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Department of Mechanical, Industrial, and Mechatronics Engineering

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Lab Report No.	2

Report Title	**The Venturi Flow Meter**

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ii. Summary

The purpose of this experiment was to investigate the flow rate of water using a Venturi meter, by applying Bernoulli's equation to calculate the theoretical flow rate based on the pressure readings. The objective is to check the accuracy of the Venturi flow meter by comparing the theoretical flow rate with the actual flow rate, and to determine the discharge coefficient. Flow rate was calculated using the manometer for both high and low flow conditions. The results were analyzed to calculate the percentage error, and the discharge coefficient. Moreover, at the throat, theoretical velocities were computed and were used to calculate theoretical flow rates ranging from $3.15 * 10^{-4}\frac{m^3}{s}$ and $3.56 * 10^{-4}\ \frac{m^3}{s}$ at reduced and full flow rates respectively. Although, the actual volume flow rate was averaged to be approximately $2.46 \times 10^{-4}\frac{m^3}{s}$. Additionally, the calculated discharge coefficient C_v, a ratio of actual to theoretical flow rate, was found to range from 0.691 and 0.781 at reduced and full flow rates respectively. Compared against the expected theoretical range of 0.9550-0.9850, the corresponding percent errors were 18.22% for reduced flow and 27.68% for full flow, likely due to friction, turbulence, and possible measurement errors during the experiment. Furthermore, Reynold's numbers were calculated to be 19913.6 at reduced flow rate, and 22453.6 at full flow rate, confirming turbulent flow. Minor differences between theoretical and experimental manometer heights were observed as well, likely due to the fluid velocities at each channel being calculated from linearly interpolated cross sectional areas. Ultimately, the experiment demonstrated an overall agreement with theoretical predictions, confirming the validity of Bernoulli's equation under our lab conditions.

1. Introduction

This experiment aims to explore the behaviour of the Venturi flow meter using Bernoulli's equation to calculate the theoretical flow rate of water based on pressure measurements. By comparing the theoretical flow rate with actual measurements, the discharge coefficient, which is the ratio between the actual and theoretical flow rates, can be determined.

The Reynolds number (Re), which is dimensionless, can be calculated using the fluid density (ρ) measured in kg/m^3, velocity of the fluid (V) in m/s, diameter (D) in meters, and the dynamic viscosity of the fluid (μ) in Pa·s.

$$Re = \frac{\rho v_1 D_H}{\mu} \quad (1)$$

To check the accuracy of the measurements, the percentage error (%Error) between the actual and theoretical flow rates (m^3/s or L/s) is calculated as:

$$\%Error = \left|\frac{Actual - Expected}{Expected}\right| \times 100 \quad (2)$$

The cross-sectional area (A) of the can be calculated using the diameter of the throat (D) in metres.

$$A = bh \quad (3)$$

Bernoulli's equation relates the pressure (P_1,P_2) in Pascals, velocity (V_1, V_2) in m/s, and the height (z_1, z_2) measured in meters, at two points in the fluid flow:

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \quad (4)$$

The hydraulic diameter (D_H) is used to describe flow in non-circular cross-sections and is defined as:

$$D_H = \frac{4A_1}{P_{wet}} \quad (5)$$

Where A is the cross-sectional area (m^2), and P is the wetted perimeter (m). The diameter is used in the Reynolds number calculation for pipes with irregular cross-sections.

The continuity equation expresses the conservation of mass and relates the velocities (V_1,V_2) and areas at two points (A_1, A_2) in a steady flow system:

$$V_1 A_1 = V_2 A_2 \quad (6)$$

Combining Bernoulli's equation with the continuity equation, solved for V_2 is shown as:

$$V_2 = \sqrt{\frac{2g[(P_1-P_2)/\gamma+(z_1-z_2)]}{(1-(A_2/A_1)^2)}} \tag{7}$$

The velocity at the throat of the Venturi meter proportional to C_v (a function of Reynolds number) can be shown as:

$$V_{2a} = C_v V_2$$

$$V_{2a} = C_v\sqrt{\frac{2g[(P_1-P_2)/\gamma+(z_1-z_2)]}{(1-(A_2/A_1)^2)}} \tag{8}$$

2. Apparatus

- Venturi Flow Meter
- Manometer
- Water Tank
- Stopwatch

Figure 1: Setup of the Experiment

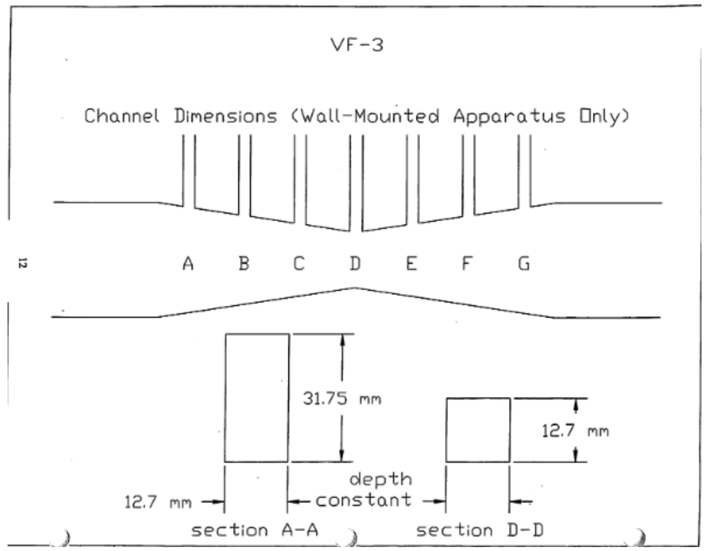


Figure 2: Dimensions of the Venturi Flow Meter

3. Procedure

1. The flow through the Venturi was adjusted to give the maximum difference between the manometer readings at the upstream location and at the Venturi throat.
2. All manometer readings were recorded.
3. The actual volume flow rate (Q_a) of the water was measured twice and averaged.
4. The flow was adjusted until the difference between the upstream manometer reading and the throat manometer reading was half of the full flow value.
5. Steps 2 and 3 were repeated for the lower flow rate.

4. Results and Calculations

It should be noted that equation (3) was verified in **Appendix A.**

Table 1: Venturi apparatus channel fluid heights readings at full flow rate.

Channel	A	B	C	D	E	F	G
Height **($\pm$ $0.0005m$)**	0.5050	0.4930	0.4560	0.3550	0.4170	0.4370	0.4505

Table 2: Venturi apparatus channel fluid heights readings at reduced flow rate.

Channel	A	B	C	D	E	F	G
Height [m] **($\pm$ $0.0005m$)**	0.5190	0.5140	0.4900	0.4370	0.4680	0.4820	0.4860

Table 3: Recordings of the theoretical velocity at the throat of the venturi apparatus and the theoretical volume flow rate. Sample calculations for the velocity and the flow rate can be found in **Appendix D** and **Appendix E** respectively.

Flow Rate	**Velocity at the Throat (V_D)** $[\frac{m}{s}]$	**Volume Flow Rate (Q)** $[\frac{m^3}{s}]$
Full	2.21	3.56×10^{-4}
Reduced	1.96	3.15×10^{-4}

Table 4: Recordings of the actual flow rate of water, measured through a cylindrical tube with a diameter of 3.05 inches. A sample calculation can be found in **Appendix F**.

	Time [s]	**$Q_A \left[\frac{m^3}{s}\right]$**
Trial 1	3.60	2.62×10^{-4}
Trial 2	4.08	2.31×10^{-4}
Average	3.84	2.46×10^{-4}

Table 5: Recordings of Reynold's number at the inlet of the Venturi meter at full and reduced flow rate. A sample calculation can be found in **Appendix G**.

Flow Rate	**Reynold's Number**
Full	22453.6
Reduced	19913.6

Table 6: Recordings of the Venturi discharge coefficient at full and reduced flow rate, the expected range of values given in **Appendix K** and a percent error from the closest value within the given range. A sample calculation can be found in **Appendix H**.

Flow Rate	**Venturi Discharge Coefficient (C_v)**	**Approximate Expected Range based on Reynolds Number**	**Percent Error from Closest Expected Value**
Full	0.691	0.9555 - 0.9850	27.68%
Reduced	0.781	0.9550 - 0.9850	18.22%

Table 7: Recordings of the actual fluid velocity at each channel/manometer at actual flow rate. A sample calculation can be found in **Appendix I**.

Channel	Fluid Velocity (V) [$\frac{m}{s}$]
A	0.610
B	0.763
C	1.017
D	1.525
E	1.017
F	0.763
G	0.610

Table 8: Recordings of the theoretical manometer/channel heights at actual flow rate, determined by the first manometer height and actual fluid velocities. A sample calculation can be found in **Appendix J**.

Channel	Channel Height [m]	
	Full Flow Rate	Reduced Flow Rate
A	0.5050	0.5190
B	0.4943	0.5083
C	0.4713	0.4853
D	0.4054	0.4194
E	0.4713	0.4853
F	0.4943	0.5083
G	0.5050	0.5190

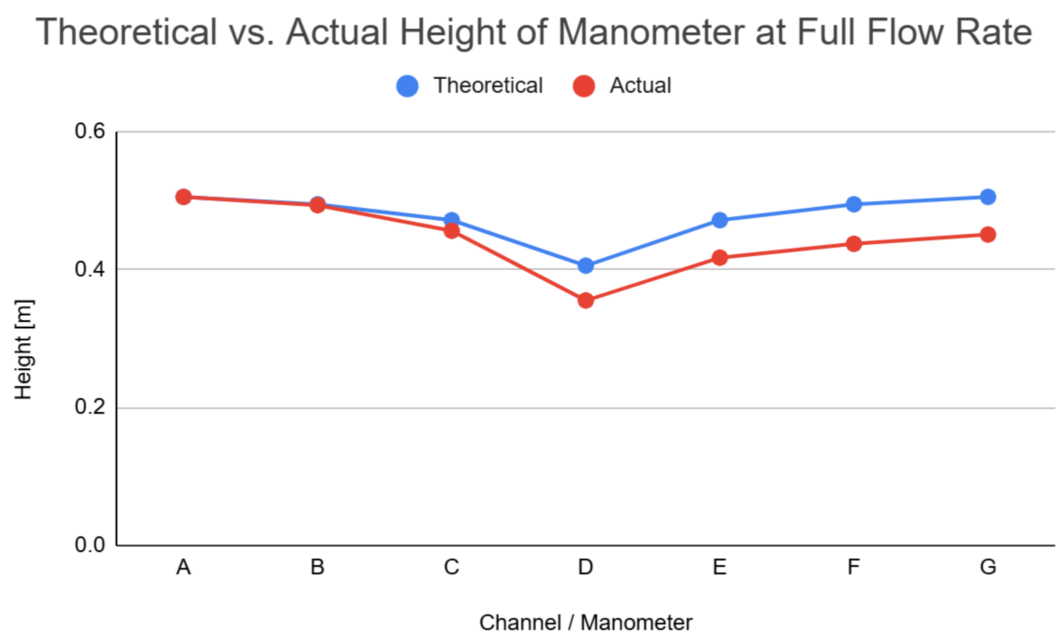


Figure 3: Theoretical vs. actual height of manometers along the Venturi at Full Flow Rate.

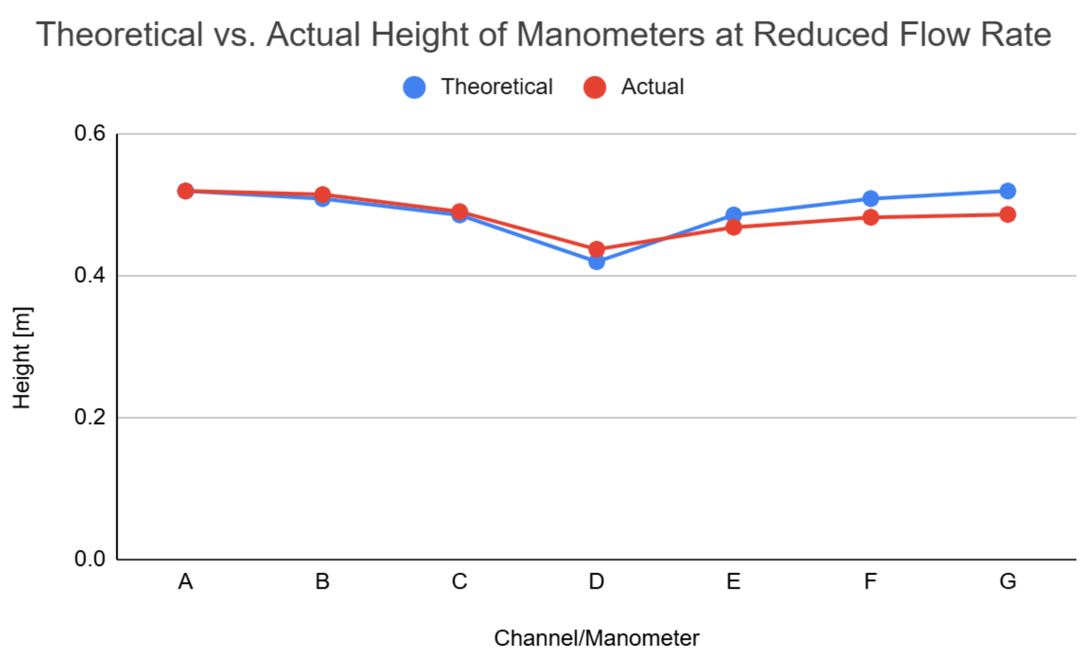


Figure 4: Theoretical vs. actual height of manometers along the Venturi at Reduced Flow Rate.

5. Discussion

Why is the actual fluid velocity different from the theoretical velocity predicted by Bernoulli's equation?

The difference in the actual and theoretical fluid velocities is due to limitations in Bernoulli's equation. The equation assumes ideal fluid conditions that are not applicable to real-world and experimental environments. For use of the equation, the fluid is seen as inviscid and with a steady flow along its streamline. These assumptions don't hold in this experiment, as the water travelling through the venturi flow meter does experience viscous shear stress, which causes unsteady flow of the fluid. These factors contribute to energy loss and, as a result, alter the experimental values from the theoretical.

Is the discharge coefficient within the expected range? If not, discuss possible reasons for the discrepancy.

Although the discharge coefficient was not within the expected range based on the Reynolds number of each flow rate, it was closely aligned and followed the general trend shown in **Appendix K**. With respect to the expected range, the discharge coefficient at the full flow rate had a percent error of 27.68%, while the reduced flow rate had a percent error of 18.22%. Factors such as measurement errors, calibration limitations, and environmental factors may have contributed to these discrepancies. Additionally, the discharge coefficients being lower than the expected range further confirms the loss from viscous shear stress within the Venturi flow meter. The magnitude of the Reynolds number also indicates this, as the lower Reynolds number of 19913.6 from the reduced flow rate leads to a smaller discrepancy from the discharge coefficient's expected range. Despite the minor deviations, the values followed the expected trend and reinforced the Venturi flow meter's ability.

According to the results, where are the head losses the greatest in the Venturi flow meter?

The areas in the Venturi flow meter with the greatest head losses can be determined by analyzing the theoretical and actual heights of the manometers, as shown by **Figure 3** and **Figure 4**. From the comparisons in the plots, it's apparent that the greatest head losses are in the "diverging" section of the Venturi flow meter as the difference between the theoretical and actual heights is the greatest at these channels (D to G). In both plots, the actual heights are lower than the theoretical due to the viscous shear stress of the fluid as it travels through the Venturi flow meter.

6. Conclusion

The purpose of this experiment was to observe the flow of water through a Venturi flow meter with connected manometers at various points. Using Bernoulli's equation, the theoretical volume flow rate and manometer heights were calculated. Through measurement, the actual volume flow rate and fluid velocities at each manometer were determined. These values were used to estimate the Venturi discharge coefficient. Through two trials, the actual flow rate was determined to be approximately $2.46 \times 10^{-4}\frac{m^3}{s}$. With a full flow rate of approximately $3.56 \times 10^{-4}\frac{m^3}{s}$, the Venturi discharge coefficient was calculated as 0.691 and differed from the expected range by 27.68%. A reduced flow rate of approximately $3.15 \times 10^{-4}\frac{m^3}{s}$ resulted in a Venturi discharge coefficient of 0.781, which differed from the expected range by 18.22%. The associated Reynolds numbers also supported the greater accuracy of the reduced flow rate, as a lower Reynolds number indicates more ideal fluid conditions and, as a result, greater accuracy of Bernoulli's equation. Despite the minor discrepancies in the theoretical and actual results, the experiment successfully explored the variations in the property of a fluid as it moves through a Venturi flow meter.

7. References

[1] B. R. Munson, D. F. Young, T. H. Okiishi, and W. W. Huebsch, Fundamentals of Fluid Mechanics, 6th. Hoboken, N.J: Wiley, 2010.

8. Appendix

Equation (3) is derived by substituting Bernoulli's equation into the continuity equation.

$$\frac{P_1}{\gamma} + \frac{V_1^{\ 2}}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^{\ 2}}{2g} + z_2 \text{ (1, Bernoulli equations from location 1 to location 2)}$$

$$V_1A_1 = V_2A_2 \text{ (2, Continuity Equation)}$$

Isolate continuity equation for V_1.

$$V_1 = \frac{V_2A_2}{A_1}$$

Suvituite the equation for V_1 from the continuity equation into Bernoulli's equation.

$$\frac{P_1}{\gamma} + \frac{(\frac{V_2A_2}{A_1})^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^{\ 2}}{2g} + z_2$$

Isolate for V_2.

$$\frac{V_2^{\ 2}}{2g} - \frac{(\frac{V_2A_2}{A_1})^2}{2g} = \frac{P_1}{\gamma} - \frac{P_2}{\gamma} + z_1 - z_2$$

$$V_2^{\ 2}(1 - (\frac{A_2}{A_1})^2) = 2g[\frac{P_1 - P_2}{\gamma} + (z_1 - z_2)]$$

$$V_2 = \sqrt{\frac{2g[\frac{P_1-P_2}{\gamma}+(z_1-z_2)]}{(1-(\frac{A_2}{A_1})^2)}}$$

Equation (3) has been successfully verified.

Appendix A: Verifying derivation of equation (3).

$$p = \gamma h = \rho g h$$

$$p_A = \rho_{water} g h_A = (1000\frac{kg}{m^3})(9.807\frac{m}{s^2})(0.5050m) = 4.953 \times 10^3 \frac{kg}{m^2s^2}$$

$$p_D = \rho_{water} g h_D = (1000\frac{kg}{m^3})(9.807\frac{m}{s^2})(0.3550m) = 3.481 \times 10^3 \frac{kg}{m^2s^2}$$

Appendix B: Pressure calculations at Channel A and Channel D.

$$A = l \cdot w$$

$$A_A = l_A \cdot w_A = (0.03175m)(0.0127m) = 0.000403\,m^2$$

$$A_D = l_D \cdot w_D = (0.0127m)(0.0127m) = 0.000161\,m^2$$

Appendix C: Cross sectional area at Channel A and Channel D.

$$V_D = \sqrt{\frac{2g[\frac{P_A - P_D}{\gamma} + (z_A - z_D)]}{(1 - (\frac{A_D}{A_A})^2)}}$$

$$V_D = \sqrt{\frac{2(9.807)[\frac{(4953-3481)}{9807} + (0-0)]}{(1 - (\frac{0.000161}{0.000403})^2)}} = 2.21\,m/s$$

Appendix D: Calculation for theoretical velocity rate at venturi throat.

$$Q = A_D V_D = (0.000161\,m^2)(2.21\,m/s) = 3.56 \times 10^{-4}\frac{m^3}{s}$$

Appendix E: Calculation for volume flow rate.

$$Q_A = A_{cylinder} V_{measured} = [\pi(\frac{d_{cylinder}}{2})^2](\frac{\Delta x}{\Delta t})$$

$$Q_A = [\pi(\frac{0.07747}{2})^2](\frac{0.2}{3.60}) = 2.62 \times 10^{-4}\frac{m^3}{s}$$

Appendix F: Sample calculation for actual volume flow rate.

$$D_H = \frac{4A_1}{P_{wet}}$$

$$D_H = \frac{4l_A w_A}{2l_A + 2w_A}$$

$$D_H = \frac{4(0.03175)(0.01270)}{2(0.03175)+2(0.01270)}$$

$$D_H = 0.0254\, m$$

$$V_1 = \frac{V_2 A_2}{A_1}$$

$$V_A = \frac{V_D A_D}{A_A}$$

$$V_A = \frac{(2.21)(0.01270)(0.01270)}{(0.03175)(0.01270)}$$

$$V_A = 0.884\, \frac{m}{s}$$

$$Re = \frac{\rho v_1 D_H}{\mu}$$

$$Re = \frac{\rho_{water} v_A D_H}{\mu_{water}}$$

$$Re = \frac{(1000)(0.884)(0.0254)}{(10^{-3})}$$

$$Re = 22453.6$$

Appendix G: Sample calculation for Reynold's Number.

$$V_{2a} = C_v V_2$$

$$C_v = \frac{V_{Da}}{V_D} \times \left(\frac{A_D}{A_D}\right) = \frac{Q_a}{Q} = \frac{2.46\times 10^{-4}}{3.56\times 10^{-4}} = 0.691$$

Appendix H: Calculation for venturi discharge coefficient.

Since the length of the manometers/channels vary linearly from A to G, the difference between their lengths can be determined from the known length of channel A and channel D.

$$\Delta l = \frac{l_A - l_D}{3} = \frac{0.03175 - 0.0127}{3} = 0.00635\, m$$

Therefore, the channel length varies by 0.00635 m. The individual channel lengths can now be determined.

$$l_B = l_A - \Delta l = 0.03175 - 0.00635 = 0.0254\, m$$

$$V = \frac{Q_A}{A} = \frac{2.46\times 10^{-4}}{(0.0254)(0.0127)} = 0.763 \frac{m}{s}$$

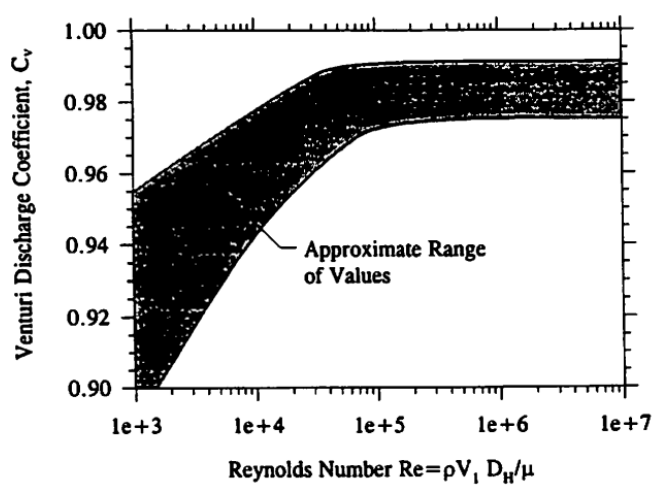
Appendix I: Sample calculation for channel width and actual fluid velocity at channel B.

$$\frac{P_A}{\gamma} + \frac{V_A^{\ 2}}{2g} + z_A = \frac{P_B}{\gamma} + \frac{V_B^{\ 2}}{2g} + z_B$$

$$h_A + \frac{V_A^{\ 2}}{2g} = h_B + \frac{V_B^{\ 2}}{2g}, \text{ where } h_{A,B} = \frac{P_{A,B}}{\gamma}$$

$$h_B = \frac{(V_A^{\ 2} - V_B^{\ 2})}{2g} + h_A = \frac{((0.610)^2 - (0.763)^2)}{2(9.807)} + 0.5050 = 0.4943\, m$$

Appendix J: Sample calculation for the channel B pressure head in reference to the channel A.



Appendix K: Approximate range of discharge coefficients for venturi flowmeters.