CORRECTING UNRELIABLE VELOCITY DISTRIBUTIONS IN SHORT CULVERTS AND CANAL REACHES

John Replogle[1]

ABSTRACT

Irrigation water management increasingly depends on good water flow measurement. Too frequently, flow disturbances from upstream elbows, the well pump, or other pipe fittings, produce distorted flow profiles that are detrimental to the proper installation and operation of common flow meters used in pipes, and the flumes and weirs used in canals associated with irrigated agriculture. Field conditions often force installation of pipe flow meters and flumes closer to these upstream disturbances than specified by standard installation recommendations. Special methods to condition flows to generate usable flow profiles over short distances are commercially offered for pipes meters Less expensive methods have been used in irrigation applications, but have been only partially studied to define their application limits. The historical installation recommendations for pipe meters and flumes are summarized and still recommended for inclusion in future constructions. For retrofit situations the field experiences and limited laboratory information on alternate approaches are presented. Suitable flow profiles for acceptable metering results in pipes can be obtained at distances about one-half to one-third the usual, historical, pipe-length requirements. These profiles, while nearly symmetrical, may be more uniform, or piston-like, than the fully developed shape.

INTRODUCTION

Water flow measurement is increasingly recognized as a major component for good irrigation water management. Too frequently existing field installations thwart retrofitting for proper meter operation because of the difficulty and expense of eliminating flow disturbances from upstream elbows or other pipe fittings, that produce distorted flow profiles that are detrimental to the proper operation of most common flow meters for pipes and canals in pipes, and also compromise the accuracy of flumes and weirs used in canals associated with irrigated agriculture. These existing field conditions and cost considerations often result in installation of pipe meters closer to upstream disturbances than specified by traditional installation recommendations. This also applies to canals where flumes are installed too closely to upstream disturbances. The traditional recommendations and more recent studies that contribute to the understanding and expectations of flow metering installations will be examined for possible

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[1] Research Hydraulic Engineer, US Water Conservation Laboratory, ARS-USDA, 4331 East Broadway Road, Phoenix, AZ 85040

application to situations that do not meet traditional recommendations. The objective is to identify the rate of deterioration in accuracy with anomalies in an installation. This is not always possible, but some general guidelines are proposed. Additionally, recent efforts to condition velocity profiles in short distances downstream from a disturbance in order to present an acceptable profile to a flow meter will be examined.

TRADITIONAL RECOMMENDATIONS

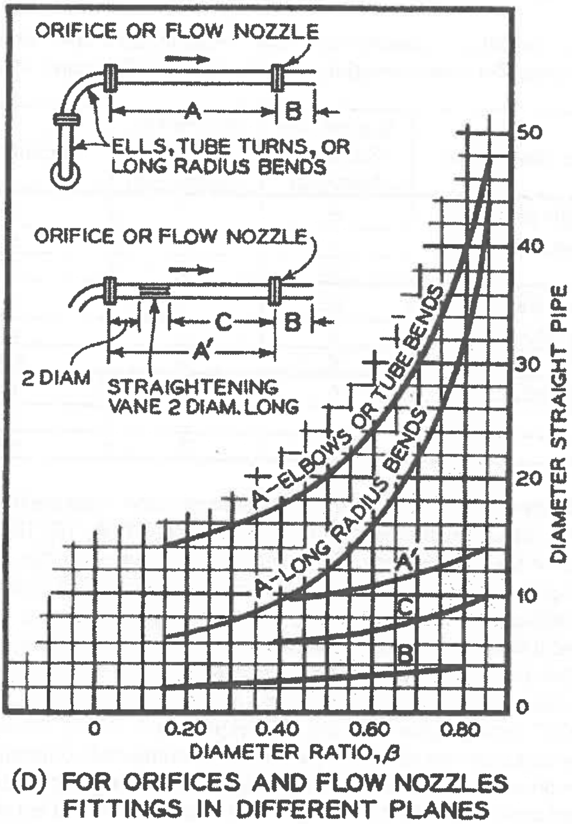
ASME and ISO Standards

The traditional recommendations for pipe flows are well summarized in ASME (1971). The highest accuracy assigned to a pipe meter depends on meeting these installation conditions. These recommendations specify piping arrangements that are meant to hold errors to within ±0.5%. Several recent studies contribute to understanding this accuracy problem (Miller, 1996; Hanson and Schwankl, 1998 ; and Johnson, et al., 2001). Miller (1996) states that several European and United States test programs have contributed data on specific kinds of upstream disturbances for application to installations of orifices, Venturi nozzles, and Venturis. These recommendations differ between the United States sources (ANSI/API 2530, 1995 and ASME MFC-3M, 1995) and those listed by ISO (ISO Standard 5167, 1991). The ISO standards are slightly more conservative.

The recommendations by ASME (1971) are basically for orifices, nozzles and Venturi tubes, and vary with the diameter ratio, $\beta = D_1/D_0$ (D_1= Diameter's of a meter throat; D_0= Diameter of pipe). An example of those recommendations in graphical form is shown in Figure 1, which is diagram "D" of eight such figures from ASME (1971). Again, this is for orifices and nozzles and does not address the deterioration of a result if these recommendations are not achieved. Also, none of the diagrams directly deal with the requirements of many modern meters that are used in irrigation, such as the ultrasonic flow meters, propeller meters, and vortex-shedding meters.

Other Considerations

Neither the ISO nor the other standards appear to address the question of deterioration of accuracy with deviation from the standard recommendations. Elsewhere, some limited discussion is offered as to the rate of accuracy deterioration with deviation from these standards. An attempt to quantify deterioration was made by the Kele Company (1998) based on published results in Benedict (1984) who in turn had provided estimates taken from studies in the International Journal of Heat and Fluid flow. These data indicate, for example, that eight pipe diameters (8*D*) of straight pipe upstream and 4*D* downstream are expected to add ±1% variance to a manufacture's stated accuracy for some situations, such as a single plane elbow, a tee, or a strainer. For most valves and two-plane elbows, 16*D* upstream and 4*D* downstream are recommended. These have been summarized and presented by the Kele Company (1998) in Table 2 for pipe Reynolds numbers in excess of 3000. Although some meters may be more sensitive to installation conditions than others, these are recommendations should present a suitable flow profile to any meter.



(D) FOR ORIFICES AND FLOW NOZZLES FITTINGS IN DIFFERENT PLANES

Figure 1. An example of recommendations of piping requirements for optimum meter performance as functions of Diameter Ratio, β. (From ASME, 1971)

For example, from Table 1, the grouping containing globe and gate valves would require16*D* of upstream straight pipe and 4*D* of downstream piping to maintain a variance of ±1%, with a deterioration to ±2% if only 8*D* are provided.

Translating these recommendations into irrigation practice, the consideration of heat exchangers, for example, can be likened to "Concentric Reducer or

Expander" and the corresponding values, ±1%, of in Table 1 can be used. Table 1 is not clear on how to apply the combinations of 8*D* and 2*D* instead of 8*D* and 4*D*, etc., or if 4*D* downstream would really decrease the variance over 2*D*. This approach of adding an increase in variance based on disturbance, however, may be somewhat oversimplified. It assumes that all meters respond similarly to a flow disturbance, which is not what Hansen and Schwankl (1998) reported.

Table 1. Additional variances for some common installation situations, not sorted for meter sensitivity. (After the Kele Company, 1998).

Upstream Obstruction	Straight Pipe Diameters Upstream	Straight Pipe Diameters Downstream	Resulting Variance
Elbow (single plane) Tee, Strainer, Air Separator	8	4	±1%
	4	2	±2%
	2	2	±5%
Globe Valve, Gate Valve Two-Plane Elbows, Bullhead Tee	16	4	±1%
	8	4	±2%
	4	2	±10%
Concentric Reducer or Expander	6	3	±1%
	3	2	±2%
	2	2	±4%

Hanson and Schwankl (1998) investigated the progressive increase in error of a variety of flow meters as they were placed at distances of 2*D*, 5*D*, 10*D* and 15*D* from sources of flow disturbance. The meters in this study were two propeller meters, a Doppler ultrasonic meter, a Hall pitot tube meter and a Collins gage pitot meter, which they classified as responding to average velocity. Additionally they included a velocity-gage flow meter, and two paddle-wheel meters, which they classified as point-velocity meters. The Hall pitot tube produces an average velocity by simultaneously sampling several points across the pipe and "hydraulically" averaging the resulting impact pressures. The Collins gage pitot meter is a point measuring device as part of a tube completely crossing the pipe through two holes on opposite sides of the pipe. The sensing part is moved from point to point across the pipe by sliding the tube through the two holes. This means that the tube crossing the pipe is always present and offers the same obstruction regardless of the sensing hole position. The combined result is used to obtain average velocity. Results showed that the propeller flow meters, the Collins meter and the Hall tube, using many points, were least affected by excess turbulence. The meters that depended on single point measurements were most vulnerable. One might think that the flow about the two sides of a butterfly valve may be symmetrical enough to cancel the effects of the valve plate and stem. However, a butterfly valve strongly affected meter performance when the meter was installed in close proximity. Apparently the centerline flow did not recover quickly. Their results reconfirm that meters should be installed upstream of most kinds of control valves. They noted that the installation of vanes downstream of a valve tended to transport distorted flow profiles further downstream, as has been noted by others (ASTM, 1971).

Johnson, et al. (2001) evaluated a transit-time flow meter with a variety of upstream disturbances and distances to the upstream disturbances. Their meter had a factory profile adjustment built into its internal software. A transit-time meter averages the velocity in a sampled slice across the pipe diameter and this slice must be translated into a "volume of revolution" to get the pipe's average velocity. For example a piston flow would have a factor of 1.0. An impractical conical profile would be 0.333, with the practical range between 0.75 and a value less than 1.0. Their results using the built-in velocity profile correction indicated discharge over-estimates averaging about 7%. This may mean that undeveloped velocity profiles after the flow disturbance were closer to the piston flow value of 1.0 than the manufacture's built-in correction value.

Their results showed that the transit time ultrasonic meter could be used with an inaccuracy of about ±5% for distances as close as 4.5*D* from disturbances caused by (a) single elbows, (b) two elbows not in the same plane, (c) a check valve, and (d) a 50% open butterfly valve.

Because the profiles were not fully developed, although consistent, at this distance, the internal correction for fully developed profiles was not applicable, and they present an adjustment ranging from about +6.5% for the profile at 4.5*D* and about +3.5% at 10*D*, reducing to no correction at about 30*D*. These are applicable to smooth pipes usually found in irrigation, such as PVC and aluminum. Standard iron pipe, which would be rougher, might be expected to produce yet different velocity-profile developments with distance, so these factors should be applied with caution in those cases.

Downstream distance requirements.

From Table 1 values presented by the Kele Company (1998), the effect of distance to a downstream obstruction seems to be important. These results were compared to the old data of Yarnell (1937). Figure 2 is one of several figures from that study and illustrates some of the information available therein. A pressure influence and a corresponding velocity disturbance are noted at the upstream plane of the 90-degree elbow shown, (Figure 2, upper row of diagrams, second from right end). At one-pipe diameter upstream (-0.5') no significant pressure or velocity influence is detectable. This was for Reynolds numbers ranging from 250,000 to 600,000.

For an obstruction such as a downstream gate valve, where the flow must bend significantly to reach the flow opening, the backpressure difference may extend further upstream, depending on the degree of valve opening. On the other hand, in this elbow installation, the entire flow is turned in a distance of one pipe diameter as it goes around the bend, so one may consider that this may be equivalent to one pipe diameter at the elbow beginning face. Thus, the one-diameter upstream is then equivalent to about two diameters upstream from the backpressure of the turning pipe's elbow.

Because of the splitting of the flow, one might expect a butterfly valve to cause less backpressure problems than a gate valve, and a ball valve opening smaller than the pipe itself could be considered similar to a "reducer" in that it passes flow near the pipe center. Using the old flow net process for potential flows in these situations, it would appear that elbows and butterfly valves would have less upstream requirement than a gate valve, depending on whether the gate valve was nearly open or nearly closed. Even gate valves seem harmless if they are about two diameters downstream, for the level of performance usually acceptable to irrigation.

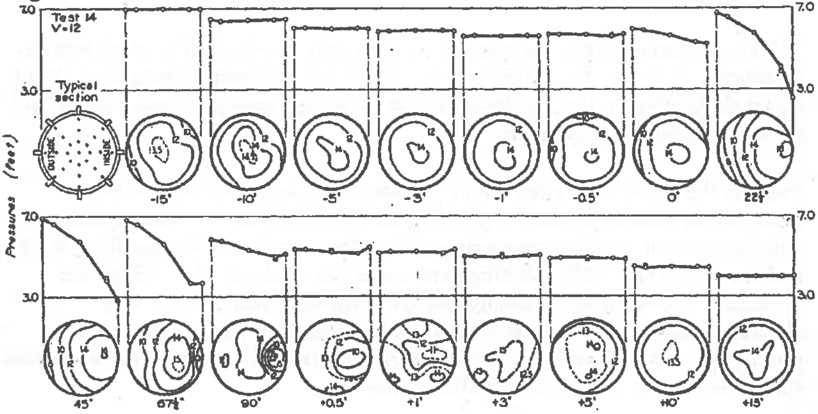


Figure 2: An example of velocity distribution and peripheral pressures in a 6-inch (15-cm) standard elbow bend with approximately uniform velocity distribution in the approach tangent. Mean velocity = 12 ft per second (3.66 m/s). (From Yarnell, 1937).

Can we support the upstream requirements stated in Table 1? Again using Yarnell (1937), Figure 2, the pressures and measured velocity distributions at 2 *D* downstream (+1' in Figure 2) from a 90-degree elbow still show some pressure differentials and asymmetrical velocity patterns. At 6*D* (+3' in Figure 2) the pressure differences around the pipe are nearly equalized, but the velocities are still slightly asymmetrical. Beyond 10*D*, some slight asymmetrical velocity patterns still persist but do not seem to improve more, even to 30*D*.

With the flow obstructed to force a jet to the inside of a 90-degree elbow (Yarnell, 1937), the disturbance persisted so that about 10*D* was required to approximately match the previous 6*D* behavior. With the jet on the elbow's outside, 20*D* was required with almost all of the effect gone by 30*D*. However, the jet at one side of the elbow bend, the disturbance was still significant at 30*D*. This supports the long pipe length recommendation associated with closely coupled elbows not in the same plane, called two-plane elbows in Table 1, and gate valves upstream of elbows with the gate valve opening to one side of the elbow bend plane.

Open-Channel Flow Metering

Flumes and weirs are the most common open channel devices used in irrigation. The recommended upstream requirements for flumes are given in Clemmens, et al., 2001, and are summarized below. They could apply as well to sharp-crested weirs.
(a) The Froude number should not exceed 0.5 at the gaging station and for a distance upstream of 30 times the maximum head reading, H_{1max}.
(b) The upstream channel should be straight and uniform for at least 30 H_{1max}.
(c) There should be no flow of highly turbulent water (e.g., undershot gates, drop strictures, hydraulic jumps) in the upstream channel for a distance from the gaging station of 30 H_{1max}.
(d) If there is a bend close to the structure (closer than 30 H_{1max}), the water surface elevations at the two sides are likely to be different. Reasonablely accurate measurements can be made with about 3% added error if the upstream straight channel is at least 6 H_{1max}. It is best to measure the water level on the inner bend of the channel.

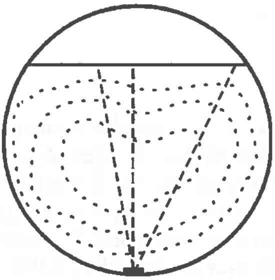


Figure 3. Doppler-based flow meter.

There is a relatively new acoustic Doppler-based flow meter, the ADFM Velocity Profiler™ (Acoustic Doppler Flow Meter, MGD Technologies, San Diego, CA). The ADFM uses, range-gated Doppler technology to measure velocity at many discrete points along several beams in the depth of flow in a channel or pipe cross section. These point velocities then are combined to determine a velocity profile and thus a flow rate for the channel or pipe, Figure 3. The developers claim that it tolerates distorted flow profiles well.

No attempt to specify conditions for other open-channel flow measuring methods such as current metering and open -channel, transit-time ultrasonic meters are given herein, although the above conditions for flumes should serve well. Sauer and Mayer (1992) have addressed part of this problem for current metering in canals and streams, and a literature review on accuracy of river measurements was prepared by Pelletier (1988).

CONDITIONING VELOCITY PROFILES

Various recommendations exist for conditioning velocity profiles to try to shorten the distance needed to improve meter performance. The idea being that if one could present a symmetrical, fully developed turbulent profile to a place that is to be used for a meter installation, then the meter would perform optimally. This means that one must provide either the suggested pipe lengths to achieve this desired profile or somehow artificially cause it. In many cases just providing a symmetrical profile whether or not it is properly shaped as a turbulent profile is a great improvement and will provide satisfactory results for applications in irrigation management.

Miller (1996) discussed in detail flow conditioners of many styles. Most of them are tube bundles or grid devices of complete cross vanes that are suited to clean flows. Many irrigation flows are pumped from canals and such straighteners are trash collectors. The eight cross vanes, two pipe diameters long will have a head loss of about one velocity head. More restrictive types can be as high as about 14 velocity heads (Miller, 1996).

Field experience

A transit-time ultrasonic meter was installed in an irrigation outlet that was 76 cm (30 in) in diameter and about 45 m (150 ft) long. A gate valve partly opened controlled flow into the pipe where it traveled about 10 diameters before turning 45-degrees left for a distance of about 40 pipe diameters. The result appeared to be a slowly rotating, distorted flow profile that the meter sampled for 16 seconds and recorded the result, which was on the order of 400 L/s (15 cfs.). This readout varied as much as 20% to 30% for consecutive readings,. The fluctuation was a random error that averaged to zero and did not affect the daily and weekly totals, but provided poor information for estimating the irrigation time for a particular field delivery. Using the reasoning, discussed later, we inserted a large opening orifice made of 2x2 inch (5x5 cm) structural metal angle forming the orifice of diameter ratio, β, of about 0.86. Because the ultrasonic meter was assumed to be fairly insensitive to rotation, unlike a propeller meter, no vanes were installed. The fluctuation in the readings was reduced to about ±3%. The head loss was negligible, calculated to be on the order of 1 cm.

A 3 m length of 15 cm diameter aluminum irrigation pipe was fitted with a propeller meter at about the 2.5-meter location. A routine check against a laboratory weigh tank system was planned. The meter location of about 16*D* from the upstream entrance was assumed more than adequate. However, a hasty connection to the water supply was made with some "lay-flat" tubing. This tubing caused enough swirl in the pipe, depending on the way it was twisted into position, that errors in the meter of as high as 30% were noted, both high and low. When vanes were installed, the meter read correctly. Even though vanes only can actually increase the action of a jet, the thought here was that a propeller meter is less sensitive to weak jets than to twisting flow, and we started with the least drastic "fix."

Highly agitated flow compromised the reading of a flume wall gage in a trapezoidal concrete channel with a 60-cm wide bottom and 1:1 sidewall slopes. The channel was flowing at about 400 L/s. A row of standard bricks was cemented down the sides and across the bottom of the canal to form an abrupt "bump" about 5 cm high. The flow surface was then damped by the construction of a small fixed bridge about 60 cm wide with its bottom inserted into the water surface by about 5 cm. This bridge was slightly downstream from the row of bricks by perhaps one flow depth of the canal. The process severely damped the downstream water surface and provided excellent reading ability at the flume gage (Clemmens, et al., 2001). Floating wave suppressors are not recommended.

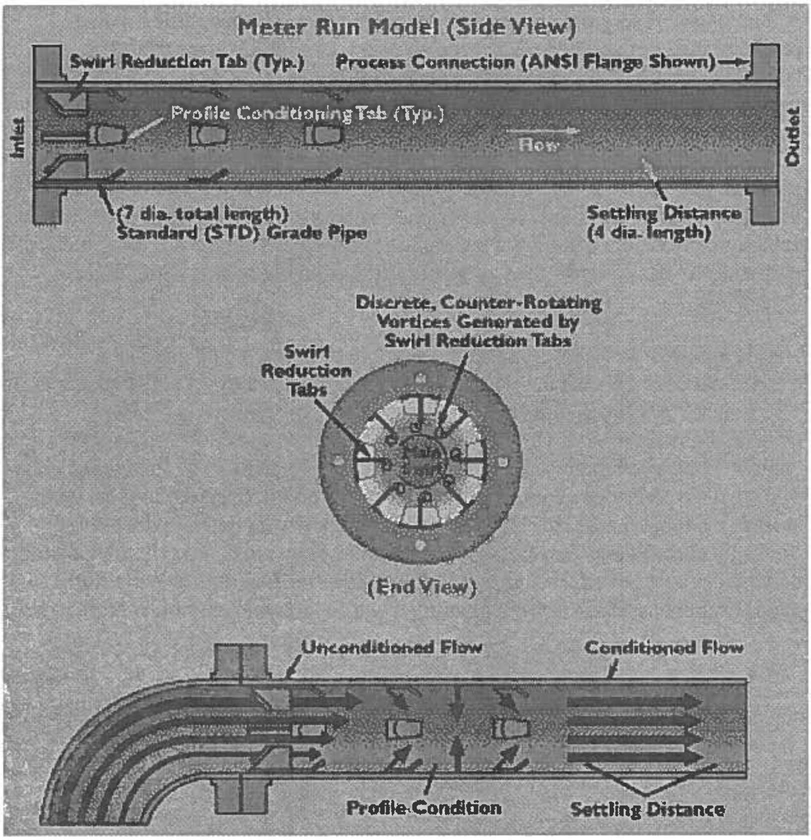


Figure 4. Vortab® flow-profile conditioner.

Commercial Flow conditioning Devices

A design objective could be to condition the flow using a length of one pipe diameter for the conditioning hardware followed by no more than two pipe diameters before reaching the metering device, for a total length of 3*D*. The objective is to present a symmetrical flow profile that may not be that of fully developed flow, but which many meters could use to produce satisfactory results for irrigation management.

A search for commercial offerings resulted in finding a device called the Vortab® flow profile conditioner, Figure 4. The head loss for most units is 0.5 to 1.0 pipe velocity heads. Swirl reduction tabs remove swirl by generating small vertices which tend to cancel the larger main swirl. Three sets of profile conditioning tabs produce cross-stream mixing, which mixes faster velocity regions with slower regions. This mixing produces a homogeneous flow profile. An additional 4-diameter length of pipe from the last profile condition tabs, allows the flow conditioning to fully occur. A flow meter would be installed somewhere at or beyond this distance. The total length is 7*D* of pipe, even for two-plane elbows, and this flow profile conditioner claims to present a fully turbulent flow profile at the7*D* location. It may have a symmetrical profile at three diameters that can suffice for many applications if the "settling" distance is sacrificed.

Work in Progress

A study has been conducted by NEL (1999) to use numerical modeling (Computational Fluid Dynamics techniques, CFD) to determine the degree of flow disturbance at the inlet of a downstream meter. They claim to be able to apply the techniques to study flow meters themselves with disturbed inlet conditions to estimate the degree of measurement error. At the time of their report, studies of orifice plates and Venturis are finished. They intend to look at ultrasonic and electromagnetic meters. These results should offer insight to the accuracy deterioration when piping requirements are compromised.

Is there an alternate design that may be more simple to manufacture than the Vortab® and be applicable to irrigation technologies? Studies like the field experiences described above are underway at the US Water Conservation laboratory. One possibility is to use vanes extending from the pipe sidewalls to a distance of 0.5 times the radius ($0.5R=D/4$). This involves the outermost 75% of the flow area. The length of these vanes should be a function of the distance between them. For example, using eight vanes, the circumference is divided into $\pi D/8$ parts, and a guess that at least twice the flow length-to-width ratio may be sufficient to satisfactorily straighten the flow, the vanes would need to be $2(\pi D/8)$ long. In general terms with n vanes, this becomes $2(\pi D/n)$ long. This does not speak to a probable need for a 3:1 sloping upstream edge to shed trash. The length of this sloping part would be $3R/2$, or $3D/4$. If half the length of the sloping vanes is considered effective, then the total length will increase by half the vane length, or $2(\pi D/\mathrm{n})+3D/8$. For example, with eight vanes, the total vane length would compute to be about 1.06*D*, with 0.75*D* of the length involved in the sloping part. The added head loss is expected to be less than the one velocity head for vanes completely across the pipe (Miller, 1996).

An orifice with a β ratio of 0.9 is to be added to the end of this structure. The resulting velocity fields at 1*D*, 2*D*, 3*D* and beyond for various disturbances are being studied. The pressure loss for an orifice to pipe ratio of 90%, ($\beta = 0.9$) is approximately 22% of the maximum differential pressure (ASME, 1959; Daugherty and Ingersol, 1954). Using this value for $\beta = 0.9$, this translates into a head loss of approximately 0.25 velocity head. However, while an orifice alone may not stop flow spin but may actually increase it, an orifice is important to block flow close to the wall (Miller, 1996). Thus, vanes placed upstream before the orifice to reduce spin would seem appropriate.

SUMMARY AND CONCLUSIONS

Several traditional recommendations for piping installation requirements for flow meters are reexamined for applications to new metering systems and to determine the expected accuracy when the traditional recommendations are not met, as is often encountered when trying to retrofit economical flow metering into exiting irrigation systems. These traditional recommendations are still valid, but are basically for older types of differential meters. They do not address the rate of accuracy deterioration as a function of deviation from the traditional piping recommendations. Similar types of recommendations for open channel devices, such as weirs and flumes, are still valid, but again do not fully address the rate of accuracy deterioration with installation anomalies. Newer types of meters for both open flow and pipe flow show variable tolerance to disturbed flow. These have not been fully studied. A limited number of recent studies do address both the accuracy deterioration and the meter tolerance issues. As might be expected, meters that sample large portions of the flow profile are more tolerant of distorted profiles than those that sample a single point and must depend on extrapolation to the entire pipe flow. For open channels, the production of smooth approach flow to weirs and flumes seems a sufficient measure to give adequate profile presentation to the metering station. Recent ongoing studies in numerical modeling are attempting to determine the rate of accuracy degradation for particular pipe installation anomalies. Commercial devices claiming to correct and present developed flow profiles within seven pipe diameters when placed downstream from flow disturbing fittings and valves are available. The design and construction of inexpensive pipe inserts are currently being tested and are meant to condition flows for most of the meters used in irrigation. These profiles, while nearly symmetrical, may be more uniform, or piston-like, than the usual, fully developed shape. These methods and their selection include effectiveness of flow conditioning, consideration of trash handling, and cost of installing the necessary equipment into the water supply system.

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