terms $\rho g z$ cancel out. Thus, between sections 1 and 3:

$$p_1 + \frac{\rho v_1^2}{2} = p_3 + \frac{\rho v_3^2}{2}.$$

Additionally, for an incompressible fluid, mass conservation (continuity) applies:

$$Q = v_1 A_1 = v_3 A_3 = \cdots ,$$

where Q is the volumetric flow rate, and A_i is the cross-sectional area at section i. This relationship links the velocities at different sections to their respective areas.

Reduced Pressure from Manometric Tubes

The Venturi setup includes vertical manometric tubes that measure the height h_i of a water column corresponding to the reduced pressure at each point i. Setting the reference pressure as p_0, we have:

$$(p + \rho g z)_i - p_0 = \rho g h_i.$$

Since $(p + \rho g z)_i$ can be thought of as the reduced pressure at section i, the reading h_i directly gives us the reduced pressure relative to p_0:

$$(p + \rho g z)_i - p_0 = \rho g h_i.$$

Flow Rate Determination from Pitot Reading

A Pitot tube placed at the throat (section 3) measures the total pressure. By Bernoulli's equation, at the throat:

$$(p + \rho g z)_3 + \frac{\rho v_3^2}{2} = p_0 + \rho g h_t,$$

where h_t is the Pitot tube reading (total head). Since we know $(p + \rho g z)_3 = p_0 + \rho g h_3$, substitue into the equation:

$$p_0 + \rho g h_3 + \frac{\rho v_3^2}{2} = p_0 + \rho g h_t.$$

Canceling p_0:

$$\rho g h_3 + \frac{\rho v_3^2}{2} = \rho g h_t.$$

Solve for v_3:

$$\frac{\rho v_3^2}{2} = \rho g(h_t - h_3) \implies v_3 = \sqrt{2g(h_t - h_3)}.$$

Once v_3 is known, and since $Q = v_3 A_3$, we obtain:

$$Q = A_3\sqrt{2g(h_t - h_3)}.$$

Velocity, Dynamic Pressure, and Total Pressure at Each Section

With Q determined, the velocity at any section i is:

$$v_i = \frac{Q}{A_i}.$$

The dynamic pressure at section i is:

$$p_{\text{din},i} = \frac{\rho v_i^2}{2}.$$

The total pressure relative to p_0 at section i is the sum of the reduced and dynamic pressures:

$$p_{t,i} - p_0 = \rho g h_i + \frac{\rho v_i^2}{2}.$$

Ideal Flow Rate and Discharge Coefficient

If we consider the ideal (inviscid, no-friction) scenario between sections 1 and 3, Bernoulli's equation and continuity give us a relationship for the ideal flow rate Q_{ideal}. Define the area ratio $\beta = \frac{A_3}{A_1}$. Under ideal conditions:

$$Q_{\text{ideal}} = A_3\sqrt{\frac{2g(h_1 - h_3)}{1 - \beta^2}}.$$

However, real flows incur frictional losses, so the actual measured flow Q differs from Q_{ideal}. We introduce the discharge coefficient C_d:

$$C_d = \frac{Q}{Q_{\text{ideal}}}.$$

Typically, $C_d < 1$ because real flows are not perfectly inviscid, but minor deviations above unity may occur due to experimental or measurement uncertainties.

Pressure Loss and Loss Coefficient

Between the entrance (1) and the exit (6) of the Venturi, some pressure is lost due to viscous effects. The permanent pressure loss Δp_{16} can be determined from the difference in heights:

$$\Delta p_{16} = \rho g(h_1 - h_6).$$

To characterize this loss in a non-dimensional form, we define the loss coefficient K_v based on the dynamic pressure at the throat:

$$K_v = \frac{\Delta p_{16}}{\frac{\rho v_3^2}{2}} = \frac{2g(h_1 - h_6)}{v_3^2}.$$

Reynolds Number at Inlet and Throat

The Reynolds number Re_i at section i is given by:

$$Re_i = \frac{\rho v_i D_{h,i}}{\mu},$$

where μ is the dynamic viscosity and $D_{h,i}$ is the hydraulic diameter of the cross section. For a rectangular cross-section Venturi:

$$D_{h,i} = \frac{4A_i}{P_i},$$

where P_i is the wetted perimeter at section i. If the Venturi has a fixed width b and a height $a_i = \frac{A_i}{b}$, then

$$P_i = 2(a_i + b), \quad \text{and} \quad D_{h,i} = \frac{4A_i}{2(a_i + b)} = \frac{2A_i}{a_i + b}.$$

By comparing C_d, K_v, and other parameters against Re_i, we can assess how close the flow is to the ideal assumptions (high Reynolds number flows tend to approach ideal behavior).

Procedure Overview

Six experiments were conducted at different flow rates by adjusting the valve setting. For each experiment:

1. We recorded the heights $h_1, h_2, \ldots, h_6$ in the static pressure manometers, and h_t in the Pitot tube at the throat.

2. Computed the reduced pressure at each tap, the flow rate Q, velocities v_i, dynamic and total pressures, and finally, the discharge coefficient C_d and loss coefficient K_v.

3. Calculated Reynolds numbers at the inlet and throat sections to analyze the flow regime and how it affects C_d and K_v.

Data and Results

Each experiment's results are presented as an image of the results table followed by a plot of the pressure distribution along the Venturi. The calculations were performed using a python script.

Experiment 1

results_experiment_1

Section	H [mm]	A [mm^2]	Pred [Pa]	Pdin [Pa]	Vi [m/s]	Ptotal [Pa]	Q [m^3/s]
1	250	338.6	2452.5	61.240090794623900	0.3499716868394470	2513.740090794620	0.00011850041316383700
2	240	233.5	2354.4	128.77630618692400	0.507496416119215	2483.1763061869200	0.00011850041316383700
3	185	84.6	1814.85	981.0000000000010	1.4007141035914500	2795.8500000000000	0.00011850041316383700
4	175	170.2	1716.7500000000000	242.37656258414500	0.6962421454984530	1959.1265625841400	0.00011850041316383700
5	190	255.2	1863.9	107.8073555930070	0.4643433117705200	1971.7073555930100	0.00011850041316383700
6	195	338.6	1912.95	61.240090794623900	0.3499716868394470	1974.190090794620	0.00011850041316383700

Figure 1: Results for Experiment 1.

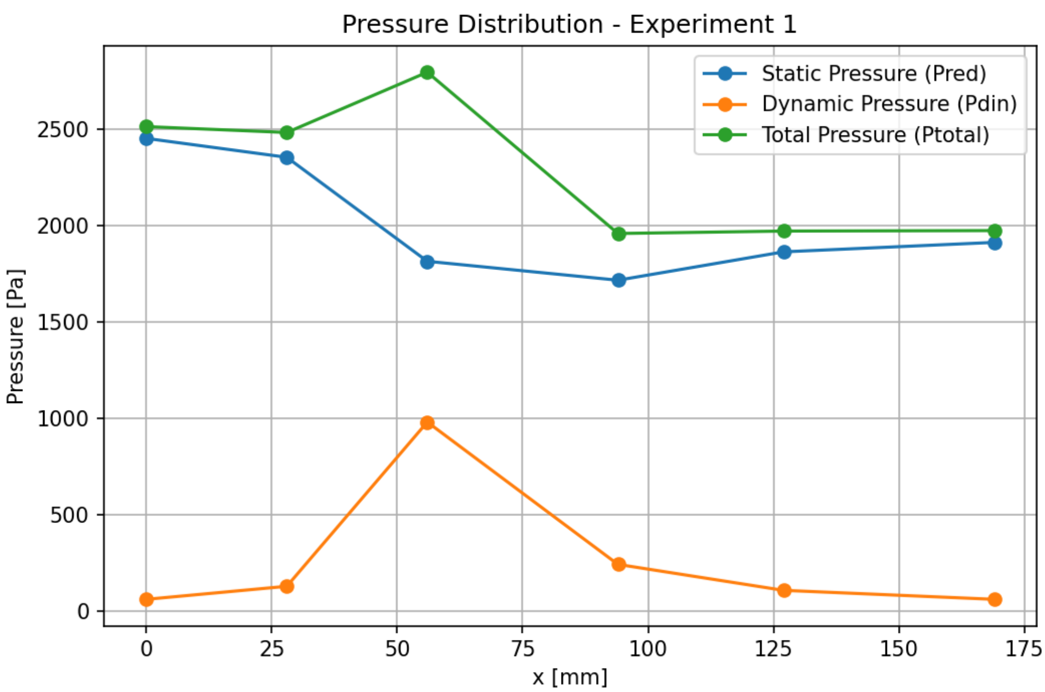


Figure 2: Pressure distribution for Experiment 1: static, dynamic, and total pressures.

Experiment 2

results_experiment_2

Section	H [mm]	A [mm^2]	Pred [Pa]	Pdin [Pa]	Vi [m/s]	Ptotal [Pa]	Q [m^3/s]
1	230	338.6	2256.3	79.61211803301110	0.39902911681482900	2335.912118033010	0.000135111258953501
2	220	233.5	2158.2	167.40919804300100	0.578634941985015	2325.6091980430000	0.000135111258953501
3	100	84.6	981.0	1275.3000000000000	1.59705979850474	2256.3	0.000135111258953501
4	170	170.2	1667.7	315.0895313593880	0.7938381842156350	1982.7895313593900	0.000135111258953501
5	185	255.2	1814.85	140.1495622709090	0.5294328328898940	1954.9995622709100	0.000135111258953501
6	190	338.6	1863.9	79.61211803301110	0.39902911681482900	1943.5121180330100	0.000135111258953501

Figure 3: Results for Experiment 2.

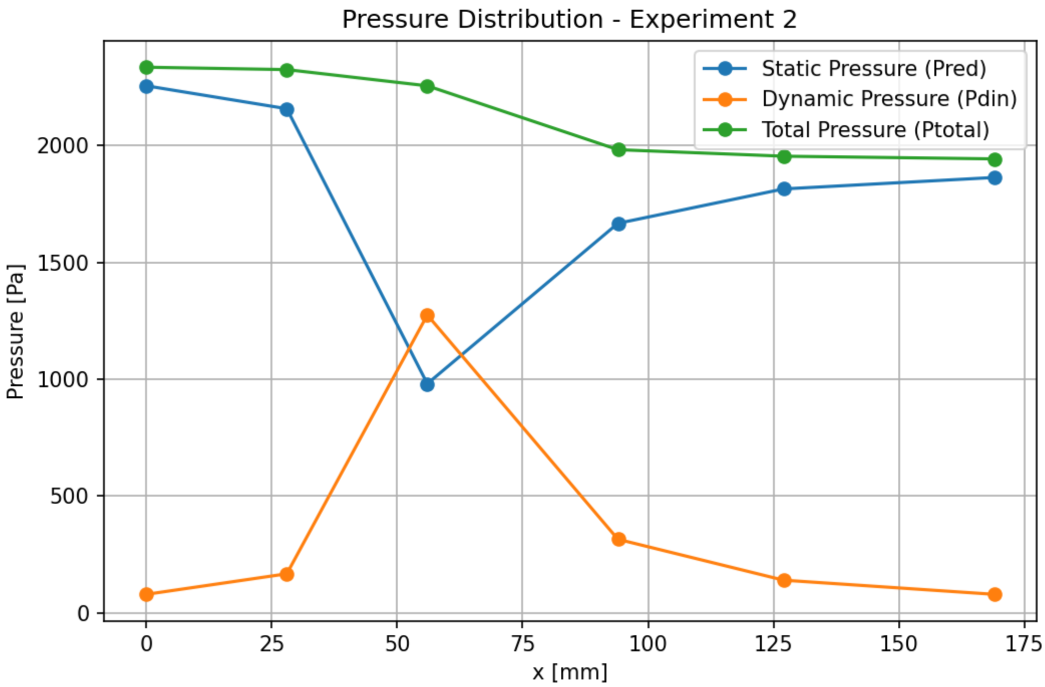


Figure 4: Pressure distribution for Experiment 2.

Experiment 3

results_experiment_3

Section	H [mm]	A [mm^2]	Pred [Pa]	Pdin [Pa]	Vi [m/s]	Ptotal [Pa]	Q [m^3/s]
1	255	338.6	2501.55	88.79813165220470	0.42142171669766800	2590.3481316522000	0.0001426933932738300
2	245	233.5	2403.45	186.72564397103900	0.6111066093097660	2590.1756439710400	0.0001426933932738300
3	95	84.6	931.95	1422.4500000000000	1.6866831356244700	2354.4000000000000	0.0001426933932738300
4	175	170.2	1716.7500000000000	351.4460157470100	0.8383865644760890	2068.19601574701	0.0001426933932738300
5	195	255.2	1912.95	156.3206656098600	0.5591433905714360	2069.2706656098600	0.0001426933932738300
6	200	338.6	1962.0	88.79813165220470	0.42142171669766800	2050.7981316522000	0.0001426933932738300

Figure 5: Results for Experiment 3.

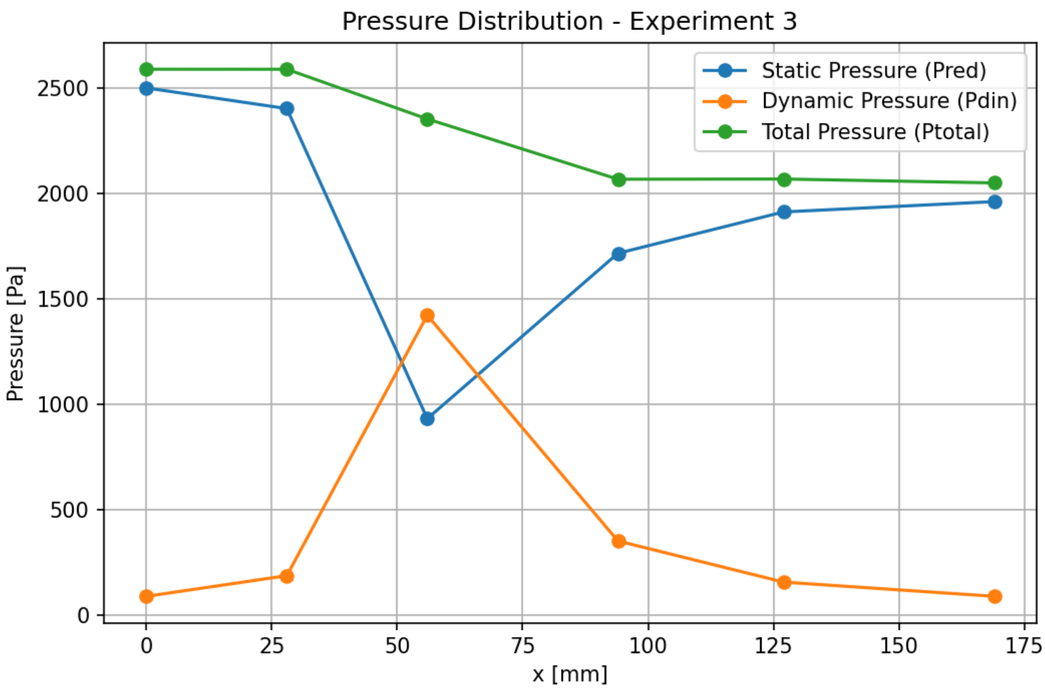


Figure 6: Pressure distribution for Experiment 3.

Experiment 4

results_experiment_4

Section	H [mm]	A [mm^2]	Pred [Pa]	Pdin [Pa]	Vi [m/s]	Ptotal [Pa]	Q [m^3/s]
1	185	338.6	1814.85	30.620045397311900	0.2474673529874680	1845.4700453973100	8.37924457215565E-05
2	180	233.5	1765.8	64.38815309346180	0.35885415726576700	1830.1881530934600	8.37924457215565E-05
3	130	84.6	1275.3	490.50000000000000	0.9904544411531510	1765.8000000000000	8.37924457215565E-05
4	155	170.2	1520.55	121.18828129207200	0.4923175424298270	1641.738281292070	8.37924457215565E-05
5	160	255.2	1569.6000000000000	53.90367779650360	0.32834030455155400	1623.5036777965000	8.37924457215565E-05
6	165	338.6	1618.65	30.620045397311900	0.2474673529874680	1649.270045397310	8.37924457215565E-05

Figure 7: Results for Experiment 4.

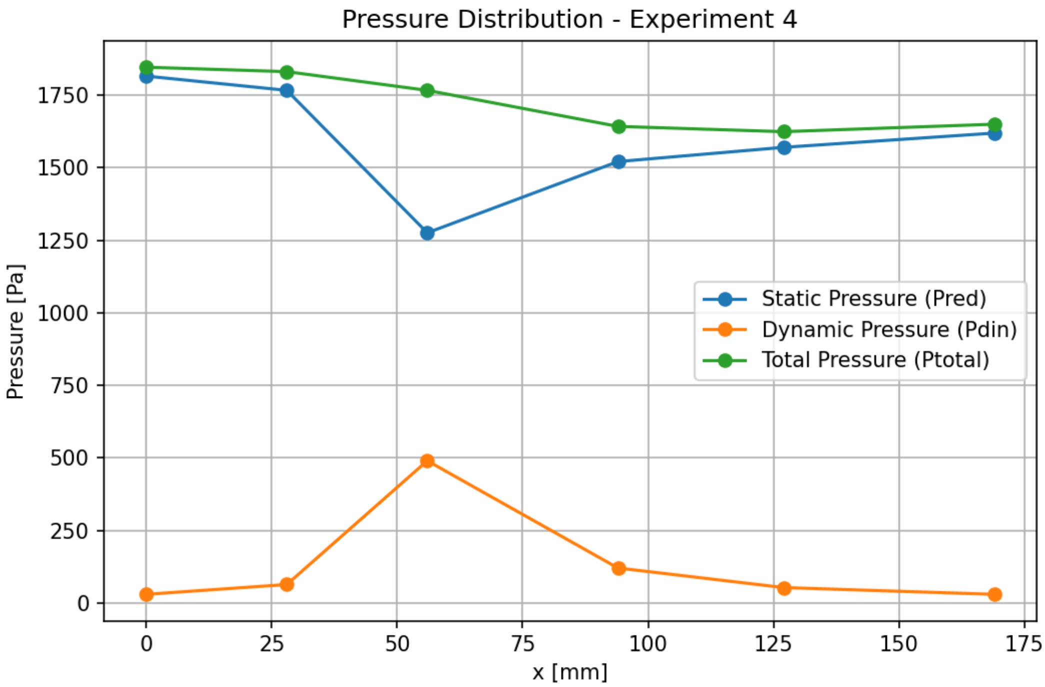


Figure 8: Pressure distribution for Experiment 4.

Experiment 5

results_experiment_5

Section	H [mm]	A [mm^2]	Pred [Pa]	Pdin [Pa]	Vi [m/s]	Ptotal [Pa]	Q [m^3/s]
1	210	338.6	2060.1	55.11608171516150	0.33201229409514800	2115.2160817151600	0.00011241936278061700
2	205	233.5	2011.0500000000000	115.89867556823100	0.48145337379279300	2126.9486755682300	0.00011241936278061700
3	115	84.6	1128.15	882.9000000000000	1.3288340754210100	2011.0500000000000	0.00011241936278061700
4	165	170.2	1618.65	218.13890632573000	0.6605132948332380	1836.78890632573	0.00011241936278061700
5	175	255.2	1716.7500000000000	97.02662003370650	0.4405147444381550	1813.7766200337100	0.00011241936278061700
6	180	338.6	1765.8	55.11608171516150	0.33201229409514800	1820.9160817151600	0.00011241936278061700

Figure 9: Results for Experiment 5.

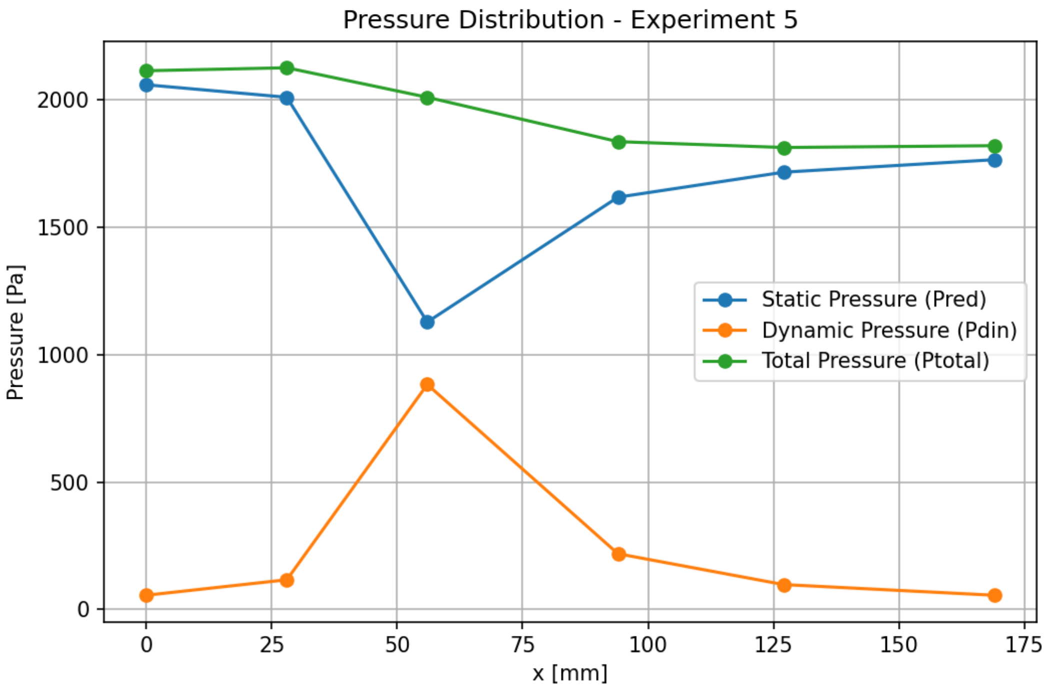


Figure 10: Pressure distribution for Experiment 5.

Experiment 6

results_experiment_6

Section	H [mm]	A [mm^2]	Pred [Pa]	Pdin [Pa]	Vi [m/s]	Ptotal [Pa]	Q [m^3/s]
1	155	338.6	1520.55	9.186013619193580	0.13554345147732900	1529.7360136191900	4.58950126702237E-05
2	155	233.5	1520.55	19.316445928038500	0.1965525167889670	1539.8664459280400	4.58950126702237E-05
3	140	84.6	1373.4	147.15000000000000	0.5424942396007540	1520.55	4.58950126702237E-05
4	145	170.2	1422.4500000000000	36.35648438762160	0.26965342344432300	1458.8064843876200	4.58950126702237E-05
5	150	255.2	1471.5	16.17110333895110	0.17983939134100200	1487.671103338950	4.58950126702237E-05
6	150	338.6	1471.5	9.186013619193580	0.13554345147732900	1480.6860136191900	4.58950126702237E-05

Figure 11: Results for Experiment 6.

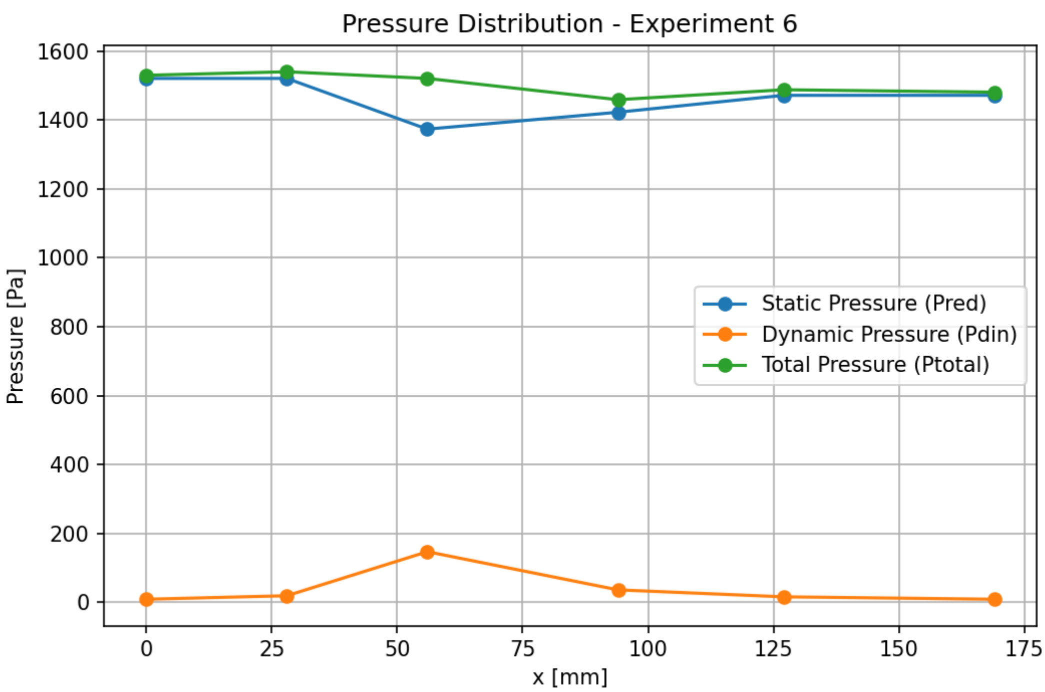


Figure 12: Pressure distribution for Experiment 6.

Summary Tables

Below are images of the three summary tables:

table_pressure_loss

Experiment	Δp16 [Pa]	Kv [-]
1	539.55	0.5500000000000000
2	392.4000000000000	0.3076923076923080
3	539.55	0.3793103448275860
4	196.2000000000000	0.40000000000000000
5	294.3	0.3333333333333330
6	49.05000000000010	0.333333333333334

Figure 13: Pressure loss results for all experiments.

table_flow_rates

Experiment	Q [m^3/s]	Q_ideal [m^3/s]	Cd [-]
1	0.00011850041316383700	9.86674283170047E-05	0.95100842988541
2	0.000135111258953501	0.00013953681529038300	0.968283951961549
3	0.0001426933932738300	0.00015480219764443800	0.9217788600235480
4	8.37924457215565E-05	9.07608334358468E-05	0.923222523962213
5	0.00011241936278061700	0.0001192831043562180	0.9424583924718810
6	4.58950126702237E-05	4.73982994112932E-05	0.9682839519615490

Figure 14: Flow rates and discharge coefficients for all experiments.

table_reynolds

Experiment	Re1 [-]	Re3 [-]
1	6439.859419382700	10305.357794756600
2	7342.569451073360	11749.91570443530
3	7754.617627262320	12409.294055385600
4	4553.668265333570	7286.988379226020
5	6109.387072961650	9776.520820320240
6	2494.146828318620	3991.247911580100

Figure 15: Reynolds numbers at the inlet and throat for all experiments.

Additional Plots: C_d vs Re_3 and K_v vs Re_3

The following figures show how C_d and K_v vary with Re_3:

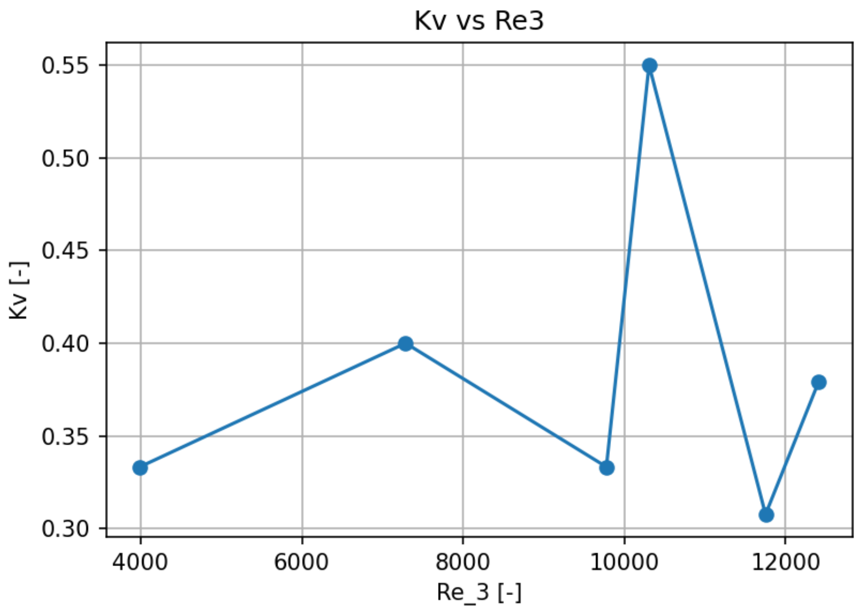


Figure 16: Loss coefficient K_v vs. Reynolds number Re_3.

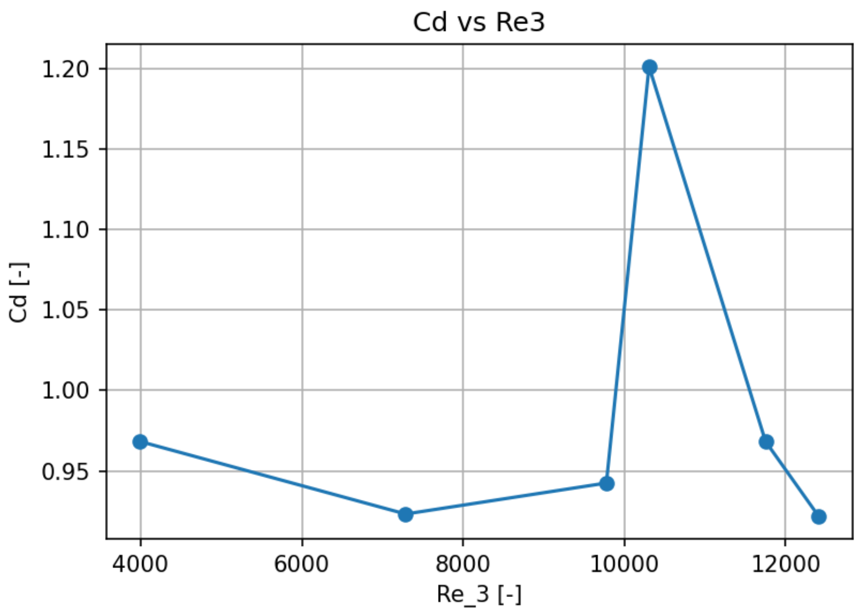
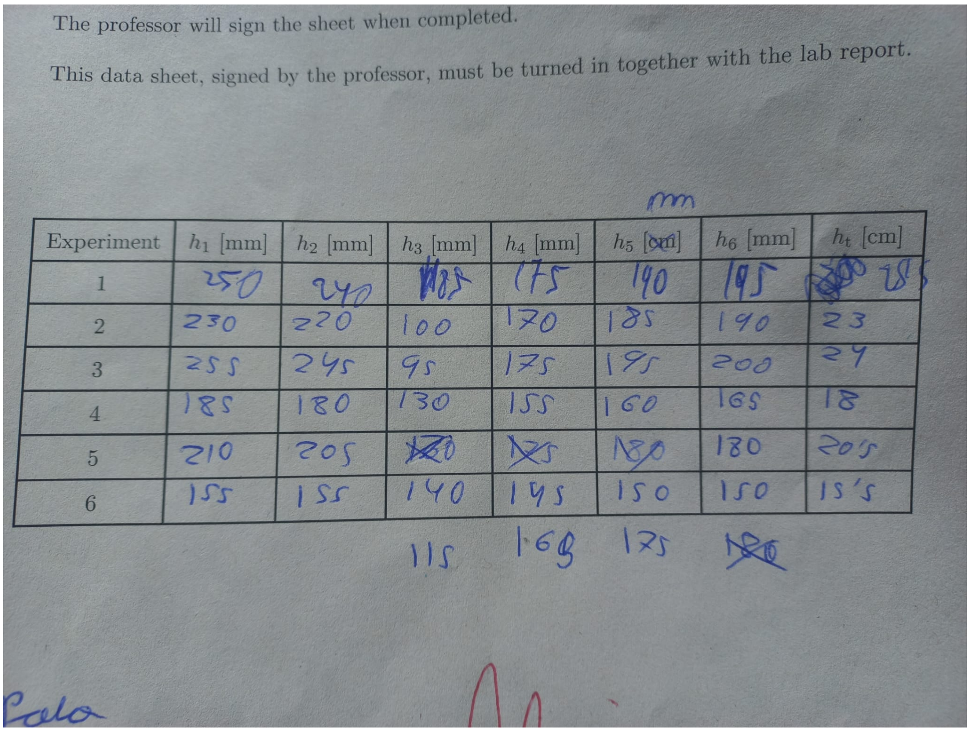


Figure 17: Discharge coefficient C_d vs. Reynolds number Re_3.

Conclusion

In this experiment, we derived and applied theoretical concepts to analyze Venturi tube flow. Starting from Bernoulli's equation and the continuity equation, we established relationships for reduced pressure, velocity, and flow rate. We introduced the discharge coefficient C_d to compare actual and ideal flows, and characterized viscous losses via the loss coefficient K_v and permanent pressure drop Δp_{16}. The measured data aligned with theoretical expectations, showing that as velocity increases in the throat, static pressure decreases, and frictional losses prevent complete pressure recovery. The Reynolds number analysis revealed the influence of flow regime on C_d and K_v, highlighting how more turbulent conditions approach more ideal behaviors. Overall, the Venturi tube proved to be an effective and illustrative device for studying fundamental fluid mechanics principles.

Appendix: Original Collected Data



The professor will sign the sheet when completed.

This data sheet, signed by the professor, must be turned in together with the lab report.

Experiment	h_1 [mm]	h_2 [mm]	h_3 [mm]	h_4 [mm]	h_5 [~~cm~~] mm	h_6 [mm]	h_t [cm]
1	250	240	85	175	190	195	~~[illegible]~~ 285
2	230	220	100	170	185	190	23
3	255	245	95	175	195	200	24
4	185	180	130	155	160	165	18
5	210	205	~~120~~	~~175~~	~~180~~	180	20'5
6	155	155	140	145	150	150	15'5
			115	168	175	~~180~~	

Figure 18: Original collected data as recorded in the lab.

Code Appendix

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import os

rho = 1000.0
g = 9.81
mu = 1.0e-3
b = 0.0184

x_positions = [0, 28, 56, 94, 127, 169]

A1_mm2 = 338.6
A2_mm2 = 233.5
A3_mm2 = 84.6
A4_mm2 = 170.2
A5_mm2 = 255.2
A6_mm2 = 338.6
areas_mm2 = [A1_mm2, A2_mm2, A3_mm2, A4_mm2, A5_mm2, A6_mm2]

```

```
areas = [A*1e-6 for A in areas_mm2]
beta = areas[2]/areas[0]

def Dh(A, b):
    a = A/b
    perimeter = 2*(a+b)
    return (4*A)/perimeter

Dh_values = [Dh(A, b) for A in areas]

df_input = pd.read_csv("lab4experiments.csv")

summary_pressure_loss = []
summary_flow_rates = []
summary_reynolds = []

Kv_list = []
Cd_list = []
Re3_list = []

os.makedirs("plots", exist_ok=True)

for idx, row in df_input.iterrows():
    exp = row['Experiment']

    h1_m = row['h1 [mm]']*1e-3
    h2_m = row['h2 [mm]']*1e-3
    h3_m = row['h3 [mm]']*1e-3
    h4_m = row['h4 [mm]']*1e-3
    h5_m = (row['h5 [mm]'])*1e-3
    h6_m = row['h6 [mm]']*1e-3
    ht_m = (row['ht [mm]'])*1e-3

    P_red = [rho*g*h for h in [h1_m, h2_m, h3_m, h4_m, h5_m, h6_m]]

    delta_h_t3 = ht_m - h3_m
    if delta_h_t3 < 0:
        delta_h_t3 = 0.0
    Q = areas[2]*np.sqrt(2*g*delta_h_t3)

    velocities = [Q/A for A in areas]

    Pdin = [0.5*rho*v**2 for v in velocities]

    Ptotal = [P_red[i] + Pdin[i] for i in range(6)]

    dp16 = rho*g*(h1_m - h6_m)

```

```python
    v3 = velocities[2]
    Kv = dp16/(0.5*rho*v3**2) if v3 != 0 else 0.0

    delta_h_13 = h1_m - h3_m
    if delta_h_13 < 0:
        delta_h_13 = 0.0
    if (1 - beta**2) > 0:
        Q_ideal = areas[2]*np.sqrt((2*g*delta_h_13)/(1 - beta**2))
    else:
        Q_ideal = 0.0

    Cd = Q/Q_ideal if Q_ideal != 0 else 0.0

    Re1 = (rho*velocities[0]*Dh_values[0])/mu
    Re3 = (rho*velocities[2]*Dh_values[2])/mu

    H_values_mm = [
        row['h1 [mm]'],
        row['h2 [mm]'],
        row['h3 [mm]'],
        row['h4 [mm]'],
        row['h5 [mm]'],
        row['h6 [mm]']
    ]

    df_single = pd.DataFrame({
        'Section': [1,2,3,4,5,6],
        'H [mm]': H_values_mm,
        'A [mm^2]': areas_mm2,
        'Pred [Pa]': P_red,
        'Pdin [Pa]': Pdin,
        'Vi [m/s]': velocities,
        'Ptotal [Pa]': Ptotal,
        'Q [m^3/s]': [Q]*6
    })

    filename = f"results_experiment_{exp}.csv"
    df_single.to_csv(filename, index=False)

    plt.figure(figsize=(8,5))
    plt.plot(x_positions, P_red, marker='o', label='Static Pressure
    ↪   (Pred)')
    plt.plot(x_positions, Pdin, marker='o', label='Dynamic Pressure
    ↪   (Pdin)')
    plt.plot(x_positions, Ptotal, marker='o', label='Total Pressure
    ↪   (Ptotal)')
    plt.xlabel('x [mm]')
    plt.ylabel('Pressure [Pa]')
```

```
    plt.title(f'Pressure Distribution - Experiment {exp}')
    plt.legend()
    plt.grid(True)
    plt.savefig(f"plots/pressures_experiment_{exp}.png", dpi=150)
    plt.close()

    summary_pressure_loss.append({
        'Experiment': exp,
        'p16 [Pa]': dp16,
        'Kv [-]': Kv
    })

    summary_flow_rates.append({
        'Experiment': exp,
        'Q [m^3/s]': Q,
        'Q_ideal [m^3/s]': Q_ideal,
        'Cd [-]': Cd
    })

    summary_reynolds.append({
        'Experiment': exp,
        'Re1 [-]': Re1,
        'Re3 [-]': Re3
    })

    Kv_list.append(Kv)
    Cd_list.append(Cd)
    Re3_list.append(Re3)

df_pressure_loss = pd.DataFrame(summary_pressure_loss)
df_pressure_loss.to_csv("table_pressure_loss.csv", index=False)

df_flow_rates = pd.DataFrame(summary_flow_rates)
df_flow_rates.to_csv("table_flow_rates.csv", index=False)

df_reynolds = pd.DataFrame(summary_reynolds)
df_reynolds.to_csv("table_reynolds.csv", index=False)

Re3_array = np.array(Re3_list)
Kv_array = np.array(Kv_list)
Cd_array = np.array(Cd_list)
sort_idx = np.argsort(Re3_array)
Re3_sorted = Re3_array[sort_idx]
Kv_sorted = Kv_array[sort_idx]
Cd_sorted = Cd_array[sort_idx]

plt.figure(figsize=(6,4))
plt.plot(Re3_sorted, Kv_sorted, marker='o')
```

```
plt.xlabel('Re_3 [-]')
plt.ylabel('Kv [-]')
plt.title('Kv vs Re3')
plt.grid(True)
plt.savefig("plots/Kv_vs_Re3.png", dpi=150)
plt.close()

plt.figure(figsize=(6,4))
plt.plot(Re3_sorted, Cd_sorted, marker='o')
plt.xlabel('Re_3 [-]')
plt.ylabel('Cd [-]')
plt.title('Cd vs Re3')
plt.grid(True)
plt.savefig("plots/Cd_vs_Re3.png", dpi=150)
plt.close()

```