A Simple, Inexpensive Venturi Experiment – Applying the Bernoulli Balance to Determine Flow and Permanent Pressure Loss

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Abstract

Experiments were conducted using a simple (two plastic funnels), easily built (in a few hours) and inexpensive (costing about the equivalent of a meal at Red Lobster) venturi meter. Three modified Bernoulli balances were used to determine mass flows and permanent pressure loss for the flowmeter. The mass flow rate from the Bernoulli balance calculation gave a mass flow rate about 88% of the experimental flow rate, yielding a discharge coefficient of 0.88. Small, well-constructed venturi meters have discharge coefficients about 0.98. Since this homemade flowmeter likely not well constructed, the low discharge coefficient is reasonable. The permanent pressure loss was correlated using a minor loss coefficient applied to the velocity head in the venturi throat. The minor loss coefficient was 0.29, which compares with the minor loss coefficient of a well-designed venturi meter of about 0.1. This inexpensive flowmeter is ideal for teaching the use of the Bernoulli Balance to model fluid systems.

Keywords

venturi meter, Bernoulli balances, laboratory experiments, fluid mechanics

Introduction

Laboratory practice, where students design and conduct experiments in support of classroom activities, is an essential part of the educational process. It has been shown that a majority of engineering students learn best when exposed to hands-on exercises and activities.[1] A variety of novel techniques have been described in the literature for delivering lab content to the students including the use of the Kolb's experiential learning cycle in conjunction with a virtual laboratory,[2] combining LEGO® Dacta building blocks with LabVIEW™ software[3] and the use of hands-on demonstrations in place of full-scale lab experiments.[4]

Fluid mechanics has been a popular subject for laboratory illustration of classroom activities. Siemionko and Kim[5] describe the use of lab experiments in building transport concepts, and Fraser *et al.*[6] describe the use of computer simulations to enhance both the classroom and laboratory experience. Wicker and Quintana[7] extended the use of fluid mechanics to the design and fabrication of lab experiments by the students, and Walters and Walters[8] even used the combination classroom instruction and lab experience to introduce fluid mechanics to talented high school students.

Issac Newton said, "*If I have seen further, it is by standing on the shoulders of giants.*"[9] In studying the venturi flowmeter, Daniel Bernoulli[10] is the first "giant" encountered; he developed his famous Bernoulli equation[11] in 1738. The second "giant" is Giovanni Venturi,[12] who "*was the discoverer of Venturi effect…* in 1797…. and… *is the eponym for the Venturi tube, the Venturi flow meter and the Venturi pump*. The venturi flowmeter was not applied commercially until Clements Herschel[13, 14] obtained a U.S. patent for using a *"venturi tube to exercise a suction action"*[15] to measure the flow of water through a pipe. Many publications exist which explain the venturi meter in detail, and there are also several excellent YouTube videos which demonstrate its use and utility.[16, 17]

The major objective of this experiment was to construct, test and model a simple, inexpensive venturi meter. More specifically, this simple venturi meter, constructed from materials available at a local hardware/auto parts store, was characterized by determining the venturi coefficient and the permanent pressure loss. This experiment is important educationally because it requires students to execute three Bernoulli balances within the overall system—and students often have trouble selecting proper endpoints for Bernoulli balances.

Experimental

Apparatus

Photographs of the simple venturi apparatus and its components are shown in Figures 1-3. Figure 1 presents an overview of the experimental setup and Figure 2 presents the apparatus as it was tested. City water was supplied to the apparatus through a garden hose connected to a clothes washer hookup hose. A ¾ in (1.9 cm) pipe tee was placed on the end of the washer hookup hose. A silicone manometer tube was connected to the branch of the tee, and this vertical tube was used to measure the pressure at the end of the hose. A 70 in x ¾ in ID (180 cm x 1.9 cm ID) Tygon® tube was used to connect the outlet of the tee to the venturi meter. The ID of the venturi (at the end of the funnels) was measured by inserting a 3/8 in (0.953 cm) metal tube, which fit snugly through the ends of the funnels.

An exploded view of the venturi meter is shown in Figure 3. Two FloTool funnels (# 10701; available at AutoZone) were used to construct the venturi meter. The funnels were connected by a 2 in (5.1 cm) long section of ½ in ID (1.27 cm ID) nylon reinforced silicone tubing. As the funnels were joined by inserting their ends into the silicone tube, the ends of the funnels were inserted into a 10.5 in (267 cm) long, 1 ¼ in ID (3.2 cm ID) Plexiglas® tube; in the tube center a threaded hole was drilled to accommodate a 1/8 in NPT (~1.0 cm) male pipe threaded hose barb. A 1/8 in (0.33 cm) hole was drilled through the silicone tubing and through the walls of funnels through the hose barb hole. Silicone caulking was used to seal the joint between the Plexiglas® tube and the funnels. The flowmeter was connected to a wooden stand for stability as is shown in Figure 2. The flowmeter centerline was 18 7/8 in (48 cm) above the concrete laboratory floor. The end of the lower funnel of the flowmeter was placed inside a 5 gallon (19 liter) pail, as is shown in Figures 1 and 2. A digital vacuum gauge (Dwyer, Model DPG-00, 0-30 in Hg (0-102 kPa)) was used to measure the pressure at the center of the flowmeter.

Figure 1. An Overview of the Experimental

Figure 2. A View of the Experimental Apparatus

Apparatus as it was Operated

Figure 3. An Exploded View of the Venturi, Including Funnels, Connecting Tube and the Vacuum Housing

Experimental Procedure

At the start of an experiment, the end of the ¾" Tygon® tubing was firmly inserted into the mouth of the upper funnel. The valve in the city water line was fully opened at the maximum flow rate to start each of the experimental runs in order to purge the venturi meter of all air. After starting at maximum flow rate the valve in the city water line was used to adjust the flow rate to the desired levels.

The flow rate was measured experimentally by removing the end of the ¾" Tygon® tube from the upper funnel and directing the flow into a tared 4 liter flask. The flow was timed using a stopwatch, and the mass of the collected water was measured using an electronic scale. Additional measurements included the height of the water in the inlet line manometer and the vacuum reading at the center of the venturi.

Experimental Data and Measured Flow Rate

Table 1 shows the experimental data and calculated mass flow rates for the six runs.

Table 1. Experimental Data and Calculated Flow Rates

Run	Mass of Water (g)	Measured Time (s)	*Calculated Flow Rate (g/s)*	Manometer Reading (in water)	Venturi Pressure (mm Hg)	Absolute Venturi Pressure (kPa)*
1	4892	7.01	698	91.75	- 317	54.7
2	4861	9.03	538	61	- 189	72.4
3	4659	13.52	345	40.5	- 95	84.3
4	4628	8.19	565	75	- 261	62.1
5	4680	7.26	645	89	- 310	55.6
6	17064	25.00	683	87	- 310	54.0

*Barometric pressure was 725 mm Hg

Model Development

The modified Bernoulli Balance (commonly called the mechanical energy balance)**,** its development and use is explained by Cengal *et al.*[18]

$$\frac{v_1^2}{2g} + H_1 + \frac{P_1}{\rho g} + H_p = \frac{v_2^2}{2g} + H_2 + \frac{P_2}{\rho g} + H_t + H_f \qquad (1)$$

The velocity, pressure and elevation terms are applicable at the defined entrance (point 1) and exit (point 2) of the system, and the pump, turbine and friction terms occur anywhere within the defined system. As was noted earlier, the modified Bernoulli balance must be applied three times to model the venturi flowmeter; thus, the entrances and exits of the three systems will change as the Bernoulli balance is applied to different systems. The inlet and exits of the three systems are defined as

System	Inlet	Point In system	Outlet	Point In system
Inlet line	Tube entrance	1	Tube exit	2
Venturi	Tube exit	2	Venturi	3
Venturi system	Venturi entrance	2	Water level in pail	4

Inlet Line Friction Loss

The Bernoulli balance was applied to the inlet line (i.e., the ¾ in (1.9 cm) x 70 in (180 cm) line) to determine the pressure at the outlet of the inlet tube, and, thus, the pressure at the inlet of the venturi meter. The fluid velocity within the inlet line is determined from the continuity equation

$$v_1 = \frac{M_1}{\rho A_1} \qquad (2)$$

where $$M_e = \frac{m}{t} \qquad (3)$$

and $$A_1 = \frac{\pi D_t^2}{4} \qquad (4)$$

There is no pump or turbine and $v_1 = v_2$; thus,

$$P_2 = \rho g \left(H_1 - H_2 + \frac{P_1}{\rho g} - H_f\right) \qquad (5)$$

where $$H_f = \frac{f L_t v_1^2}{2 g D_t} \qquad (6)$$

The friction factor, f, may be determined from McCabe *et al.*,[19] for a smooth tube

$$f = 0.0014 + \frac{0.125}{Re^{0.32}} \qquad (7)$$

and $$Re = \frac{v_1 D_t \rho}{\mu} = \frac{v_t D_t \rho}{\mu} \qquad (8)$$

Flow Rate Determination by Venturi Measurements

With no pump or turbine and friction losses ignored in the inlet funnel, the balance becomes

$$\frac{v_2^2}{2g} + H_2 + \frac{P_2}{\rho g} = \frac{v_3^2}{2g} + H_3 + \frac{P_3}{\rho g} \qquad (9)$$

Thus, $$v_3 = \left[2g\left(\frac{v_2^2}{2g} + H_2 + \frac{P_2}{\rho g}\right) - H_3 - \frac{P_3}{\rho g}\right]^{1/2} \qquad (10)$$

This calculated throat velocity, v_3, is used in determining the calculated mass flow rate as determined by the venturi flow rate measurement

$$M_3 = M_c = v_3 \rho A_3 \tag{11}$$

where $A_3 = A_t = \frac{\pi D_3^2}{4} = \frac{\pi D_t^2}{4}$ (12)

The calculated mass flow rate is to be compared with the experimental mass flow rate to determine the discharge coefficient of the venturi meter, where the discharge coefficient is defined as

$$C_d = \frac{M_3}{M_e} = \frac{M_c}{M_e} \tag{13}$$

Correlation for Permanent Pressure Loss by Performing an Overall Bernoulli Balance

Applying the Bernoulli balance to the system defined as that contained between point 2 (the entrance of the venturi meter) and point 4 (the free surface of the water in the pail) allows the determination of the friction losses within the venturi meter. Equation (1) reduces to

$$\frac{v_2^2}{2g} + H_2 + \frac{P_2}{\rho g} = H_4 + H_f \tag{14}$$

Thus, $H_f = \frac{v_2^2}{2g} + H_2 + \frac{P_2}{\rho g} - H_4$ (15)

Minor losses for fluid fittings and devices are normally correlated by determining the head loss by multiplying a minor loss coefficient by a characteristic velocity head. In this case, the appropriate characteristic velocity head is the velocity head at the venturi throat (i.e., point 4)

$$H_f = H_{minor\ loss} = K\left(\frac{v_v^2}{2g}\right) = K\left(\frac{v_3^2}{2g}\right) \tag{16}$$

Thus, $K = \frac{H_f}{\left(\frac{v_v^2}{2g}\right)} = \frac{2gH_f}{v_v^2}$ (17)

Reduced Results and Discussion

The calculated results are summarized in Table 2, and the calculations required to reduce the data are shown in an appended Excel program. The experimental mass flow rate is compared to the mass flow rate determined from the Bernoulli balance, showing an average error of 12.5%. The experimental discharge coefficient ranged from 0.82 to 0.92, with the average of 0.88. This discharge coefficient may be compared with discharge coefficients for very well designed venturi meters which, according to McCabe *et al.*,[19] "….is about 0.98 for pipe diameters of 2 to 8 in and about 0.99 for larger sizes." The minor loss coefficient varied from 0.27 to 0.33, with an average of 0.28; thus, the permanent pressure loss is about 28% of the velocity head within the throat of the venturi. When compared with the recommendation of McCabe *et al.*,[19] regarding pressure loss, "typically 90% of the pressure loss in the upstream cone is recovered."

Table 2. Results for the Mass Flow Measurements and for the Minor Loss Coefficient

Run	Experimental Mass Flow Rate (M_e) (kg/s)	Calculated Mass Flow Rate (M_c) (kg/s)	Mass Flow Error, (M_c vs. M_e)	Orifice Coefficient, C_d	Venturi Minor Loss Coefficient, K
1	0.698	0.762	8.46 %	0.916	0.283
2	0.538	0.578	6.84 %	0.931	0.288
3	0.345	0.415	17.0 %	0.831	0.327
4	0.565	0.687	17.7 %	0.822	0.279
5	0.645	0.754	14.5 %	0.855	0.284
6	0.697	0.760	10.6 %	0.917	0.267
Average			12.5%	0.879	0.288

Conclusions

1. The experiment is an excellent teaching tool because it involves application of three separate Bernoulli balance to reduce the experimental data.
2. The inexpensive venturi meter is not nearly as efficient as a well-designed venturi meter.
3. C_d was in the range of 0.88 and, for a well-designed venturi meter, $C_d \approx 0.98$.
4. The pressure loss is about 30% of the velocity head within the verturi throat; a well-designed meter would experience a 10% loss of the throat velocity head.
5. A more complete experimental program, with several more experimental runs and more duplicate runs, would result in less scatter in the results.

Nomenclature

Latin Symbols

A_t	Area of the Tygon® tube, m^2
A_v	Area of the throat of the venturi, m^2
$D_t = D_1$	Diameter of the Tygon® tube, m
$D_v = D_3$	Diameter of the throat of the venturi, m
g	Gravitational constant, m/s^2
H_1	Elevation of the laboratory floor, 0 m
H_2	Elevation of the exit of the ¾” Tygon® feed tube above the floor, 0.63 m
$H_3 = H_v$	Elevation of the venturi above the floor, 0.48 m
H_4	Elevation of the water level in the 5 gallon pail above the floor, 0.43 m
H_f	Friction loss in the defined system, m fluid
L_t	Loss in the ¾” Tygon® tube, m
M_c	Calculated mass flow rate of the water through the system, kg/s
M_e	Experimental mass flow rate of the water through the system, kg/s
P_1	Pressure at Point 1 in the system, i.e., the tube entrance, m water
P_2	Pressure at Point 2 in the system, i.e., the tube exit, m water
P_3	Pressure at Point 3 in the system, i.e., the venturi throat, m H_2O

P_4	Pressure at Point 4 in the system, i.e., the water level in the pail, m water
$v_1 = v_v$	Velocity at Point 1 in the system at the tube entrance, m/s
$v_2 = v_v$	Velocity at Point 2 in the system at the tube exit, m/s
$v_3 = v_v$	Velocity at Point 3 in the system in the venturi throat, m/s
v_4	Velocity at Point 4 in the system at the water surface in the pail, ≈ 0 m/s
v_t	Velocity in the Tygon® Tube, m/s

Greek Symbols

μ	Viscosity of water, kg/m s
ρ	Density of water, kg/m^3

Dimensionless Parameters

f	Friction factor
Re	Reynolds number, $\frac{v_{tD_t}\rho}{\mu}$
K	Minor loss coefficient for friction losses in the venturi meter, $K = \frac{H_f}{\left(\frac{v_v^2}{2g}\right)}$

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Biographical Information

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Ms. Foley, Mr. Thompson and Ms. Williams are currently seniors (juniors when the lab work was performed) in Chemical Engineering at the University of Arkansas. Their lab reports in CHEG 3232 were selected as a source of material for this paper.

W. Roy Penney

Dr. Penney currently serves as Professor Emeritus of Chemical Engineering at the University of Arkansas. His research interests include fluid mixing and process design, and he has been instrumental in introducing hands-on concepts into the undergraduate classroom. Professor Penney is a registered professional engineer in the state of Arkansas.

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Dr. Clausen currently serves as Professor, Interim Department Head and the Ralph E. Martin Leadership Chair in Chemical Engineering at the University of Arkansas. His research interests include bioprocess engineering, the production of energy and chemicals from biomass and waste, and enhancement of the K-12 educational experience. Professor Clausen is a registered professional engineer in the state of Arkansas.

Appendix: Screenshot of the Excel Data Reduction Program

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1		m	t	M_e	v_t	Re	f	Hf	Hm	P_1	P_2	Pvmm	P_v	v_v	M_c	Error	Hf_v	Kv	
2		4891.5	7.01	0.698	2.45	46637.9	0.0216	0.619	91.75	119755.5	107525	-317	54664.9	10.7	0.762	-8.46	1.642	0.2804	
3		4861	9.03	0.538	1.89	35979.3	0.023	0.392	61	112095.9	102088.4	-184	72397.6	8.13	0.578	-6.84	0.962	0.286	
4		4659.2	13.5	0.345	1.21	23033	0.0257	0.179	40.5	106989.6	99065.43	-95	84263.9	5.84	0.415	-17	0.546	0.3143	
5		4628.4	8.19	0.565	1.99	37771.3	0.0228	0.427	75	115583.2	105233.1	-261	62131.3	9.66	0.687	-17.7	1.302	0.2739	
6		4680.3	7.26	0.645	2.27	43087.6	0.022	0.539	89	119070.5	107629.5	-310	55598.2	10.6	0.754	-14.5	1.608	0.2807	
7		17064.1	25.1	0.679	2.39	45402.4	0.0218	0.591	87	118572.3	106622.1	-322	53998.2	10.7	0.76	-10.6	1.534	0.2637	
8											DEFINITION OF TABLE VARIABLES								
9	g	9.81	= Earth gravity, m/s^2								Hm = Water manometer reading at tube inlet, in H2O								
10	ρ	998	= Water density, kg/m^3								v_t = m/(1000*t); = Water velocity, inlet tube, m/s								
11	Dt	0.01905	= ID inlet tube, m								Re = v_t*Dt*ρ/μ; = Reynolds number in the inlet tube								
12	Dv	0.009525	= ID venturi, m								f = 4*(0.0014+0.125/Re^0.32); Friction factor in the inlet tube								
13	At	0.000285	= Cross-sectional area inlet tube, m^2								Hf = f*(Lt/Dt)*v_t^2/(2*g); Head loss in the inlet tube, mH2O								
14	Av	7.13E-05	= Cross-sectional area venturi throat, m^2								P_1 '= Hm*249.09 + Patm; Pressure at the inlet tube inlet, Pa								
15	μ	0.001	= Dynamic viscosity water, kg/m s								P_2 = ρ*g*(H_1-H_2+P_1/(ρ*g)-Hf); Pres., tube exit, Pa								
16	H_1	0	= Height. Lab. floor, m (this is the datum elevation)								P_v = ((727+Pvmm)/727)*101330*(727/760); Pres., v. throat, Pa								
17	H_2	0.63	= Height, venturi inlet (i.e., tube outlet) above floor, m								v_v = (2*g*(v_t^2+H_2+P_2/(ρ*g)-H_3-P_v/(ρ*g)))^(1/2)								
18	H_3	0.48	= Height, venturi throat above the floor, m								M_c = ρ*Av*v_v; Mass flow water, calculated, kg/s								
19	Lt	1.778	= Length of the inlet tube, m								Error = 100*(M_e - M_c)/M_c; % Difference, exp. vs. calc.								
20	Patm	96901.45	= (727/760)*101300; Atm. Pres., barometer reading, mmHg								m = Mass of collected water for flow measurement, kg								
21											t = Elapsed time for water flow measurement, s								
22											M_e = Experimental mass flow rate of water, kg/s								
23											Hf_v = v_t^2/(2*g)+H_2+P_2/(ρ*g)-0.38-Patm/(ρ*g); v. loss, m H2O								
24											Kv = Hf_v/(v_v^2/(2*g)); Venturi loss coefficient								