Comparison of Selected Differential-Producing, Ultrasonic, and Magnetic Flow Meters

JOHNNY B. PRETTYMAN,[1] MICHAEL C. JOHNSON,[2] AND STEVEN L. BARFUSS[2]

[1]Tierra Group International, Salt Lake City, Utah
[2]Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah

Selecting the best flow meter for a specific application can be challenging because of the many types and designs of flow meters, with each having its own merits and drawbacks. Illustrating these specific benefits and drawbacks can help the buyer select the meter best suited for the desired application. The flow meters investigated in this research include five designs of differential-pressure meters (i.e., differential-producing), a magnetic flow meter, and an ultrasonic flow meter. The differential meters included the Venturi designs, the wedge flow meter, and the V-cone meter. Testing was completed at the Utah Water Research Laboratory to quantify the accuracy and head loss (pressure loss) of each meter design. The meter longevity and life cycle costs were determined from manufacturer-supplied information and literature reviews. Although this list is not all-inclusive, this study was designed to assist those responsible for selecting a flow meter for their specific application.

Keywords: *accuracy, discharge coefficients, flow meter types, flow meters, head loss*

For many applications, there is a process that requires precise measurement of the fluid flow rate—examples include petroleum, water/wastewater supply and management, industrial processes, food processing, pharmaceuticals, and power generation. For these applications, it is essential to have accurate and precise flow measurements; otherwise, serious problems could occur, including defective products, loss of revenue, damage to systems, process inefficiencies, or potential danger to the public. There are many types of flow meters that can accurately measure flow, and each type has its merits and drawbacks. Those making meter application decisions should be educated about flow metering and the merits and drawbacks of each meter type. Important considerations include accuracy across a range of flows, pressure loss, construction materials, fluid characteristics, meter longevity, and life cycle costs.

The meters used in this study were provided by four manufacturers. Some manufacturers donated the meters knowing they were to be used in the study; the remaining meters were purchased through normal supply channels. Seven meters were used for this study: three designs of Venturi meters (classical,[1] Halmi,[2] and HBX[3]), a wedge meter,[4] a V-cone meter,[5] an ultrasonic meter,[6] and a magnetic meter.[7]

The flow meters tested consisted of three metering technologies: magnetic, ultrasonic, and differential pressure (i.e., differential-producing). The function of the magnetic flow meter is based on Faraday's law of electromagnetic induction in which the sensor converts the conductive flow into an electrical voltage proportional to the velocity of the flow (Siemens A/S 2010). For the purposes of this study, a coefficient (C), which is the ratio of indicated flow rate to actual flow rate, was used for the ultrasonic and magnetic meters for comparative purposes.

The ultrasonic meter used for this research is a strap-on portable flow meter that functions by sending ultrasonic wave pulses from the upstream sensor of the meter to the downstream sensor. The difference in time (transit time) it takes to travel is caused by flow velocity and is used to calculate the flow rate (Fuji Electric 2013).

All differential-pressure flow meters require a flow-area constriction to create a differential pressure that varies consistently with flow. These meters use the differential pressure across high- and low-pressure taps to infer the flow rate on the basis of Bernoulli's theorem and the conservation of mass. The differential meters included the three Venturi designs, the wedge flow meter, and the V-cone meter. The classical and Halmi Venturi flow meters are constricted by reducing the diameter of the pipe in a conical shape. The HBX Venturi meter has an abrupt change of diameter. The wedge flow meter constriction is a wedge placed in the meter. The V-cone has a cone placed in the flow area and forces the water to flow around it. All of these constrictions create a differential pressure that is used to infer the flow rate. Figure 1 shows each of the differential-pressure meters. All of the differential meters in this research have similar beta ratios (β), which is the ratio of the diameter (or equivalent diameter in the case of the V-cone and wedge meters) at the constriction to the pipe or meter inlet diameter.

Differential-pressure meters require a coefficient to determine the actual flow rate, known as a discharge coefficient (C_d). The C_d is the ratio of actual flow rate to theoretical flow rate. Meters generally have a predictable C_d at high Reynolds numbers (Re), but at a lower *Re*, the C_d has not been well documented. The *Re* is the ratio of inertial forces to viscous forces, and it decreases as velocity decreases or viscosity increases. The *Re* is useful because the C_d is the same for all fluids at identical *Re*. To achieve low *Re* in this study, the velocity was decreased and the corresponding C_d was calculated. The total expected *Re* range of the C_d is important to know for measuring low flows or leaks. Processes, such as oil production and related slurries, require low *Re* measurements, and it is essential to know how the meter will perform under the range of conditions into which it will be installed. This article provides important insight for C_d values at low *Re* values as well as normal *Re* ranges. *Re* is defined as

$$Re = \frac{DV}{\nu} \tag{1}$$

where V is the average velocity of the fluid at the inlet of the meter in ft/s or m/s; ν is the kinematic viscosity of the fluid in ft^2/s or m^2/s; and D is the inside diameter of the meter inlet or upstream pipe in ft or m.

Differential-pressure flow meters add head loss to the system; the amount of loss is dependent on the type of meter used and its design. Because each meter design has different performance characteristics, testing is required to determine the precise head loss. The head loss associated with any flow meter results in additional pumping costs or hydraulic constrictions that can be significant, depending on the system and the meter design. Magnetic and ultrasonic meters can add head loss and length to the system when the diameters are slightly different. The applicability of any meter not only depends on metering performance, but also on lifetime and associated costs of the meter and its maintenance.

This article discusses the performance of the previously mentioned meters based on C_d or C performance, head loss, useful life, and associated costs. The observations from this study will provide additional information to those selecting meters and therefore will be able to assist in selecting a meter that is most appropriate for the user's specific applications.

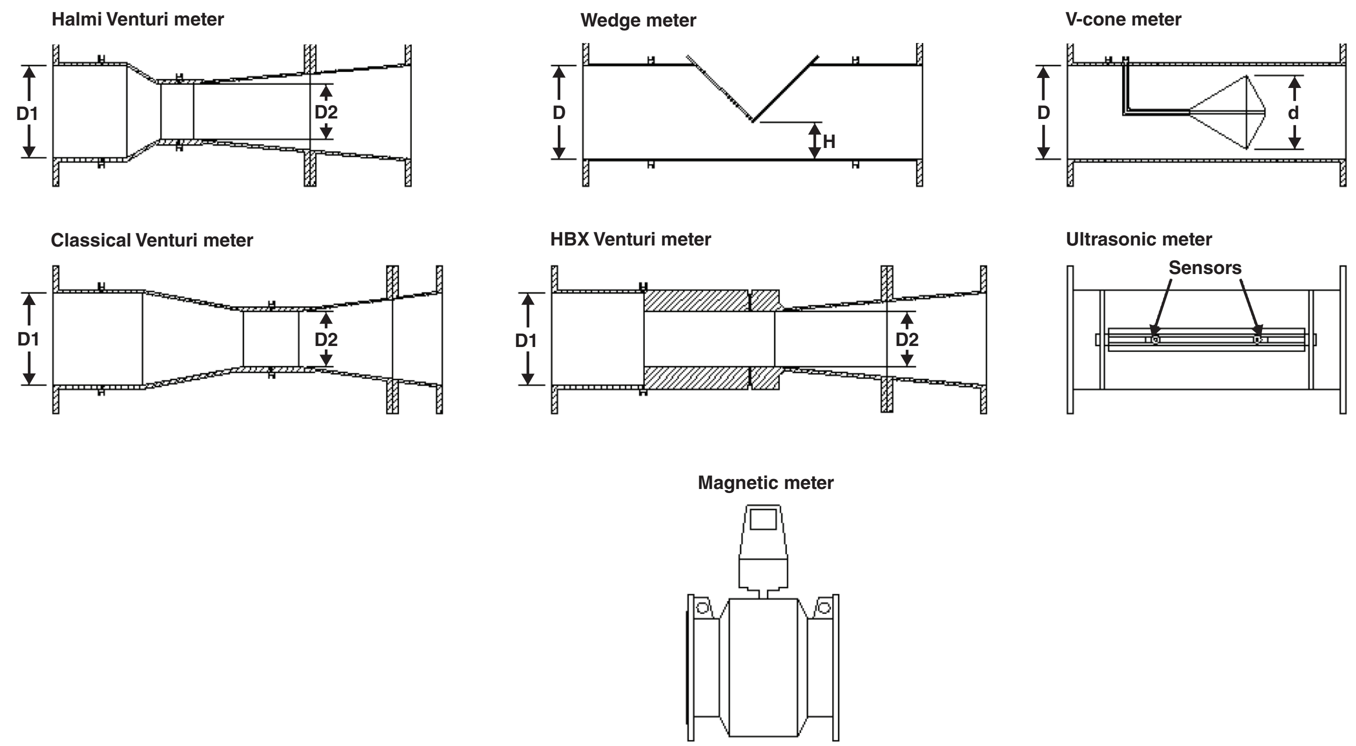
BACKGROUND

Theoretical background. To infer flow for differential-pressure flow meters, Bernoulli's theorem coupled with the conservation of mass is used where energy between the high-pressure tap (location 1) and the low-pressure tap (location 2) are conserved. Volumetric or mass flow rates can be obtained using the conservation of mass coupled with Bernoulli's theorem. A C_d is used to account for real energy losses between the high- and low-pressure taps; thermal expansion is also considered. For liquid applications, the equation is given as

$$Q = A_2 \frac{\sqrt{2g\Delta H}}{\sqrt{(1 - \beta^4)}} C_d F_a \tag{2}$$

where Q is volumetric flow rate in ft^3/s or m^3/s; A_2 is the area at the throat based on the throat diameter or equivalent diameter in ft^2 or m^2; ΔH is the differential pressure in ft or m; g is the

FIGURE 1 Flow meters



gravimetric constant in ft/s^2 or m/s^2; C_d is the discharge coefficient; and F_a is the thermal expansion factor, which, for this study, is equal to 1.00.

The equation for β of each differential-pressure meter differs. For the Venturi meters, β is calculated the using Eq 3, with D_2 being the diameter of the throat and D_1 being the diameter of the inlet of the meter. For the wedge meter and the V-cone, Eqs 4 and 5 are used to calculate β, respectively (Miller 1996).

$$\beta_{\text{Venturi}} = \frac{D_2}{D_1} \tag{3}$$

$$\beta_{\text{wedge}} = \frac{\mathrm{d_e}}{\mathrm{D}} = \left(\frac{1}{\pi} \left\{ \arccos\left[1 - \frac{2H}{D}\right] - 2\left[1 - \frac{2H}{D}\right]\left(\frac{H}{D} - \left[\frac{H}{D}\right]^2\right)^{½} \right\} \right)^{½} \tag{4}$$

where D is the inner diameter of meter in ft or m; H is the segment height in ft or m; and d_e is the equivalent diameter in ft or m.

$$\beta_{\text{V–cone}} = \frac{d_e}{D} = \sqrt{1 - \frac{d^2}{D^2}} \tag{5}$$

where d is the diameter of the cone in ft or m.

Eqs 6 and 7 can be used to calculate flow for the magnetic meter and ultrasonic meters. Depending on the meter's output settings, the outputs are frequency, pulses, or mA:

$$Q_{\text{magnetic}} = \frac{Range}{Hz_{\text{max}}}\, Hz \tag{6}$$

$$Q_{\text{ultrasonic}} = \frac{Range}{16}\,(mA - 4) \tag{7}$$

where *Range* is the maximum flow rate to be metered, Hz_{max} is the hertz corresponding to maximum range, and mA is milliamps (usually ranging from 4 to 20 mA, corresponding to 0 and maximum flow).

Discharge coefficients. A wide range of C and C_d versus Re was tested in this study. C_d has been well documented at high Re values for each differential producer. However, there is little physical research available for C_d values at low Re because of difficulties with measuring such low flows and associated differential pressures accurately. Many studies have reported research for lower Re values with computational fluid dynamics, and some will be addressed in the following paragraphs.

Table 1 shows the manufacturers' predicted or previously researched C_d or C values and the variation for a range of Re or velocity for all meters. The literature describes the geometry of each meter, including wedge angles and β; the literature selected contains meters with similar β to flow meters in this article.

The magnetic and ultrasonic meters also have little research regarding low-flow accuracy except for what manufacturers report. One manufacturer has reported that the magnetic meter has good accuracy at low flow to measure leaks (Siemens A/S 2010). Of course, other magnetic and ultrasonic meters may have different performance characteristics from those presented in this study.

Head loss. Limited research has been conducted for head loss for differential-pressure flow meters. Miller (1996) developed equations for Venturi, Lo-Loss tubes, nozzles, orifices, Annubars, Pitot, and target flow meters. The head loss for the Venturi meter is dependent on β and differential pressure for $Re > 6{,}000$.

The providers of the differential-pressure meters have each made statements as to how much head loss their meter creates. As reported, the classical Venturi meters are expected to have a head loss ranging from 5 to 20% of the differential pressure across the pressure taps and depend on the β ratio, inlet geometry, throat length, and the recovery cone geometry (PFS 2009). The Halmi Venturi is reported to have head loss of 3% and greater (PFS 2012a); the HBX Venturi is reported to have modest head loss that falls between that of the Halmi Venturi and an orifice plate (PFS 2013). One manufacturer's website indicates that the head loss is low (but not quantified) and is dependent on the differential pressure and β ratio (McCrometer Inc. 2014). The magnetic and ultrasonic meters can have head loss associated with their length and, in some cases, from diameters slightly smaller than the pipe into which they are installed. The ultrasonic meter, depending on the design, will not introduce any additional loss if attached directly to the exterior of the system piping. For this study, the ultrasonic meter was attached externally to a pipe, adding 3 ft to the system and therefore causing head loss. The head losses of the magnetic and ultrasonic meter designs are minimal compared with the differential producers because there are no intrusive components.

Lifetime of meters. The lifetime of the meters was determined by contacting the meters' manufacturers and local sales representatives. These values are based on general lifetimes for all applications. Depending on the application, the meter will need to be built and protected accordingly for harsh, corrosive, or mild fluids. The meters' accuracy is precise over the lifetime of the meter and tends to decrease after subjection to harsh or abrasive media, although some are as accurate as new meters in a few cases, as will be discussed in the following paragraphs.

The wedge meter lifetime expectancy is 20 to 40 years and depends on the material selected and the harsh types of media applications for which the wedge meter is typically used (e.g., slurry-type flows). There are wedge meters that are still in service after 30 years that have been inspected and put back into service (Briggs 2014).

The life expectancy for the Venturi meters is 75 to 100 years depending on the material selection and media. There are thousands of Venturi meters in use around the world that are 50 to 125 years old and still perform well. Venturi meters have a natural self-cleaning action in which acceleration occurs between the inlet and throat. This acceleration can prevent and remove buildup on the meter (Briggs 2014). The Utah Water Research Laboratory (UWRL) recently tested a cast iron Venturi meter that was more than 90 years old and had a near-pristine bronze throat; however, the inlet coating was bubbling from corrosion between the meter body and the coating. Even with the poor inlet conditions, this meter calibrated to within 2% of the stated discharge coefficient. Repairing the inlet liner would return the meter to near-new condition.

The anticipated lifetime of the V-cone meter is 15 to 20 years or more based only on how long the meters have been in the field so far; the V-cone has been in production for only 20 years. The lifetime of the meter may be longer, but this has yet to be seen (Stone 2014).

The differential-pressure meters do not have a direct output reading; consequently, a separate device is required to read differential pressure. For this research, differential pressure transmitters were used. It has been reported that the differential pressure transmitters have a lifetime of 15 years (Cureton 2014).

The average life for the ultrasonic meter in continuous use is five to six years. Under proper conditions, the battery can last up to 10 years, and the LCD screen normally lasts five to 10 years. These values are typical results and do not include how the performance of the meter changes over its lifetime (Glanville 2014).

The lifetime of the magnetic meter is approximately 10 years for the tube and five years for the transmitter electronics. The lifetime can increase or decrease depending on the application of

TABLE 1 Discharge coefficients review

	Meter	Author	Data Type	*Re* Range	Velocity Range	β	Wedge Angle *degrees*	Average C_d	C_d/C Variance %
	Wedge	PFS 2012b	Physical	Unlimited	—	—	—	—	±0.50 (when calibrated)
		Yoon et al. 2007	Physical	12,000–380,000	—	0.5023	90	0.813	Approximately ±0.50
					—	0.6112	90	0.797	
					—	0.7071	90	0.786	
					—	0.7915	90	0.832	
					—	0.8647	90	0.930	
		Buhidma & Pal 1996	Physical	~500–100,000	—	0.8647	60	~0.89	±5.00
					—	0.7071	60	~0.73	
					—	0.8647	90	~0.93	
					—	0.7071	90	~0.80	
		Banchor et al. 2002	CFD	37,100	—	0.7071	60	0.655	N/A
					—	0.7071	90	0.678	N/A
		Hollingshead 2011	CFD	500–50,000,000	—	0.5023	90	0.7312	±0.22
					—	0.5023	90	0.7285	±0.35
					—	0.6110	90	0.7010	±0.60
	V-cone	McCrometer Inc. 2014	Physical	≥8,000	—	—	—	—	±0.50
		Singh et al. 2006	Physical	1,250–218,000	—	0.64	—	0.7256	±1.78
				1,500–254,000	—	0.77	—	0.7315	±1.97
		Hollingshead 2011	CFD	4,000–50,000,000	—	0.6611	—	0.7903	±2.73
					—	0.6955	—	0.7788	±2.38
					—	0.8203	—	0.7297	±1.13
Venturi	Classical	PFS 2009	Physical	200,000–6,000,000	—	—	—	—	±0.25 (when calibrated)
	Halmi	PFS 2012a	Physical	>75,000	—	—	—	—	±0.25 (when calibrated)
	HBX	PFS 2013	Physical	>6,000	—	—	—	—	±0.25 (when calibrated)
	Classical	Stobie et al. 2007	Physical	50,000–100,000	—	0.6270	—	0.9735	±0.35
	NA	Miller et al. 2009	Physical	500–24,000	—	NA	—	NA	<2.00–4.00
	Smooth	Hollingshead 2011	CFD	100,000–50,000,000	—	0.661	—	0.9762	±0.26
	Sharp	Hollingshead 2011	CFD	100,000–50,000,000	—	0.661	—	0.9658	±0.28
	Magnetic	Siemens A/S 2010	Physical	—	3–10 ft/s	—	—	—	±0.20
	Ultrasonic	Fuji Electric 2013	Physical	—	<0.3 m/s	—	—	—	±1.00

β—beta ratio, C_d—discharge coefficient, CFD—computational fluid dynamics, NA—not available, *Re*—Reynolds number the meter, such as harshness of the fluid or if the meter is submerged (Harper 2014).

As expected, when a meter's effective life is over or if the meter fails, the buyer can seek to either repair or replace the meter. One advantage to the differential-pressure flow meters is that the buyer can visually inspect the meter, observe the state of the meter, and determine whether repair or replacement is necessary. The ultrasonic and magnetic meters, when failing, are difficult to fix because the user will generally not know what electronic component is causing the failure or how to fix it. Consequently, a professional would need to assist in repairing these electronic flow meters.

Costs of meters. The 2014 meter costs were found by contacting the providers and local distributors. The average costs for 12-in. meters are as follows and can vary significantly depending on materials and size used for construction:

- 12-in. wedge meter: $4,000
- 12-in. Halmi Venturi meter: $5,000
- 12-in. HBX meter: $6,000
- 12-in. classical Venturi meter: $5,700
- 12-in. V-cone meter: $4,000–5,000
- Ultrasonic strap-on meter: $6,550
- 12-in. magnetic meter: $5,100
- Pressure transmitter: $1,400

CALIBRATION PROCEDURE

To calculate the C_d, C, and head loss of each meter during this study, a 12-in. pipeline was installed so that meter calibrations could be performed at UWRL. The pipeline was 12-in. steel standard wall, with more than 20 diameters of straight upstream pipe and more than 10 diameters of straight downstream pipe. Water was discharged into a National Institute of Standards and Technology traceable weight tank that was used to calculate the volumetric flow rate. Water (at an average temperature of 48°F) was the medium for the tests and was supplied by a reservoir having approximately 35 ft of head. Some very low-flow tests were also conducted with a constant-level tank that supplied approximately 12 ft of head. To calculate the head loss across the meters, pressure transmitters were attached to pressure taps located two and six diameters upstream (high) and downstream (low), respectively, from the inlet and exit of the meter.

The differential pressure across the meters was measured using pressure transmitters attached to the high and low taps located on the differential pressure meters. With the flow and differential pressures precisely measured, the C_d was calculated using Eq 8 for the Venturi, V-cone, and wedge meters. β is specified for each differential-pressure meter in Eqs 3–5. The magnetic meter output was in hertz and the ultrasonic meter output was in milliamps. The C for the magnetic and the ultrasonic meters were calculated using Eq 9 (Miller 1996).

$$C_d = \frac{Q\sqrt{(1-\beta^4)}}{A_2\sqrt{\Delta H 2g}} \tag{8}$$

$$C = \frac{Q_{\text{actual}}}{Q_{\text{indicated}}} \tag{9}$$

where $Q_{\text{indicated}}$ is the flow inferred by the magnetic or ultrasonic flow meter (with the gpm as given in Eqs 6 and 7) and Q_{actual} is the flow calculated from weight and time.

The range of the testing was 4,000–1,200,000 Re (0.06–18.9 ft/s) based on the upstream pipe diameter or meter inlet diameter with water being the test fluid.

RESULTS AND DISCUSSION

The results from this study are presented in graphical form as C_d versus Re and head loss versus flow. The differential meters had β ratios that were approximately 0.60 and are as follows:

- Wedge: $\beta = 0.5940$
- V-cone: $\beta = 0.5960$
- Classical Venturi: $\beta = 0.6044$
- Halmi Venturi: $\beta = 0.6024$
- HBX Venturi: $\beta = 0.6024$

Discharge coefficient results. The general trend for all the differential-pressure meters was to reach a relatively constant C_d for $Re > 100{,}000$ (velocity [V] > 1.6 ft/s). For $Re < 100{,}000$ ($V < 1.6$ ft/s), the behavior of the C_d is different for all meters. The maximum uncertainty at 95% confidence intervals for the data of $Re > 100{,}000$ ($V > 1.6$ ft/s) was ±0.42%. The results are specific to the meters tested in this study and do not apply to all flow meters of similar types. The predicted C_d rates provided by the manufacturers for each meter are predictions and approximations based on geometry of the meters and known C_d from past calibrations. In general, when meters are calibrated, the C_d does not match exactly to the predictions.

The water temperature was consistent for all flow meter tests, which resulted in a V versus C identical to Re versus C. Both comparisons are shown as results for preference.

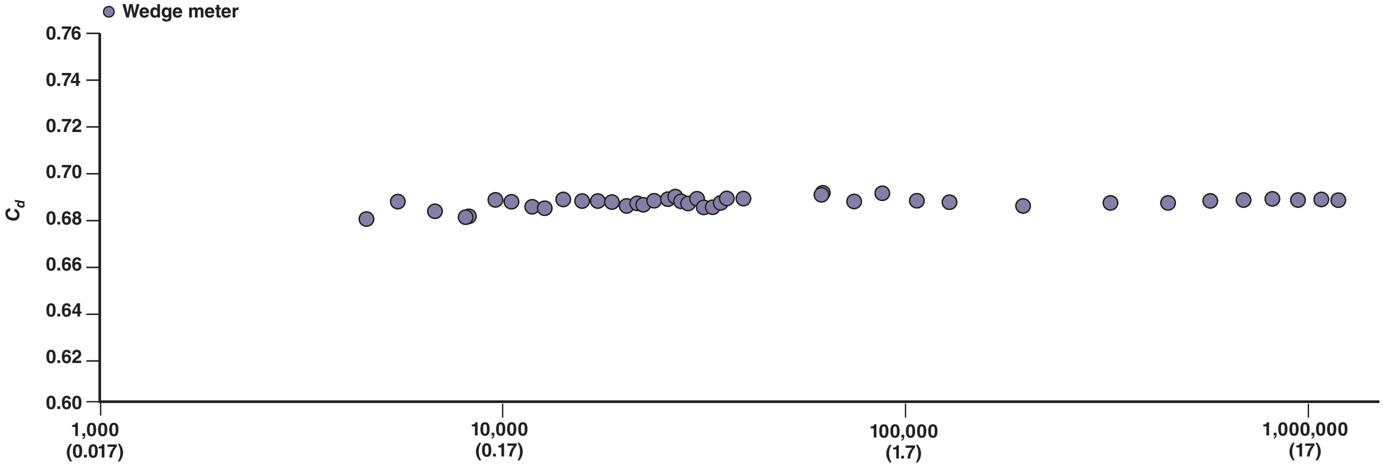
Wedge meter. The wedge C_d average was consistent to within ±1.02% for $Re > 4{,}600$ ($V > 0.07$ ft/s) but has more scatter at lower Re as shown in Figure 2. The wedge meter had an average C_d of 0.6876 ± 1.02% over the entire range of the experiment. The average C_d from $Re > 100{,}000$ ($V > 1.60$ ft/s) was 0.6882 ± 0.29%. The manufacturer's prediction was 0.6987, which is 1.61% higher than the average C_d of the wedge meter tested. The manufacturer indicated that it is difficult to accurately predict the C_d for wedge meters because of the slight variations in construction associated with installing the wedge in the flow path. The current work matches the findings of Yoon et al. (2007), Hollingshead (2011), and Buhidma and Pal (1996) for wedge flow meters. Banchor et al. (2002) found a β_{wedge} of 0.7071 for a C_d of 0.6780, which matches closely to the current study. Buhidma and Pal's (1996) research showed a C_d of 0.8 for a β_{wedge} of 0.7071. They further showed that when β_{wedge} decreases, C_d decreases, which would have a C_d approximate to the current research.

V-cone meter. The V-cone meter had an average C_d of 0.8008 ± 0.50% for $Re > 100{,}000$ ($V > 1.30$ ft/s). The turndown of 10:1 for $50{,}000 < Re < 500{,}000$ ($0.64 < V < 6.40$ ft/s) is ±0.47%. Any turndowns below this are greater than a 0.50% variance. From $10{,}000 < Re < 100{,}000$ ($0.13 < V < 1.3$ ft/s), the C_d changed from 0.7908 to 0.8008 and for an $Re < 10{,}000$ ($V < 0.13$ ft/s), the C_d decreases significantly, as shown in Figure 3. The manufacturer predicted an Re of 0.8143 for the meter, which was

1.60% higher than the average C_d for the tested V-cone. The V-cone C_d for $Re \geq 8{,}000$ ($V \geq 0.10$ ft/s) falls outside of ±0.50% as predicted by the manufacturer. The V-cone followed the same pattern as Hollingshead's research (2011). Singh et al. (2006) had an average of 0.7256 over the range of testing for a β ratio of 0.64. The Singh data stayed relatively constant for the entire range, whereas the current study decreased at the lower end of the range. This could be the geometry of the V-cone or the placement of the taps. Not all V-cone meters have the same tap orientation as the V-cone used in this study.

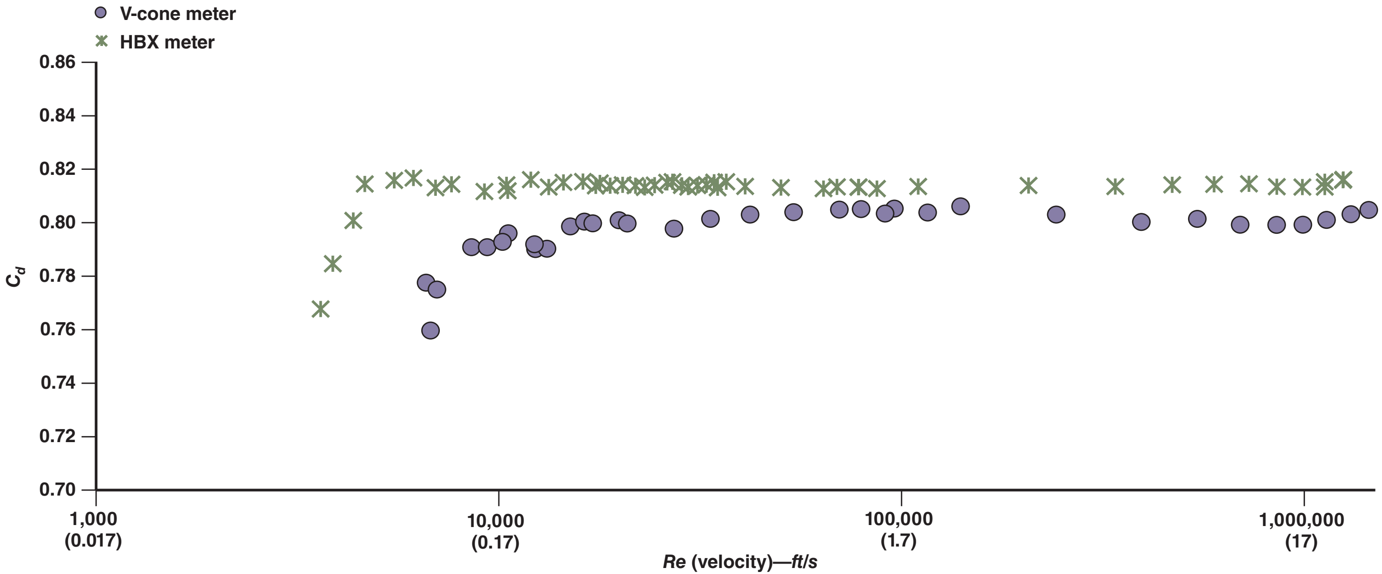
Classical Venturi meter. The classical Venturi approximates 0.99 C_d, as described by the American Society of Mechanical Engineers for $200{,}000 < Re < 6{,}000{,}000$, and had a variance of ±0.25%. The average C_d was 0.9948 ± 0.29% for $Re > 100{,}000$ ($V > 1.70$ ft/s). The C_d then gradually reduced between $10{,}000 < Re < 100{,}000$ ($0.17 < V < 1.70$ ft/s), as shown in Figure 4. Below an Re of 10,000 ($V < 1.70$ ft/s), the C_d reduced significantly. The reduction in the Hollingshead data (2011) occurs at an Re of 75,000, and the current research reduced at an Re of 100,000. This could be a result of the different β ratios, but the shape of the C_d curve appeared similar.

FIGURE 2 Wedge meter coefficients



C_d—discharge coefficient, *Re*—Reynolds number

FIGURE 3 HBX and V-cone meters coefficients



C_d—discharge coefficient, *Re*—Reynolds number

Halmi Venturi meter. The Halmi Venturi meter had a C_d of 0.9862 ± 0.27% for an $Re > 100{,}000$ ($V > 1.70$ ft/s). The C_d then followed a pattern similar to the classical Venturi, seen in Figure 4, as it slowly decreased from $10{,}000 < Re < 100{,}000$ ($0.17 < V < 1.70$ ft/s). The variance of the C_d was slightly above what the manufacturer predicted at ±0.61% for $Re > 75{,}000$ ($V > 1.30$ ft/s) and is close to the predicted C_d of 0.9900. The Halmi had a steeper decline in C_d compared with the classical Venturi. Both the classical and the Venturi matched the C_d curve found by Miller et al. (2009), but had a slightly higher C_d. The higher C_d could be a result of different β ratios because Miller et al. (2009) did not specify the β ratio of the meter for their experiment. The data from Stobie et al. (2007) matched well with the classical and Halmi Venturi meters when using the Re for the throat diameter, except for the hump, which did not exist in the current research.

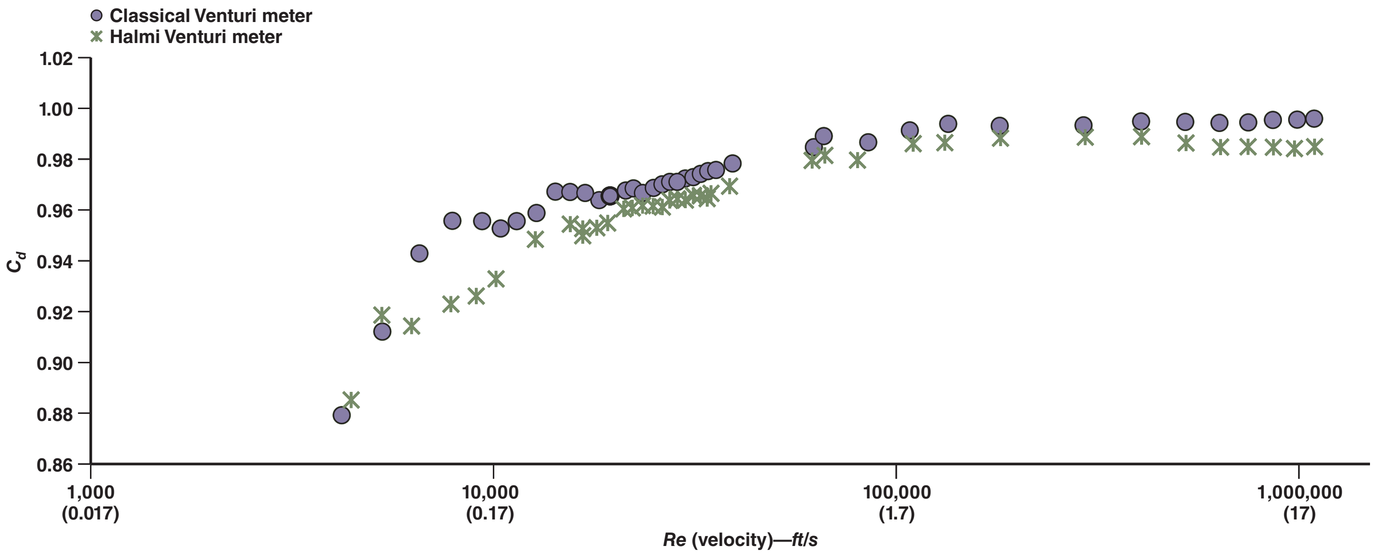
HBX Venturi meter. The HBX Venturi meter had an average C_d of 0.8143 ± 0.23% for an $Re > 100{,}000$ ($V > 1.50$ ft/s). The meter had an average C_d of 0.8141 ± 0.33% from an $Re > 4{,}600$ ($V > 0.07$ ft/s). For an $Re < 4{,}600$ ($V < 0.07$ ft/s), the C_d decreased quickly, as shown in Figure 3. The results were close to the manufacturer's prediction of variance of ±0.25% for an $Re > 6{,}000$ ($V > 0.09$ ft/s); the current work variance was ±0.33% for that range. The HBX Venturi meter's inlet geometry is different from the classical and Halmi Venturi meters. The HBX has a sudden contraction that causes the lower C_d values, whereas the classical and Halmi meters are gradual contractions that produce higher C_d values.

The C_d values found for all differential producing meters were consistent with previous calibrations performed at the UWRL. Although there was only one of each meter tested, it is important to note that the discharge coefficients of each design were consistent with many tests of similarly designed meters. The discharge coefficient results were expected and predictable.

Magnetic flow meter. The magnetic meter had an average C of 0.9945 ± 0.20% over the range of $Re > 100{,}000$ ($V > 1.30$ ft/s). The C was constant until an Re of 19,000 (approximate $V = 0.24$ ft/s) with a variance of 0.34%; below this, the C drops as shown in Figure 5. The magnetic meter matched the specifications provided by the manufacturer. The accuracy of the meter was ±0.14% for the range of $230{,}000 < Re < 800{,}000$ (3–10 ft/s) (Siemens A/S 2010). The accuracy was within the specifications for the range of $Re > 100{,}000$ ($V > 1.30$ ft/s) for the testing at ±0.20%. The C was constant until $Re = 20{,}000$ (approximate $V = 0.26$ ft/s) with an accuracy of ±0.29%. When $Re < 20{,}000$ ($V < 0.26$ ft/s), the accuracy of the magnetic meter drops off. The magnetic meter, after calibration, can be adjusted to have an average C of 1.0 higher than $Re = 20{,}000$ ($V = 0.26$ ft/s) if desired. The magnetic meter tested in this study is not representative for all magnetic meters. Previous calibrations performed at the UWRL have shown identical magnetic meters' C tends to drops more significantly at lower Re than this study found. It is important to note that this was a single calibration of one meter and is not representative of all magnetic meters' performance.

Ultrasonic flow meter. The ultrasonic meter had an average C of 1.0100 ± 2.50% over the entire range of the test. The average C was 1.0127 from $Re > 100{,}000$ ($V > 1.30$ ft/s) ± 0.43%. The manufacturer reports that the meter is ±1.00% accurate for velocities of 0.3 m/s (0.98 ft/s) and greater (Fuji Electric Co. 2013). The results showed for $Re > 60{,}000$ ($V > 0.77$ ft/s) the accuracy of the ultrasonic was ±1.48%. The data would fit the manufacturer's specifications if a high data point were removed at $Re = 82{,}300$ ($V = 1.06$ ft/s), in which case the accuracy would improve to ±0.43%. The C for $Re < 100{,}000$ ($V < 1.30$ ft/s) has a much higher deviation. As the Re increases, the deviation improves, as illustrated in Figure 5. Notable is that the meter was

FIGURE 4 Classical and Halmi Venturi meters coefficients

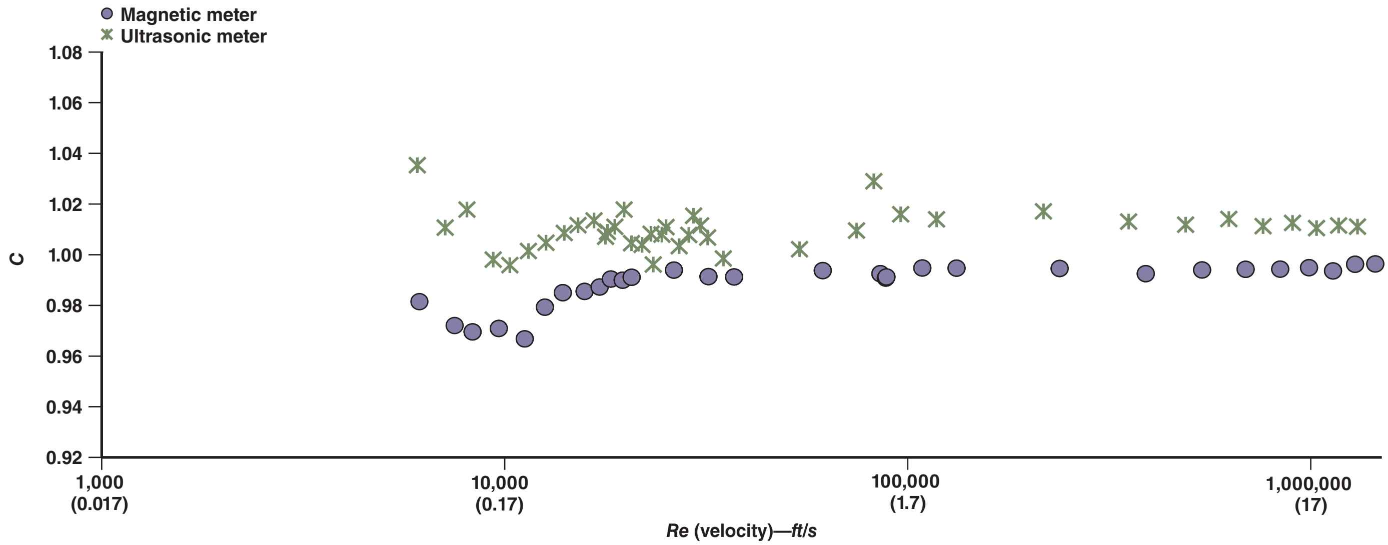


C_d—discharge coefficient, *Re*—Reynolds number a single path strap-on meter; more advanced ultrasonic meters having multiple paths for measurement would likely produce different and more accurate results. This is a single meter and is not representative of all ultrasonic meters.

Head loss. The head losses for each meter are presented in Figure 6. The losses generally follow an exponential increase as the *Re* increases; consequently, the plot was made logarithmic for comparison. For differential-pressure flow meters, the ratio of head loss to differential pressure will reach a relatively constant number as the *Re* increases. At a lower *Re*, the ratio increases as the *Re* decreases because of increased fluid friction losses. Table 2 shows a range of flow rates and the resulting head loss. There is no ratio of head loss to differential pressure for the magnetic and ultrasonic meters because they are not differential producers.

The comparison of the differential meters showed that the wedge and V-cone meters have the highest head losses while the classical and Halmi Venturi meters had similar losses. Miller's prediction for the seven-degree exit cone, which is close to the classical Venturi meter, shows similar results to data collected in the laboratory (Miller 1996). The HBX has higher head loss than

FIGURE 5 Ultrasonic and magnetic meters coefficients



C—coefficient, *Re*—Reynolds number

FIGURE 6 Head loss of meters

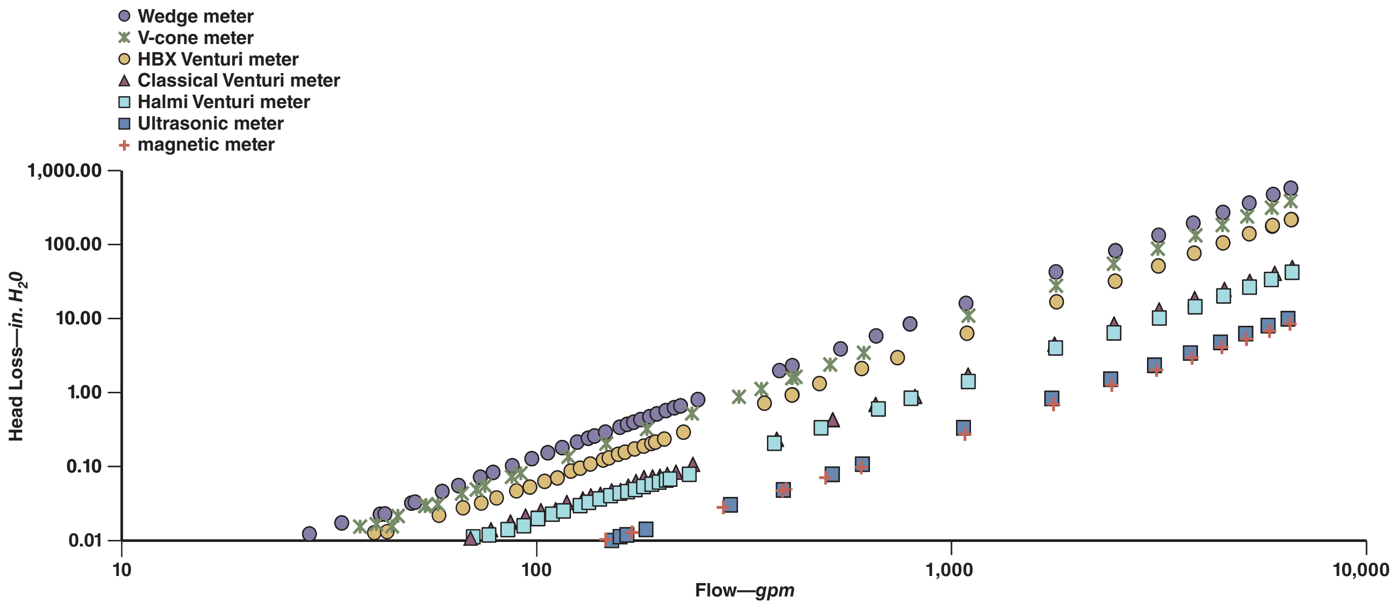


TABLE 2 Flow meters head loss

Meter	Flow Range *gpm*	Head Loss Range *in.* H_2O	Head Loss/ Differential Pressure for *Re* >100,000 %
Wedge	28–6,579	0.01–573.75	59.3
V-cone	31–6,558	0.086–386.80	57.3
Classical Venturi	40–6,620	0.013–49.25	13.2
Halmi Venturi	38–6,618	0.006–42.13	10.5
HBX Venturi	31–6,594	0.008–216.25	36.7
Magnetic	34–6,535	0.0002–8.48	NA
Ultrasonic	32–6,536	0.0031– 9.89	NA

NA—not available, *Re*—Reynolds number

the classical and Halmi meters, which is expected because of the hydraulic shape. The magnetic and ultrasonic meters were virtually as if no meter were in the line.

The head losses for the differential-pressure meters found in this research apply only to the meters with the same geometry and shape. Head loss is directly related to the β ratio and decreases for increasing β ratios and increases for decreasing β ratios. All the differential-pressure meters used for this research have β ratios of approximately 0.60, but the losses differ greatly from one to another because of the hydraulic shape of each design. The wedge and cone of the wedge and V-cone meters are directly in the flow path, which creates more losses because of flow separation and turbulent losses, whereas the classical and Halmi Venturi meters have a smooth transition into and out of the contraction, resulting in less head loss. The HBX had higher head losses than the classical and Halmi because of its sudden contraction from the inlet to the throat.

Costs. The costs of meters are important in terms of budget. The cost can increase depending on construction materials, pressure, flowing media, lifetime, head loss, installation, and meter diameter. For larger meters, costs increase for more materials and installation, with the exception of the ultrasonic meter. Installation for the ultrasonic meter is the same for most sizes and attaches directly to the system, saving material costs and installation time. Harsh, abrasive, and viscous mediums will require a meter that is built to sustain and accurately measure the medium, which will increase the cost of the meter and may affect its service life. It is important to know the expected life and performance for the meter. If the system is to last longer than the meter, a new meter or meter maintenance will need to be considered in the budgeting phase of the project. The head loss of meters will increase operating costs if pumping is required; consequently, pumping costs should be included in the decision-making process, as should the potential for outages should meter removal be required.

USING THESE RESULTS

The results from this study are designed to assist those selecting meters and help them decide which flow meter will best fit the needs of their system. A brief example is presented to demonstrate what should be considered for selecting a meter—for example, a pipeline system needs a meter to measure the flow with minimal head loss. The expected lifetime of the system is 50 years and the medium is clean water with a need to accurately measure flow at 3,800 gpm in a 12-in. line. Assuming a 6% interest rate and pumping costs of $0.10/kW·h, Table 3, part A, shows the annualized costs of the meters that were obtained considering the purchase price, yearly maintenance, interest rate, additional pumping costs at the given flow rate, and the meter lifetimes as given by company or sales representatives. Yearly maintenance was assumed to be $200, and the pumping costs were based on the corresponding head loss at the given flow rate.

Deciding which meters qualify is based on what the buyer needs. For this situation, the desired meter needed low head loss and high accuracy and was designed for clean water use. The meters with the lower head losses were selected: the ultrasonic, magnetic, Halmi Venturi, and classical Venturi. Of these meters, the accuracy is within ±0.5%. The cost of these meters differs by $890 annually and the lifetime ranges from five to 75 years. It now depends on the buyer's judgment. The ultrasonic meter in this study had the lowest head loss but the shortest lifetime and lower accuracy. The magnetic meter had the lowest annual cost and head loss and the accuracy was within ±0.20%, but it had a short lifetime. The classical Venturi had ±0.27% accuracy and a long lifetime but a higher head loss.

Not all situations are the same. If head loss is not a concern (i.e., no pumping costs), the annual cost of the previous example changes, as shown in Table 3, part B. The wedge, V-cone, and HBX meters now become optimal. The expected flow ranges would affect the meter selection because some meters have higher accuracy at lower *Re*. Additionally, the fluid can affect the meter selection, and not all meters will function properly with every fluid. The Venturi, V-cone, HBX, and wedge meters can be used in all gases (vapors) and liquids (including slurries) (Miller 1996). The magnetic meter is designed for conductive liquids only and can read flow in both directions as can the ultrasonic, wedge, and certain bi-directional Venturi designs; the ultrasonic meter is designed for use in clean gases (vapors) and clean, viscous, and corrosive liquids (Miller 1996); and the ultrasonic meter waves can return early or late to the other sensor and produce false flow rates with entrained solids in a liquid.

CONCLUSION

Although this study does not purport to be comprehensive in nature, it does provide those making metering decisions with information useful to consider when selecting a flow meter. It was simply not possible for this study to test all types of flow meters available or multiple meters of the same type and design. Using a single sample of each meter type and technology cannot answer all the questions that may be asked about the representative technologies; however, this study provides information that has not been published previously to assist those who are interested. There are many different flow meters available and each has merits that should be considered. Those selecting a meter should carefully consider the flowing fluid, required accuracy, construction materials, initial and associated costs, life cycle, and hydraulic characteristics. When

TABLE 3 Selection Considerations

A. Annual Cost Example

Meter	Accuracy *Re* >100,000 %	Head Loss *in.*	Pump Cost *$/year*	Designed for Clean Water	Lifetime *years*	Total Cost *$/year*
Wedge	0.29	192.08	12,552	Yes	40	13,178
V-cone	0.50	131.70	8,606	Yes	20	9,356
HBX	0.23	70.37	4,599	Yes	75	5,327
Ultrasonic	0.43	3.39	222	Yes	5	1,977
Classical	0.29	18.77	1,227	Yes	75	1,935
Halmi	0.27	13.40	876	Yes	75	1,541
Magnetic	0.20	3.01	197	Yes	10	1,087

B. Annual Cost Example—No Pumping Costs

Meter	Accuracy *Re* >100,000 %	Head loss *in.*	Pump Cost *$/year*	Designed for Clean Water	Lifetime *years*	Total Cost *$/year*
Wedge	0.29	192.08	0	Yes	40	626
V-cone	0.50	131.70	0	Yes	20	750
HBX	0.23	70.37	0	Yes	75	728
Ultrasonic	0.43	3.39	0	Yes	5	1,755
Classical	0.29	18.77	0	Yes	75	709
Halmi	0.27	13.40	0	Yes	75	665
Magnetic	0.20	3.01	0	Yes	10	969

Re—Reynolds number

considering purchasing a flow meter, buyers need to compare multiple meters and consider all the pertinent characteristics to obtain the optimal flow meter for their application.

ENDNOTES

[1] PFS-CVF classical meter, Primary Flow Signal, Cranston, R.I.
[2] PFS-FVF Halmi meter, Primary Flow Signal, Cranston, R.I.
[3] PFS-HBX Wedge meter, Primary Flow Signal, Cranston, R.I.
[4] Wedge PFS-HBX meter, Primary Flow Signal, Cranston, R.I.
[5] VS12ND03N V-cone meter, McCrometer, Hemet, Calif.
[6] Portaflow X ultrasonic meter, Fuji Electric, Edison, N.J.
[7] Siemens mag 5100W magnetic flow meter, Siemens AG, Munich, Germany

ABOUT THE AUTHORS

Johnny B. Prettyman *(to whom correspondence may be addressed) is a staff engineer with Tierra Group International, 111 East Broadway, Ste. 220, Salt Lake City, UT 84111 USA; jbprettyman@tierragroupintl.com. He worked at the Utah Water Research Laboratory for six years, assisting with meter calibrations and other hydraulic models. He earned his master and bachelor of science degrees from Utah State University, Logan, Utah.* ***Michael C. Johnson*** *and* ***Steven L. Barfuss*** *are both research associate professors at the Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah.*

PEER REVIEW

Date of submission: 04/28/2015
Date of acceptance: 08/05/2015

REFERENCES

Banchor, P.K.; Singh, S.N.; Seshardri, V.; & Gandhi, B.K., 2002. Performance Characteristics of Wedge Flowmeter Using CFD. *Computation Fluid Dynamics Journal,* 11:3:279.

Briggs, B., 2014. Personal communication.

Buhidma, A. & Pal, R., 1996. Flow Measurement of Two-Phase Oil-in-Water Emulsions Using Wedge Meters and Segmental Orifice Meters. *The Chemical Engineering Journal,* 63:1:59. http://dx.doi.org/10.1016/0923-0467(95)03076-X.

Cureton, A., 2014. Personal communication.

Fuji Electric, 2013. Fuji Ultrasonic Flowmeter Series. Fuji, Tokyo, Japan. www.fujielectric.com/products/instruments/library/catalog/box/doc/21A1-E-0008.pdf (accessed Mar. 3, 2014).

Glanville, R., 2014. Personal communication.

Harper, S., 2014. Personal communication.

Hollingshead, C.L., 2011. Discharge Coefficient Performance of Venturi, Standard Concentric Orifice Plate, V-cone, and Wedge Flow Meters at Small Reynolds Numbers. Master's thesis, School of Civil and Environmental Engineering, Utah State University, Logan, Utah.

McCrometer Inc., 2014. V-Cone Flow Meter, McCrometer, Hemet, Calif. www.mccrometer.com/products/product_vcone.asp (accessed Mar. 7, 2014).

Miller, G.; Pinguet, B.; Theuveny, B.; & Mosknes, P., 2009. The Influence of Liquid Viscosity on Multiphase Flow Meters. TUV NEL, Glasgow, U.K. www.vannforeningen.no/ikbViewer/Content/778329/14_Miller%20HV_Multiphase.pdf (accessed Oct. 11, 2015).

Miller, R.W., 1996. *Flow Measurement Engineering Handbook.* McGraw-Hill Companies Inc., Boston.

PFS (Primary Flow Signal), 2013. HBX-1 Halmi-Briggs, Primary Flow Signal, Warwick, R.I. www.primaryflowsignal.com/images/stories/ProductsPDFs/pfs_data_hbx1.pdf (accessed May 5, 2014).

PFS, 2012a. HVT-FV Fabricated Venturi Pressure Vessel, Primary Flow Signal, Warwick, R.I. http://primaryflowsignal.com/images/stories/ProductsPDFs/pfs_cv_asme_fabricated_pressure_vessel.pdf (accessed Mar. 9, 2014).

PFS, 2012b. Wedge Type Flow Meter, Primary Flow Signal, Warwick, R.I. www.primaryflowsignal.com/products/wedge-type-flow-elements/technical-materials (accessed Mar. 12, 2014).

PFS, 2009. PFS-CV, Primary Flow Signal, Warwick, R.I. www.primaryflowsignal.com/images/stories/ProductsPDFs/pfs_cv_asme_fabricated_pressure_vessel.pdf (accessed Apr. 19, 2014).

Siemens A/S, 2010. Which Cost Efficient Flowmeters Are Both Reliable and Tailored to Your Needs? Siemens A/S, Munich, Germany. www.automation.siemens.com/mcms/infocenter/dokumentencenter/sc/pi/Documentsu20Brochures/E20001-A450-P710-V2-7600.pdf (accessed Mar. 2, 2014).

Singh, S.; Seshadri, V.; Singh, R.; & Gawhade R., 2006. Effect of Upstream Flow Disturbances on the Performance Characteristics of a V-Cone Flow Meter. *Flow Measurement Instrumentation Journal,* 17:5:291. http://dx.doi.org/10.1016/j.flowmeasinst.2006.08.003.

Stobie, G.; Hart, H.; Svedeman, S.; & Zanker, K., 2007. Erosion in a Venturi Meter with Laminar and Turbulent Flow and Low Reynolds Number Discharge Coefficient Measurements. 25th International North Sea Flow Measurement Workshop, Oslo, Norway.

Stone, M., 2014. Personal communication.

Yoon, J.; Sung, N.; & Lee, C., 2007. Discharge Coefficient Equation of a Segmental Wedge Flow Meter. *Journal of Process Mechanical Engineering,* 222:E:79.