MAAE 2300 L4
Fluid Mechanics I

Lab 3

Lab 3:
Uncertainty in
Fluid Flow Measurements

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Abstract:

This experiment investigated the uncertainty associated with fluid flow measurements using five different devices: Venturi meter, Orifice meter, Rotometer, Ultrasonic meter, and Turbine. A closed loop water system was used to collect ten repeated measurements at two different flow rates and using the bucket method after to determine the actual flow rate. Statical analysis was performed to calculate mean, standard deviation and uncertainty values by combined measured and instrument error. The results showed that the Rotometer provided readings closest to the actual flow rate, followed by Venturi and Turbine, and the Orifice for both flows underestimated the flow and was the furthest from the measured actual value. The Ultrasonic wasn't as far off as the Orifice meter, however still underestimated flow rate for high and low flows. These results show the importance of uncertainty analysis in determining the reliability of different flow measurement devices and techniques such as the bucket method.

Nomenclature:

A: Area [m2]

D : Diameter [m]

Q: Flow rate[m^3/s]

ρ: Density of water: 1000 [kg/m3]

P: Pressure [Pa]

Cd: Discharge coefficient [unitless]

s : Sample standard deviation

$\bar{q}$: Sample mean (average)

ui,q: Instrument uncertainty for flow rate [m3/s]

um,q: Measurement uncertainty for flow rate [m3/s]

$utot,q$: Total uncertainty for flow rate [m3/s]

$um,\Delta P$: Measurement uncertainty for pressure [Pa]

$u\Delta P$: Uncertainty for pressure [Pa]

$ui,\Delta P$: Instrument uncertainty for pressure [Pa]

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Introduction:

Accurate measurement of fluid flow is essential in various engineering applications. However all these devices used to measure are subject to uncertainty which must be analyzed and accounted for to determine the reliability of the various systems. This lab focuses on comparing five different flow meters by analysing their performance relative to the actual flow, while accounting for uncertainty.

Uncertainty and Flow Analysis:

Mean Calculation: Find average of the mean by adding all the flow rates as well as change in pressure for Venturi and Orifice, and divide them by the number of data taken(10).

$$\bar{q} = \frac{1}{n}\sum_{i=1}^{n} qi \quad [1]$$

Calculate Standard Deviation:

$$S = \sqrt{\frac{\sum_{i=1}^{n} (qi-\bar{q})^2}{n-1}} \quad [2]$$

Uncertainty for measurement is done with 95% confidence interval using t-table which results in t=2.2.

$U_{m,q} = t_{95}\, S$ [3]

Uncertainty in regards to instruments is done by multiplying the mean by the error percent given from instruments.*As appendix A

$U_{i,\,q} = i\bar{q}$ [4]

$U_{total} = \sqrt{Um, q^2 + Ui,\ q^2}$ [5]

Venturi and Orifice meters were taken as change in pressure, using Bernoulli's equation this can be converted into flow rate so it can be compared against the other meters.

$Q = \frac{\pi}{4} C_d D_2^2 \sqrt{\frac{2\Delta P}{\rho(1-(\frac{D2}{D1})^4}}$ [6]

The same process is repeated for uncertainty calculations.

$U_{m.\Delta P} = t_{95}\ S$ [7]

$U_{i,.\Delta P} = i\bar{q}$ [8]

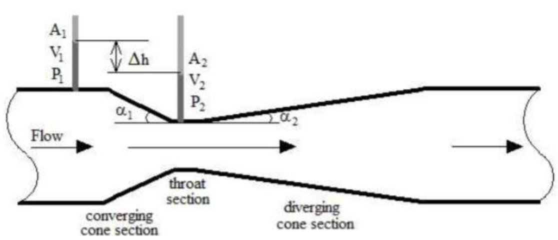
$U_{total} = \sqrt{Um.\Delta P^2 + Ui,.\Delta P^2}$ [9]

$U_{m,q}^2 = (\frac{\partial Q}{\partial \Delta P})^2 U_{t,\Delta P}^2$ [10]

$U_{m,q} = \frac{\frac{\pi}{4} CdD2^2}{\sqrt{\rho(1-(\frac{D2}{D1})^4}} \frac{1}{\sqrt{2\Delta P}} U_{t,\Delta P}$ [11]

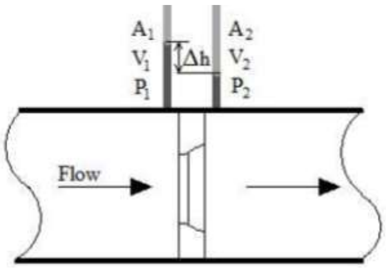
Flow Analysis of how each different meter functions:

Venturi:



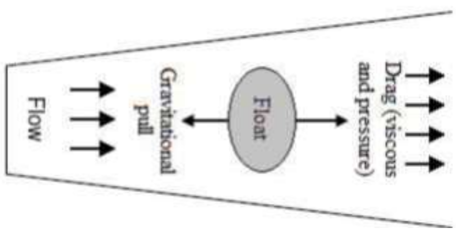
Venturis works by narrowing a section so that the fluid velocity increases, pressures are measured at both wide and narrow sections. The change in pressure is taken as ρg(change in height). This change in pressure is used to determine the fluid's flow.

Orifice:



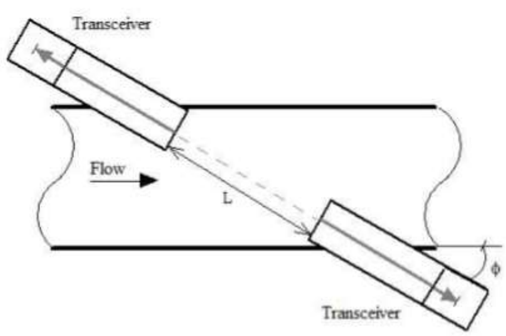
Orifice plates work very similar to venturi meters. Instead of the pipe being narrowed there is a plate inside, called an orifice plate that has a hole to restrict the flow and calculate the pressure difference when it drops after passing through the plate. This can be converted to flow rate using Bernoulli's equation in the same way it is converted for a venturi meter.

Rotometer:



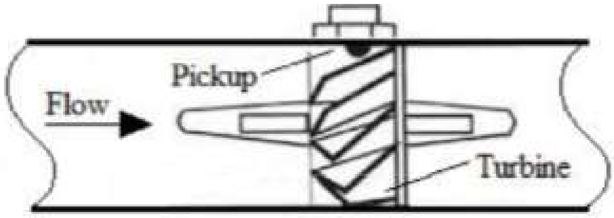
Rotometers have a tube that is tapered and with a float on the inside as detailed in the image. The meter works to measure flow rate based on the height that the float moves upwards as fluid passes through. This height directly corresponds with a flow rate reading.

Ultrasonic:



The ultrasonic flow meter uses two sensors that send pulses diagonally across the pipe, and the distance in time gives the velocity. The Doppler method can also be used by tracking sound waves and the frequency change can be used to determine flow velocity.

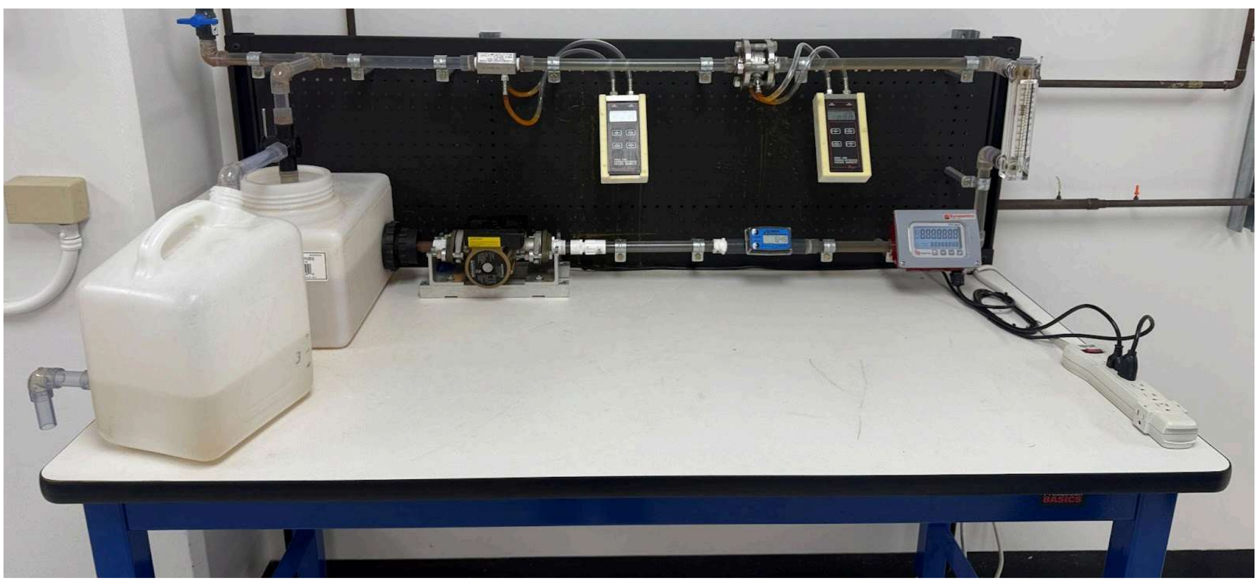
Turbine:



This flow meter uses a small turbine so that as the fluid passes it hits the blades and the turbine speeds up as flow rate speeds up. The pulse of each time the blade passes are recorded and the frequency of these pulses is used in determining flow rate.

Procedure:

Experiment set up



This lab was set up using a closed loop system for water to flow through the 5 separate meters at various points. Once it is ensured that the system is closed it is run momentarily before data is collected to ensure air bubbles don't impact results. The data was collected 10 times with a couple seconds in between for each meter. This is repeated for both flows 1 and 2. Using the bucket method the water from the system is then used to fill up a container till it reaches 4 L and the time this takes is measured so that the actual flow rate can be found for both the high and low flows.

Initial Values from Data Collected Flow 1(a)

Flow 1	Turbine(m^3/s)	Ultrasonic(m^3/s)	Rotameter(m^3/s)	Orfice(kPa)	Venturi(kPa)
1	0.000202	0.00019855	0.0002	2790	5780
2	0.000200667	0.000197583	0.0002	2720	5710
3	0.0002	0.000197433	0.000191667	2860	5660
4	0.000200333	0.000196933	0.000196667	2860	5720
5	0.000200333	0.000196483	0.0002	2700	5670
6	0.0002	0.000196767	0.0002	2650	5560
7	0.000200333	0.000196667	0.0002	2790	5600
8	0.0002	0.000196583	0.000196667	2720	5720
9	0.000199667	0.000196467	0.0002	2700	5770
10	0.000199333	0.000196067	0.000191667	2720	5840
			Actual Flow 1 Rate		0.000213m^3/s

Initial Values from Data Collection Flow 2(b)

Flow 2	Turbine(m^3/s)	Ultrasonic(m^3/s)	Rotameter(m^3/s)	Orfice(m^3/s	Venturi(m^3/s)
1	0.0002625	0.000255167	0.000258333	4560	9650
2	0.000262833	0.0002555	0.000258333	4690	9760
3	0.000262833	0.000255833	0.000258333	4690	9890
4	0.0002625	0.000255333	0.000266667	4620	10000
5	0.0002625	0.000254833	0.000258333	4690	9710
6	0.000263167	0.000255333	0.000258333	4620	9950
7	0.0002625	0.000255333	0.000266667	4560	9710
8	0.000262333	0.000255167	0.000263333	4680	9890
9	0.000262	0.000255	0.000258333	4620	9540
10	0.000262333	0.0002545	0.000258333	4690	9770
			Actual Flow 2 Rate		0.000270m^3/s

Results & Discussion:

Turbine Flow and Uncertainty Calculation(c)

Turbine	Low Flow(m^3/s)	High Flow(m^3/s)
1	0.000202	0.0002625
2	0.000200667	0.000262833
3	0.0002	0.000262833
4	0.000200333	0.0002625
5	0.000200333	0.0002625
6	0.0002	0.000263167
7	0.000200333	0.0002625
8	0.0002	0.000262333
9	0.000199667	0.000262
10	0.000199333	0.000262333
Mean	0.000200267	0.00026255
Standard Dev	7.16645E-07	3.24418E-07
Um,q	1.57662E-06	7.13719E-07
Ui,q	0.000006008	7.8765E-06
Utot,q	6.21142E-06	7.90877E-06
q	0.000200267+- 6.21142*10^-6	0.00026255+- 7.90877*10^-6

Ultrasonic Flow and Uncertainty Calculations(d)

Ultrasonic	Low Flow(m^3/s)	High Flow(m^3/s)
1	0.00019855	0.000255167
2	0.000197583	0.0002555
3	0.000197433	0.000255833
4	0.000196933	0.000255333
5	0.000196483	0.000254833
6	0.000196767	0.000255333
7	0.000196667	0.000255333
8	0.000196583	0.000255167
9	0.000196467	0.000255
10	0.000196067	0.0002545
Mean	0.000196953	0.0002552
Standard Dev	7.20716E-07	3.66835E-07
Um,q	1.58558E-06	8.07037E-07
Ui,q	2.9543E-06	0.000003828
Utot,q	3.3529E-06	3.91215E-06
q	0.000196953+-3.3529*10^-6	0.0002552+-3.91215*10^-6

Rotameter Flow and Uncertainty Calculations(e)

Rotameter	Low Flow(m^3/s)	High Flow(m^3/s)
1	0.0002	0.000258333
2	0.0002	0.000258333
3	0.000191667	0.000258333
4	0.000196667	0.000266667
5	0.0002	0.000258333
6	0.0002	0.000258333
7	0.0002	0.000266667
8	0.000196667	0.000263333
9	0.0002	0.000258333
10	0.000191667	0.000258333
Mean	0.000197667	0.0002605
Standard Dev	3.44265E-06	3.6047E-06
Um,q	7.57383E-06	7.93033E-06
Ui,q	9.88333E-06	0.000013025
Utot,q	1.24516E-05	1.52493E-05
q	0.000197667+-1.24516*10^-5	0.0002605+-0.00001525

Orifice Meter Flow and Uncertainty Calculations(f)

Orfice	Low Flow ΔP(Pa)	q(m^3/s)	High Flow(Kpa) ΔP(Pa)	q(m^3/s)
1	2790	0.000148815	4560	0.000190251
2	2720	0.000146936	4690	0.0001974
3	2860	0.00015067	4690	0.0001974
4	2860	0.00015067	4620	0.000195921
5	2700	0.000146395	4690	0.0001974
6	2650	0.000145033	4620	0.000195921
7	2790	0.000148815	4560	0.000194645
8	2720	0.000146936	4680	0.000197189
9	2700	0.000146395	4620	0.000195921
10	2720	0.000146936	4690	0.0001974
Mean	2751	0.00014776	4642	0.000196387
Standard Dev	70.78135348	1.89626E-06	53.29165038	2.21447E-06
Um, Δp	155.7189776		117.2416308	
Ui, Δp	27.51		46.42	
Utot, Δp	158.1303263		126.0968533	
Um,q		4.17177E-06		4.87183E-06
Ui,q		1.4776E-06		1.96387E-06
Utot,q		4.42572E-06		5.25276E-06
q		0.00014776+-4.42572E-06		0.000196387+-5.25276E-06

Venturi Meter Flow and Uncertainty Calculations(g)

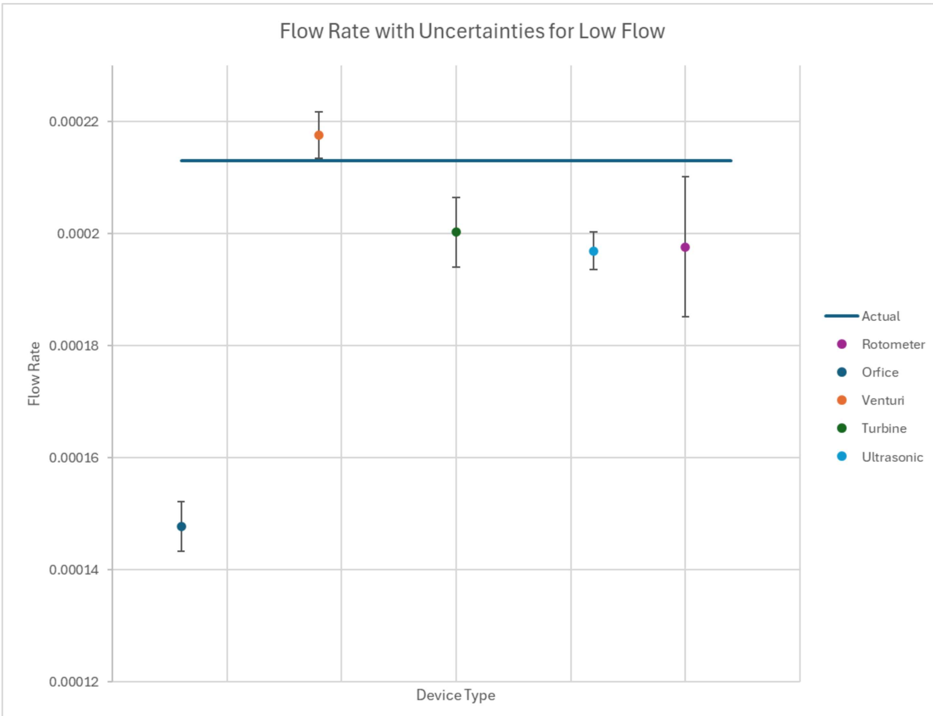
Venturi	Low Flow		High Flow(Kpa)	
	ΔP(Pa)	q(m^3/s)	ΔP(Pa)	q(m^3/s)
1	5780	0.000219141	9650	0.000283155
2	5710	0.00021781	9760	0.000284764
3	5660	0.000216855	9890	0.000286654
4	5720	0.000218001	10000	0.000288244
5	5670	0.000217046	9710	0.000284034
6	5560	0.00021493	9950	0.000287523
7	5600	0.000215702	9710	0.000284034
8	5720	0.000218001	9890	0.000286654
9	5770	0.000218952	9540	0.000281537
10	5840	0.000220276	9770	0.00028491
Mean	5703	0.000217672	9787	0.000285151
Standard Dev	84.20213774	1.60793E-06	143.6856136	2.09405E-06
Um, Δp	185.244703		316.1083499	
Ui, Δp	57.03		97.87	
Utot, Δp	193.8247169		330.9124141	
Um,q		3.53744E-06		4.60691E-06
Ui,q		2.17672E-06		2.85151E-06
Utot,q		4.1535E-06		5.418E-06
q		0.000217672+-4.1535E-06		0.000285151+-5.418E-06

Summary of Flow Rates(h)

Flowmeter	Low Flow(m^3/s)	High Flow(m^3/s)
Orifice	0.00014776+-4.42572E-06	0.000196387+-5.25276E-06
Venturi	0.000217672+-4.1535E-06	0.000285151+-5.418E-06
Turbine	0.000200267+-6.21142*10^-6	0.00026255+-7.90877*10^-6
Ultrasonic	0.000196953+-3.3529*10^-6	0.0002552+-3.91215*10^-6
Rotometer	0.000197667+-1.24516*10^-5	0.0002605+-0.00001525
Actual	0.000213m^3/s	0.000270m^3/s

The method of the various meters was detailed above, and the actual flow rate the data collection is being compared against was done using the bucket method. The bucket method is calculating the time it takes to fill a bucket to a certain amount and determine the flow of that water accordingly. In the case of flow 1 it was measured to be ~4L in 19.23 seconds and ~4L in 14.81 seconds for flow 2, these values are then converted to m^3/s which is shown in table h. While this is a great process to determine actual flow it is not exempt from errors, particularly human error. The time was stopped when the bucket filled to around 4L however this was not a very exact measurement. In future experiments if more accuracy is desired a system could be designed using sensors to stop counting time once water reaches a certain level. However, in this experiment the results are reasonable meaning the error is not too much.

Low Flow Graph Showing Flow Uncertainties with Actual Flow(a)



High Flow Graph Showing Flow and Uncertainties with Actual Flow(b)

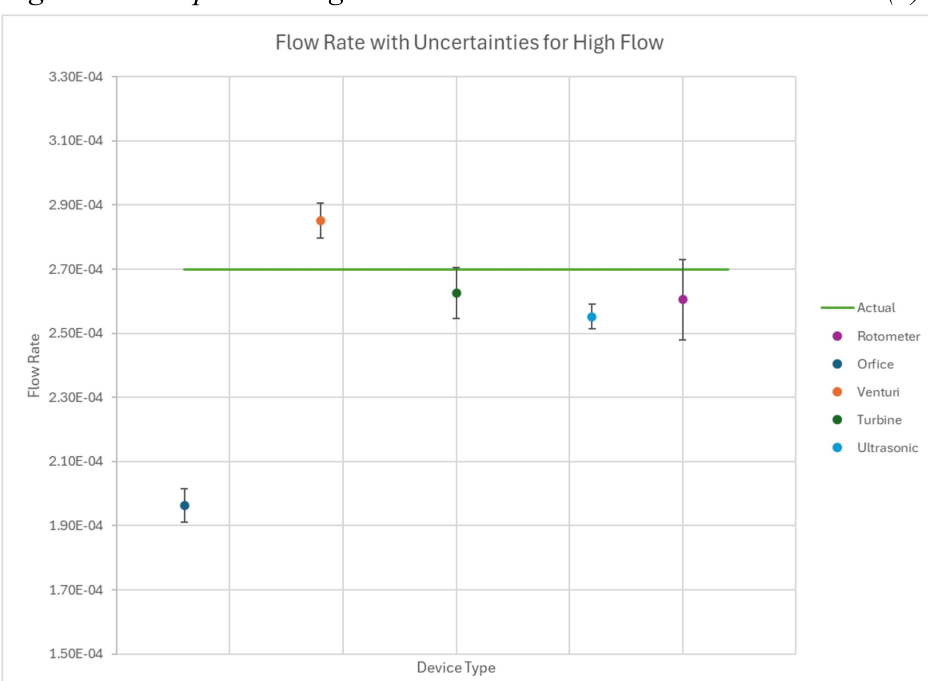
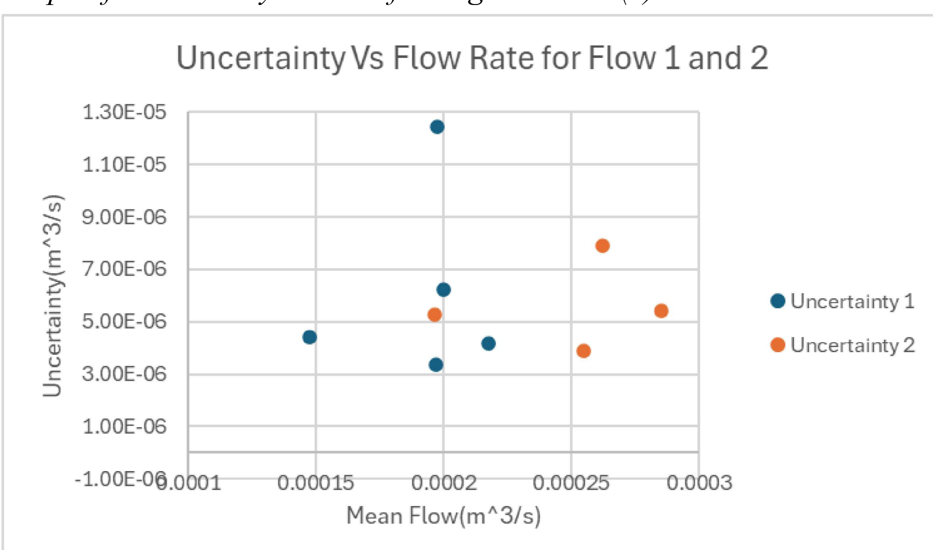


Table c and d are the results converted to q from the Venturi and Orifice meters which were measured as change in pressure(KPa). This was done using equation [6] which rearranges Bernoulli's equation to find the flow rate using, discharge coefficient, diameters, density, and pressure change. Once values are calculated for all meters and in terms of flow rate, the means and standard deviations are found, as well as total uncertainty. Total uncertainty is found using the uncertainty of measurement and the uncertainty from the instrument. Measurement uncertainty uses a t0.975 to get a 95% confidence interval and multiples the result by the standard deviation. Instrument uncertainty is found using % error for the particular meter which is given in the lab manual and divided by 100% and multiplied by the mean. The flow rates and uncertainties calculated were evaluated and analyzed by coming them to the actual flow rate which was measured during the experiment. Graphs a and b show the comparison and from this it can be concluded that for the low flow, the Venturi and Rotormeter were the most accurate and for High Flow Rotameter and Turbine were most accurate. The actual value for flow rate falls within the range including uncertainty for the Rotormeter and Turbine in high flow. For low flow none of the measuring devices overlap their range with the actual flow rate, however the Venturi comes very close. The graphs a and b also demonstrate the significant deviation from actual flow rate for the Orifice meter, with it consistently measuring a lower flow rate. The Venturi and Ultrasonic meter also measure with deviation from the actual flow however this is less extreme than the Orifice meter. The Venturi meter for both flows measured higher than the actual rate and contrastingly the Ultrasonic measured slightly lower than the actual rate for both flows. These results suggest the reliability from best to least is: Rotormeter, Turbine, Venturi, Ultrasonic, Orifice.

Graph of Uncertainty vs Flow for High and Low(c)



Graph 3 shows a trend between average flow rate and uncertainties. For both flow 1 and 2 there is very little correlation but there is still a slight positive linear relationship. This means as flow rate increases so does uncertainty, however as stated this is a very weak relationship.

This makes sense since uncertainty is percent so the larger the number the larger the uncertainty, however instrument error percents also plays a role.

References

1) Lab 3: Uncertainty in Fluid Flow Measurements: MAAE 2300 FLuid Mechanics I Lab Manual, Departments of Mechanical & Aerospace Engineering- Carleton University

Conclusion:

The uncertainty analysis demonstrated clear differences in the reliability of the five flow meters tested. The Rotameter consistently produced values that aligned closely with the actual flow very near its uncertainty range, making it the most dependable device in this experiment. The Turbine meter also performed well, particularly at high flow rates, though its low-flow measurements slightly underestimated the actual value. The Ultrasonic meter showed good precision but measured slightly lower than the bucket method. In contrast, the Venturi meter overestimated flow though it still performed well, specifically for low flow where it was within range. The Orifice meter consistently underestimated, both deviating significantly from the actual values. Overall, the experiment confirmed that uncertainty analysis is critical in evaluating flow measurement devices, and that Rotameter, Turbine, and Venturi meters provided the most reliable results in this setup. Future improvements could include automated timing for the bucket method to reduce human error and further refine accuracy.

Appendix A(Given Values):

Instrument Uncertainties

Instrument	% Error
Manometers	±0.5%
Rotameter	±5%
Turbine	±3%
Ultrasonic	±1.5%
Orifice	±1%
Venturi	±3%

Constants

Instrument	D1	D2
Venturi	29.455mm	9.525mm
Orifice	21.34mm	10.92mm

Appendix B(Sample Calculations):

Fluids Lab 3 Sample Calculations(Low Flow)

Sample Mean Calculation (Turbine)

$$\bar{q} = \frac{1}{n}\sum_{i=1}^{n} q_i \rightarrow = \frac{(0.000202 + 0.000200667 + 0.002 \ldots)}{10}$$

$$\bar{q} = 0.000200267$$

Sample Standard Deviation Calculation (Turbine)

$$s = \sqrt{\frac{\sum_{i=1}^{n}(q_i - \bar{q})^2}{n-1}} = \sqrt{\frac{(0.000202 - 0.000200267)^2 + (0.0002009 - 0.000200267)^2 + \ldots (0.000199333 - 0.000200267)^2}{10-1}}$$

$$S = 7.16645 \times 10^{-7}$$

Uncertainty Sample Calculations (Turbine)

$t_{0.975} = 2.2$

$$U_{m,q} = t_{0.975} \times S_q \rightarrow (2.2)(7.16645 \times 10^{-7})$$

$$U_{m,q} = 1.57662 \times 10^{-6}$$

$$U_{i,q} = \bar{q} \times i \qquad i = \frac{3\%}{100\%} \rightarrow (0.000200267)(3/100)$$

$$U_{i,q} = 0.000006008$$

$$U_{tot,q} = \sqrt{U_{m,q}^2 + U_{i,q}^2} \rightarrow \sqrt{(1.57662E\text{-}06)^2 + (6.008E\text{-}06)^2} = 6.21142 \times 10^{-6}$$

Sample Calculation (Converting ΔP to Q) (Venturi)

$$q = C_d \frac{\pi}{4} D_2^2 \sqrt{\frac{2\Delta P}{\rho_w\left(1-\left(\frac{D_2}{D_1}\right)^4\right)}} \rightarrow (0.9)\left(\frac{\pi}{4}\right)(0.009525)^2 \sqrt{\frac{2(5780)}{1000\left(1-\left(\frac{0.009525}{0.029435}\right)^4\right)}} = 0.000219141$$

$$U_{m,q} = \sqrt{\left(\frac{\delta q}{\delta \Delta P}\right)(U_{\Delta P})^2} \rightarrow \left(\frac{\frac{\pi}{4} C_d D_2^2}{\sqrt{\rho\left(1-\left(\frac{D_2}{D_1}\right)^4\right)}}\right)\left(\frac{1}{\sqrt{2\Delta P}}\right)(U_{\Delta P}) \rightarrow \left(\frac{\frac{\pi}{4}(0.9)(0.009525)^2}{\sqrt{1000\left(1-\left(\frac{0.009525}{0.029435}\right)^4\right)}}\right)\left(\frac{1}{\sqrt{2(5780)}}\right)(193.6247164)$$

$$\rightarrow U_{m,q} = 3.53744 \times 10^{-6}$$

q_{actual} (low flow sample)

4L in 19.23 seconds $\rightarrow \frac{4}{19.23}$

0.208L in 1 second $\qquad 1\,L = 0.001\,m^3$

0.00021 m^3/s