Laboratory Calibration of the Mag-Tube Flow Meter

May 2003

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The Mag-Tube flow meter is a device proposed for measuring the flow rate of water through circular pipes in ground-water well pumping applications on the Elephant Butte Irrigation District, Albuquerque, New Mexico. The device is named for its developer, Henry Magallanez. The Water Resources Research Laboratory (WRRL) was asked to perform a calibration test of the Mag-Tube flow meter for use in 6- to 16-inch diameter pipes flowing full. This test was conducted in early 2003. This report provides background information about the flow meter, describes the testing program, and presents the results of the testing, including rating equations for the flow meter. This work was performed under Cooperative Agreement Number 02-FC-40-6510 between the U.S. Bureau of Reclamation and Elephant Butte Irrigation District.

Background

Two prototype Mag-Tube flow meters are shown in Figure 1. The meter consists of a hollow 1/2-inch diameter tube, threaded on both ends so that it may be passed through the walls of a circular pipe and sealed against the pipe wall at each end by a hex nut and rubber bushing. The tube is plugged at one end and open at the other. At the mid-point of the tube and at 2 inches off center to each side, three 1/16-inch diameter holes are drilled through the wall of the tube to allow water to enter the tube. The Mag-Tube is installed so that these three pressure ports face directly upstream. Alignment marks on the plugged end of the tube facilitate accurate installation. A piece of clear vinyl tubing is connected to the open end of the Mag-Tube and then to a manometer board or pressure transducer to allow measurement of the total pressure of the flow impacting the upstream edge of the tube. The second part of the measurement system is a simple static pressure port drilled through the pipe wall, located about 6 inches upstream from the Mag-Tube device. This port is also connected to the manometer board or transducer. The difference between the total pressure on the Mag-Tube ports and the static pressure at the pipe wall is proportional to the square of the flow velocity in the pipe, and can thus be used to compute the flow rate. The same tube design is used to make measurements in pipes ranging from 6 to 16 inches in diameter. Figure 2 shows a mock-up installation of the flow meter in a PVC pipe. The Mag-Tube flow meter is potentially a relatively low-cost device to produce and install. The highest cost is associated with the pressure transducer and data logging equipment, if such devices are chosen for measuring and recording the differential pressure. A simple pressurized U-tube manometer can be constructed for about $50 if automated measurement and data recording are not needed.

Figure 1. — Prototype Mag-Tube flow meters. Note the three pressure ports on the nearest tube.

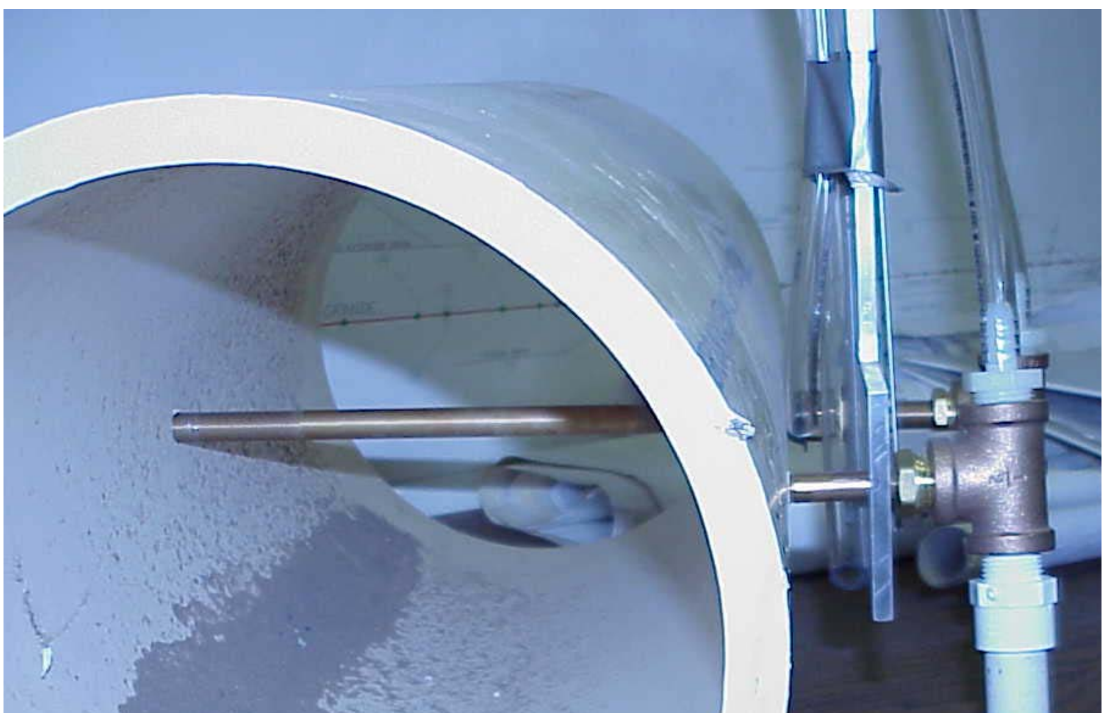

Figure 2. — Mag-Tube flow meter installed in a pipe. The upstream static pressure port through the pipe wall is in the right foreground.

Literature Review

The Mag-Tube makes use of the very old flow measurement concept of the Pitot tube, and devices similar to the Mag-Tube have been used for decades in the course of field and laboratory investigations by the WRRL and others. These devices were typically custom-calibrated. Their designs varied enough that calibration data are probably not applicable to the Mag-Tube, but they are evidence that the concept is very viable.

Two commercial flow meters are available that are conceptually similar to the Mag-Tube. Since 1947, the *Hall flow meter* (also known as the *Cox flow meter* or *modified Hall Pitot tube*) has been sold by the C.W. Cox Co. of Fullerton, California (http://www.cw-cox.com/products/hfm.htm). The cost of the 6 to 12-inch standard set is $1595, and the kit to extend this meter to 13 to 18-inch pipes is $685. Calibration testing of the Hall flow meter was performed in 1961 at Colorado State University and more recently at the University of California at Davis. The most detailed work was that conducted at Colorado State University (Robinson 1961).

The second similar device is the Annubar flow meter, available from the Dieterich Standard division of Power Specialties Co. Rahmeyer and Britton (1981) described several enhancements to the Annubar device that improve its flow measurement accuracy and extend its range of application.

Hall Flow Meter

Robinson dates the development of the Hall flow meter to the Frank tube, described by Albert Frank in two 1888 German publications. The flow meter sold by the C.W. Cox Co. consists of a 3/4-inch diameter tube with a series of 3/16-inch diameter holes drilled in the upstream face. The tube passes through one pipe wall and is inserted until it makes contact with the opposite pipe wall. The 6-12 inch set contains 10 impact holes in the upstream face, and as the length of the tube is increased by adding variable length tips, the number of holes is also increased so that there is always an even distribution of holes across the diameter of the pipe. Three static pressure taps are integrated into the tube, unlike the Mag-Tube in which a separate piezometer tap is installed in the pipe sidewall. The dynamic taps are manifolded together, as are the static taps. The pressure taps are connected to a U-tube manometer with a custom-graduated scale intended to provide a reading proportional to the average flow velocity. Multiplying the reading by the cross-sectional area of the pipe yields the discharge.

Robinson's test showed that the "calibrated" scale on the U-tube manometer was not accurate, partly because the manifolded impact taps tended to indicate the maximum velocity in the pipe, rather than the average, and secondly because the static pressure taps sensed an unstable pressure lower than the ambient pressure. In an effort to improve the accuracy of the device, Robinson installed a static port piezometer tap in the pipe wall and used this in place of the static ports integrated into the tube. This makes the tested configuration nearly identical to the Mag-Tube, except for the spacing and number of impact holes, and the diameter of the tube and holes. With this arrangement, more consistent calibration results were obtained. A discharge equation and a chart for determining the discharge coefficient as a function of the pipe size were developed. Flow measurement uncertainty was reported to be about ±4 percent. Robinson recommended not using the Cox-provided manometer and scale.

Hanson and Schwankl (1998) tested the Hall flow meter and several other devices to determine their accuracy in poorly conditioned flows, such as those downstream from elbows or valves. The Hall flow meter and several of the other tested devices performed well in flows with excessive turbulence, but all of the meters were strongly affected when installed downstream from a partially opened butterfly valve.

Annubar Flow Meter

The Annubar flow meter is also an integrating pitot-type meter utilizing multiple impact ports and a static pressure port integrated into the tube. The impact ports are specifically located to obtain the best estimate of the average velocity; there is intentionally not a hole at the pipe centerline, where the sensed velocity would be the maximum, not the average velocity. An internal interpolating tube (essentially a piezometer inside the manifold that senses the pressure in the manifold midway between the impact ports) also reduces errors in the sensed impact pressure caused by manifold effects. The early Annubar devices used a circular cylinder tube, but Rahmeyer and Britton (1981) cited studies that showed the circular shape produced unstable performance at a Reynolds number above about 4×10^5 (approximately 3.5 ft/s velocity in a 16-inch diameter pipe). To improve the performance, the tube shape was changed to a modified diamond shape (a square tube with chamfered corners, with one corner pointing upstream). This eliminated the Reynolds number effect.

Calibration Testing

The calibration testing program for the Mag-Tube flow meter utilized a test stand facility in the Water Resources Research Laboratory that provides 45-ft long straight sections of circular pipe with nominal diameters of 4, 6, 8, and 12 inches. All flows into the test stand are measured by venturi flow meters ranging in size from 3 to 14 inches inlet diameter. The venturi meters are periodically calibrated using a timed weigh-tank and have an approximate flow measurement uncertainty of ±0.5% or better. Pressure measurements were made with a 5 lb/in^2 differential pressure transducer having a manufacturer's stated measurement uncertainty of ±0.25% of full scale, or ±0.0125 lb/in^2. A pressurized, air-and-water, inverted U-tube manometer provided a backup indication of the pressure difference. The manometer and inline dampening coils also provided some stabilization (i.e., filtering) of the pressures. Calibration of the transducer against the visual readings taken from the manometer confirmed the stated uncertainty level for the transducer.

The test plan was designed to determine the best-fit calibration parameters for the Mag-Tube flow meters and the relative uncertainty of flow measurements made with the tubes. Several elemental sources of uncertainty affect the Mag-Tubes themselves and the calibration equipment. Uncertainty sources can be grouped into those that bias the results (and can potentially be eliminated through a calibration procedure) and those that are random and independent of the specific characteristics of an individual tube or installation. Some of these sources of uncertainty include:

- **Sources of bias uncertainty:**
  - Construction of impact ports and static port,
  - Alignment of impact ports with alignment mark on end of tube,

    - Ability to accurately align impact ports with flow direction, using alignment mark,
    - Accurate installation of tube so that middle dynamic pressure port is at pipe centerline,
    - Transducer bias,
    - Tube Reynolds number effects on relation between sensed impact pressure and actual velocity,
    - Pipe Reynolds number and relative pipe wall roughness effects on the velocity profile and the relation between sensed pressure and average velocity, and
    - Geometric scale effects due to relative size of Mag-Tube and pipe, the position of the dynamic pressure ports relative to the shape of the velocity profile, and the flow disruption caused by the tube itself.
- **Sources of error and uncertainty that are independent of tube-to-tube variability (cannot be eliminated through calibration):**
    - Transducer random uncertainty,
    - Random uncertainty in laboratory flow measurements, and
    - Random uncertainty in flow condition.

It is, of course, impossible to isolate, quantify, or eliminate all of these sources of uncertainty. However, the testing program can provide an estimate of the collective effect of many of these factors, and some can be isolated in individual tests.

Two Mag-Tube flow meters were tested. The majority of the tests were carried out on a tube designated Tube #1. Tube #2 was tested to evaluate the variability in the performance of individual tubes due to slight manufacturing differences. Five distinct series of tests were conducted:

A) Tube #1 was tested in 3 pipe sizes over a range of flow rates in each pipe, resetting the probe in the pipeline (i.e., the probe alignment with the flow) prior to making the measurements for each flow rate. Resetting the probe alignment before each reading causes the alignment error to be a random error.

B) Tube #1 was tested in the 12-inch diameter pipe in a fixed installation at a single flow rate, with 10 repetitions. In this test, any misalignment of the probe with the flow would cause an error that uniformly biases all of the repetitions. There would be no random error due to probe alignment.

C) Tube #1 was tested in a manner similar to (B), but with the probe alignment with the flow reset before each repetition. Comparing the random uncertainties of the (B) and (C) tests allows determination of the uncertainty due to probe alignment when the probes are used in practice.

D) Tube #2 was tested in the same manner as (B) and at the same set flow rate. Comparing the results from (B) and (D) gives an indication of the potential errors related to manufacturing variabilities.

E) Tube #1 was tested at several intentional angles of misalignment to the flow to gain a better understanding of the effects of misalignment on measurement accuracy.

The data were used to determine the empirical velocity coefficient C_v in the calibration equation

$$Q = C_v A\sqrt{2g\Delta H} \qquad (1)$$

where Q is discharge, A is the cross-sectional area of the pipe, g is the acceleration of gravity, and ΔH is the differential pressure measured between the Mag-Tube and the pipe-wall static pressure tap. The velocity coefficient is the ratio of the average flow velocity, Q/A, and the dynamic velocity sensed by the Mag-Tube flow meter.

$$C_v = \frac{Q/A}{\sqrt{2g\Delta H}} \qquad (2)$$

The tubes were generally installed and tested in each configuration during the span of only a few days. On one occasion a tube was left installed in the pipeline for 54 days, and at the end of that period heavy encrustation and corrosion were found on the tube, partially blocking the dynamic pressure ports.

Results

Figure 3 shows the discharge vs. differential head measurements for the tests of tube #1 in 6-, 8-, and 12-inch diameter pipes (nominal pipe sizes, inside diameters were slightly smaller). The figure includes data from tests in series A, C, and D.

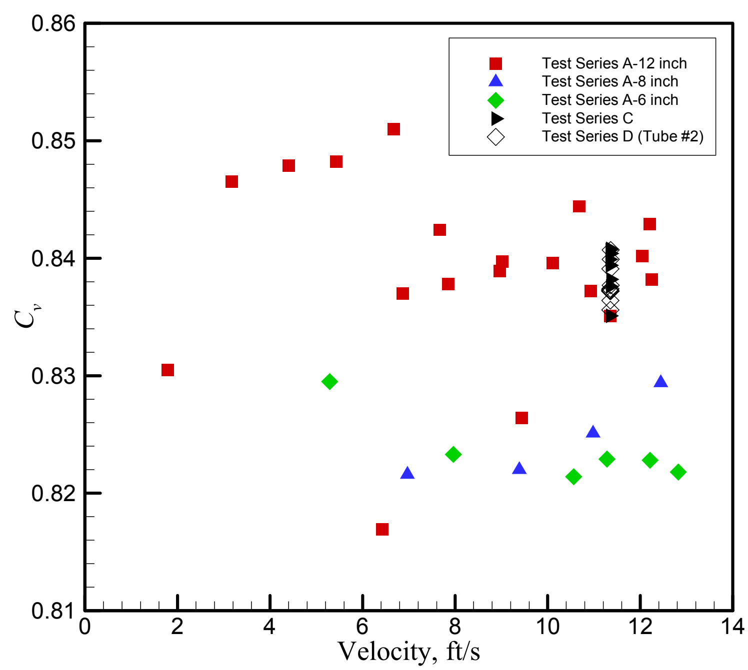

Figure 3. — Velocity coefficients for Mag-Tube flow meters.

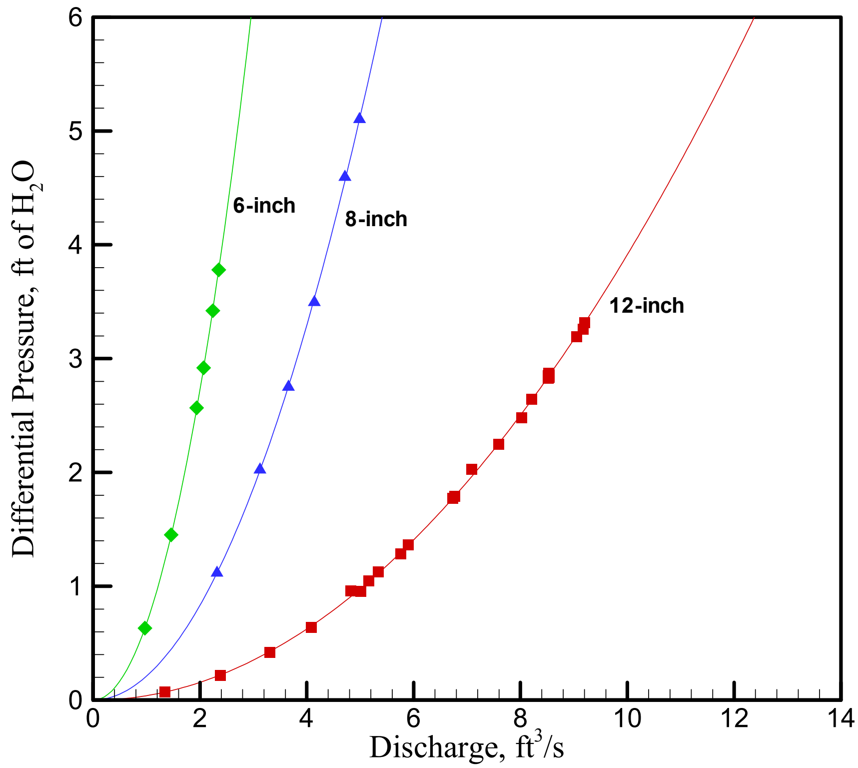

Figure 4. — Discharge vs. differential pressure for Mag-Tube flow meters.

For each data point collected, the velocity coefficient was computed from eq. 2, and the data were plotted against the average pipeline velocity to investigate trends (fig. 4). This analysis shows that there are no trends and thus no significant tube Reynolds number effects. The plot does suggest some difference in velocity coefficients when the meter is installed in different pipe sizes. These differences are probably related to the pipe Reynolds number (which can affect the shape of the velocity profile), the relative locations of the dynamic pressure ports in the different sizes of pipe, and the difference in the relative fraction of the pipe cross section that is obstructed by the Mag-Tube itself.

For each pipe size, the average velocity coefficient was determined, and these data were plotted in figure 5 to allow determination of the velocity coefficient for other pipe sizes. With tests on only three pipe sizes, nothing more sophisticated than a linear regression was warranted. The velocity coefficient as a function of the pipe inside diameter was determined to be

$$C_v = 0.806 + 0.00274D \qquad (3)$$

where D is the pipe inside diameter expressed in inches.

To determine the influence of uncertainties and errors in aligning the Mag-Tube with the flow direction, the variation of the velocity coefficients between test data from series B and C (described previously) were compared. The relative uncertainties in the velocity coefficients

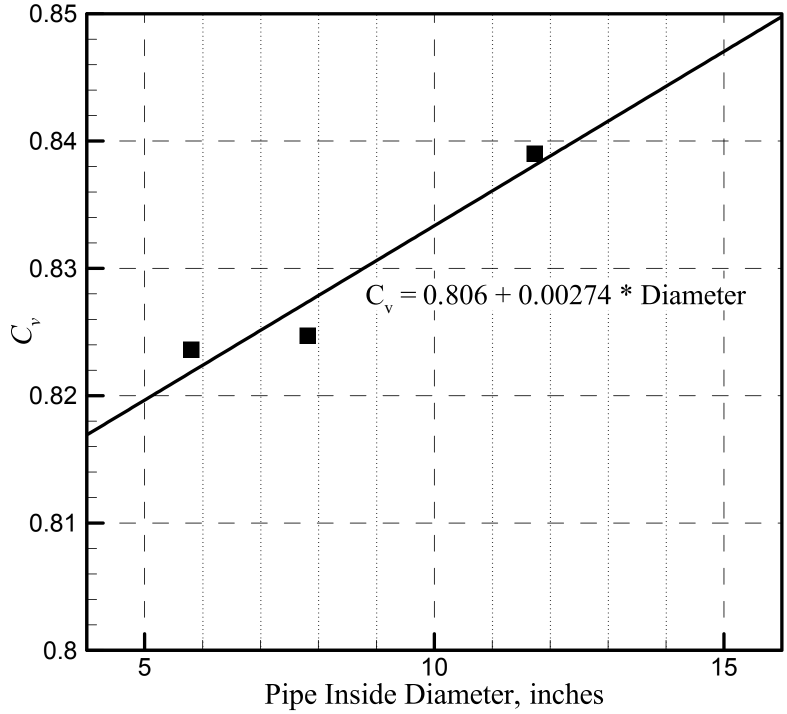

Figure 5. — Velocity coefficients of Mag-Tube flow meters as a function of pipe diameter.

were compared for each test series, and as expected, the data from test series C exhibited a greater uncertainty (±0.63%) than the similar data from test series B (±0.35%). (All relative uncertainties cited in this report are at approximately the 95 percent confidence level.) The only difference between these tests was the fact that the probe alignment was fixed for all repetitions of the B series tests, while it was reset before each repetition in the C series. Thus, the uncertainty contribution from probe alignment could be isolated. The total uncertainty is the root-sum-square of the uncertainties due to probe alignment, U_{align} and the uncertainties due to all other sources, U_{etc}.

$$U_{total} = \sqrt{U_{align}^2 + U_{etc}^2} \tag{4}$$

The total uncertainty was ±0.63%, from series C, and the uncertainty from all sources except probe alignment was ±0.35%, from series B. The uncertain contribution from probe alignment is thus ±0.53%.

The small uncertainty contribution from probe alignment was verified by the tests in series E, in which the probe was twisted specific angles from the flow. The angles were measured with a digital level and a straightedge inserted into the alignment slot on the end of the tube. Figure 6 shows the change in velocity coefficient caused by twisting the probe. The curve fit shows that for small angles of misalignment, the effect is very slight. It is believed that the probe can be readily aligned by eye with an error of ±1° or less.

The uncertainties obtained in the B and C series tests were extremely low because these tests were conducted at a single discharge (to further limit the outside factors affecting the investigation of alignment uncertainty). The A series tests in the 12-inch diameter pipeline provide the largest, best set of data for evaluating the total uncertainty of discharge measurements made with the Mag-Tube. The total uncertainty in the velocity coefficients for these tests was ±1.9%. This includes probe alignment and all other factors affecting these tests.

Conclusions

Two Mag-Tube flow meters were tested in 6-, 8-, and 12-inch diameter pipes. As expected, the flow meters provide a reliable indication of the pipeline velocity and can be used to compute discharge using the equation

$$Q = C_v A\sqrt{2g\Delta H}$$

where Q is discharge, A is the cross-sectional area of the pipe, g is the acceleration of gravity, and ΔH is the differential pressure measured between the Mag-Tube and the pipe-wall static pressure tap. The velocity coefficient, C_v is

$$C_v = 0.806 + 0.00274D$$

where D is the pipe inside diameter in inches.

A 16-inch diameter pipe was not available for testing. The discharge equation given above can be used for the 16-inch diameter pipe, but should be verified as soon as practically possible by additional field or laboratory testing.

Encrustation and corrosion of the tubes did occur and should be closely monitored in any long term installation. Constructing the tubes from alternative materials might significantly reduce this problem.

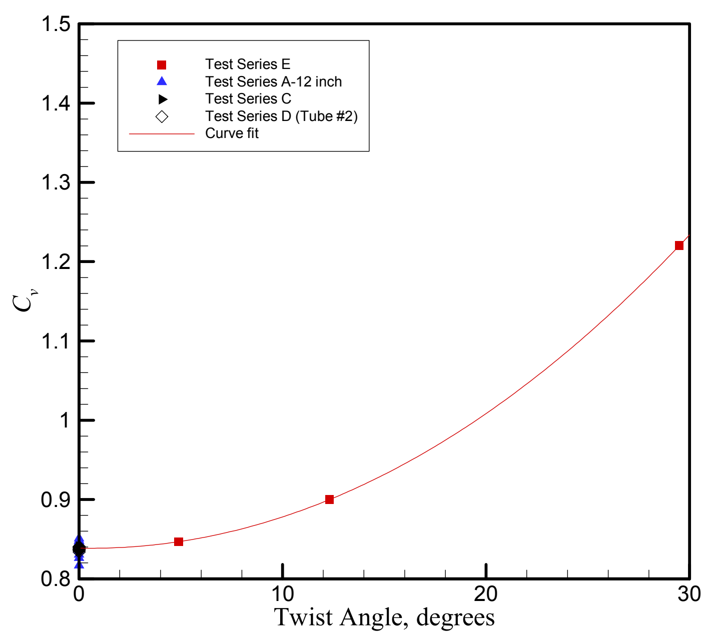

Figure 6. — Effect of probe alignment angle.

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