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Applying the Energy-Momentum Method to Radial Gate Discharge Calibration

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ABSTRACT

The Bureau of Reclamation (Reclamation), the Agricultural Research Service (ARS), and the Salt River Project (SRP) are collaborating to produce a practical means for applying the Energy-Momentum method to the problem of calibrating canal radial gates for the measurement of discharge. A new series of experiments conducted at the ARS hydraulic laboratory in Phoenix is being used to refine the submerged flow energy correction, a key parameter of the method, and empirical factors in the momentum equation. The experiments are also examining the feasibility of measuring the pressure in the vena contracta jet, which might simplify application by alleviating the need for applying the momentum equation. The results of the laboratory tests will be incorporated into a new computer program that will make radial gate calibration practical for a variety of situations.

INTRODUCTION

Accurate flow measurement is a basic necessity for the efficient delivery of irrigation water. Many modern methods for operating canals in a more efficient manner depend upon real-time knowledge of flow rates throughout a canal system and require the ability to quickly and easily adjust flow rates at check gates, bifurcations, and turnouts. Accurate flow measurements have traditionally been obtained from structures and equipment dedicated to that purpose (e.g., flumes and weirs). Another alternative is to make use of gates to provide flow measurement. There are several potential advantages of using gates:

- savings of cost and time associated with design, construction, or procurement of dedicated flow measurement structures and equipment,
- no additional head loss beyond that associated with existing operations, and

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- improvements in automatic control through accurate setting of gates to quickly achieve target flow rates.

In the pursuit of improved flow measurement, the highest priority needs in many irrigation systems are initially at major check structures and canal bifurcations. Radial (tainter) gates are commonly used at many of these large checks, so this type of gate is the focus of current efforts to improve flow measurement at canal gates.

BACKGROUND

Radial gates are one type of hydraulic sluice gate. Flow under a sluice gate and the calibration of sluice gates are classical problems in hydraulics, but despite many decades of research, universal calibration accuracy has remained elusive due to the complexity and variability of the flow situation. Both free and submerged flow are possible, gate seals have an important influence, and variations in the geometry of check structures can play a large role (Fig. 1).

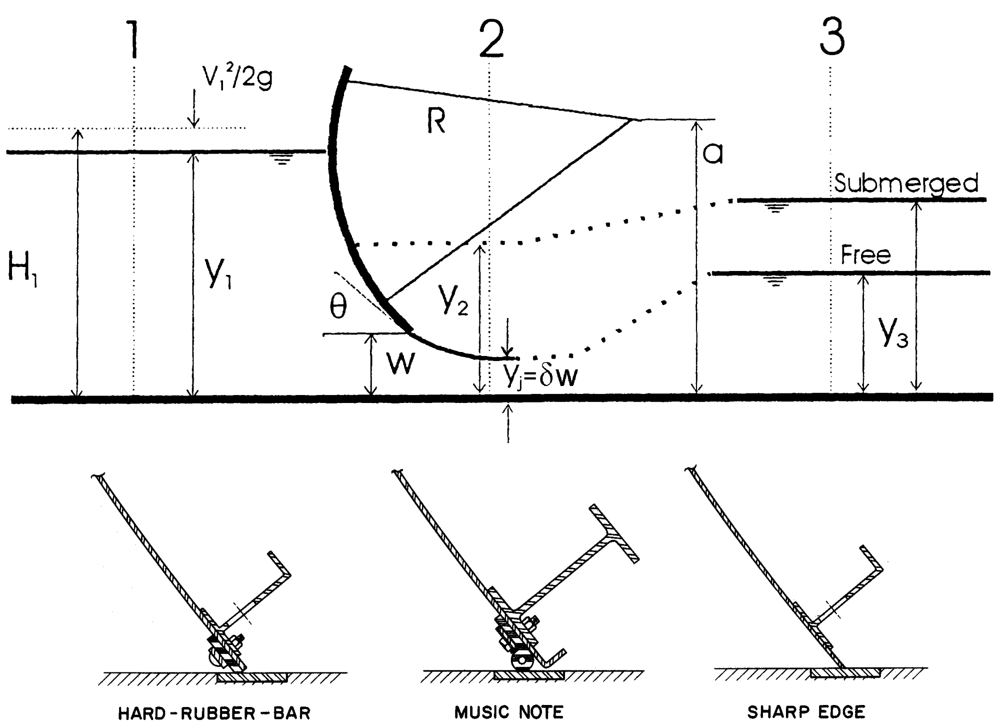

Figure 1. — Some variables affecting radial gate calibration.

Sluice gates have traditionally been calibrated by applying the energy equation across the gate, treating it as a submerged orifice. Discharge coefficients have been determined empirically by laboratory and field testing. In the case of radial gates, discharge coefficients can vary widely as a function of gate position, seal details, and other factors. Accuracy in free flow has been reasonably good in most cases, but in submerged flow, accuracy has ranged from mediocre to poor. The most difficult conditions are the transition zone from free to highly submerged flow and sites where the downstream channel is much wider than the gate chamber. In addition, the complexities of the problem demand computer software to simplify application for the end user, but existing programs (e.g., RADGAT by Buyalski 1983) are obsolete with respect to both computer technology and the underlying hydraulic algorithms.

Energy-Momentum Method for Radial Gates

Our current research is focused on a new approach to the calibration of radial gates described as the Energy-Momentum (E-M) method (Clemmens et al. 2003). This method also applies the energy equation, but only from the upstream pool to the vena contracta of the jet issuing from beneath the gate (section 2 in Fig. 1). In free flow, only the energy equation is needed. Energy losses on the upstream side of the gate and the contraction coefficient for flow through the gate opening are estimated from empirical relations. The free flow discharge equation is

$$Q = \delta w b_c \sqrt{\frac{2g(H_1 - \delta w)}{1+\xi}} \qquad (1)$$

in which Q is the discharge, δ is the contraction coefficient, w is the vertical gate opening, b_c is the gate width, g is the acceleration due to gravity, H_1 is the total head at section 1, and the quantity $1+\xi$ accounts for energy losses on the upstream side of the gate and the effects of nonuniform velocity distribution at the vena contracta. In free flow, the method provides flow measurement accuracy approaching that of flumes and weirs. The greatest source of uncertainty in most cases is the contraction coefficient, which is affected by the presence and condition of gate seals. The majority of laboratory testing has been performed on sharp-edged gates (no seal).

In submerged flow, the energy equation is still applied from section 1 to the vena contracta. The calibration equation for submerged flow is

$$Q = \delta w b_c \sqrt{\frac{2g(H_1 - y_2 + E_{\text{corr}})}{1+\xi}} \qquad (2)$$

where y_2 is the depth immediately downstream from the gate and E_{corr} is an energy correction term. The energy correction accounts for the fact that in slightly submerged flow, the jet at the vena contracta is thickened and slowed by the adverse pressure gradient created in the partially submerged hydraulic jump that takes place on the downstream side of the gate (as suggested by Tel 2000). This change in the hydrodynamics of the jet reduces the total energy head at the vena contracta, increasing the net energy available to drive flow through the gate. As a result, in the transition zone there is not a one-to-one correspondence between increases in the y_2 depth and the y_1 depth at a given constant flow rate (Clemmens et al. 2001a) as one would otherwise expect for an orifice-controlled flow; the tailwater conditions only slightly affect the performance of the gate in this region, with the tailwater influence increasing as the submergence increases.

To apply eq. (2), one could measure y_2, but in practice it has been difficult to accurately measure y_2 in the field, so the momentum equation is applied from section 2 to section 3:

$$Qv_e + b_c g \frac{y_2^2}{2} + \frac{F_w}{\rho} = Qv_3 + \frac{F_3}{\rho} + \frac{F_{\text{drag}}}{\rho} \qquad (3)$$

where v_e is an effective velocity in the jet (see Clemmens et al. 2003), ρ is the fluid density, F_3 is the hydrostatic pressure force exerted by the downstream water depth, F_w is the streamwise component of the force of water on all surfaces between sections 2 and 3, including hydrostatic forces on all walls, and F_{drag} is the drag force on the channel boundaries. This allows y_2 to be estimated from a depth measurement, y_3, made in a zone of quiescent flow.

The use of an effective velocity in eq. (3) rather than the jet velocity accounts for the increased thickness and reduced velocity of the submerged jet, as discussed earlier, which is also accounted for by the E_{corr} term in the energy equation (see Clemmens et al. 2003). The hydrostatic force F_w is computed from an effective water depth, y_w, computed as a weighted average of y_2 and y_3. The drag force has generally been neglected thus far since velocities downstream from the vena contracta are low in submerged flow conditions, but it is likely to be important in some special situations, such as parallel operation of gates in a mixture of free and submerged flow conditions (Clemmens 2004).

Clemmens et al. (2003) described the Energy-Momentum method in greater detail and provided empirical relationships for δ, $1+\xi$, E_{corr}, and the weighting parameter needed to estimate F_w. These relationships were developed using data collected by the Agricultural Research Service (ARS) in their laboratory at Phoenix, Arizona (Tel 2000).

Submerged Flow Energy Correction

The energy correction model developed by Clemmens et al. (2003) was based on data collected by Tel (2000) from a relatively small range of flow conditions comprising four flow rates at a single gate position, with varying upstream and downstream depths. Values of E_{corr} were computed using eq. (3), with the y_2-depth determined by measurement of the static pressure in the vena contracta jet using a Prandtl tube. Clemmens et al. (2003) speculated that the energy correction relationship might vary as a function of the relative gate opening, w/H_1, but this could not be verified from the limited data.

Wahl (2005) used a data set collected at the Bureau of Reclamation (Buyalski 1983) to examine the energy correction in more detail. The data set contained only measurements of y_3, so y_2 was determined by solution of the momentum equation, eq. (3), neglecting the drag term. Wahl's analysis showed that the relative jet thickness, y_j/H_1, (similar to w/H_1, except that w/H_1 includes the contraction coefficient) was an important parameter affecting the relationship between the relative energy correction and the relative submergence. Wahl (2005) developed a new model for the energy correction that significantly improved the accuracy of calibrations in the transition zone.

NEW EXPERIMENTAL WORK

Despite the progress made thus far, several issues still needed to be addressed to improve and apply the Energy-Momentum method.

- More experimental data are needed (especially at very slight submergence levels) to help resolve differences between the models for E_{corr} developed by Clemmens et al. (2003) and Wahl (2005) (Fig. 2), and to obtain data at relative gate openings greater than 0.667, for which free flow cannot exist and the value of δ must be extrapolated.

- The weighting factor used to determine the effective force on the walls of the downstream channel expansion needs to be investigated in a wider variety of flow situations and structure configurations.

- The possibility of measuring y_2 directly in the field using a measurement of vena contracta pressure should be investigated.

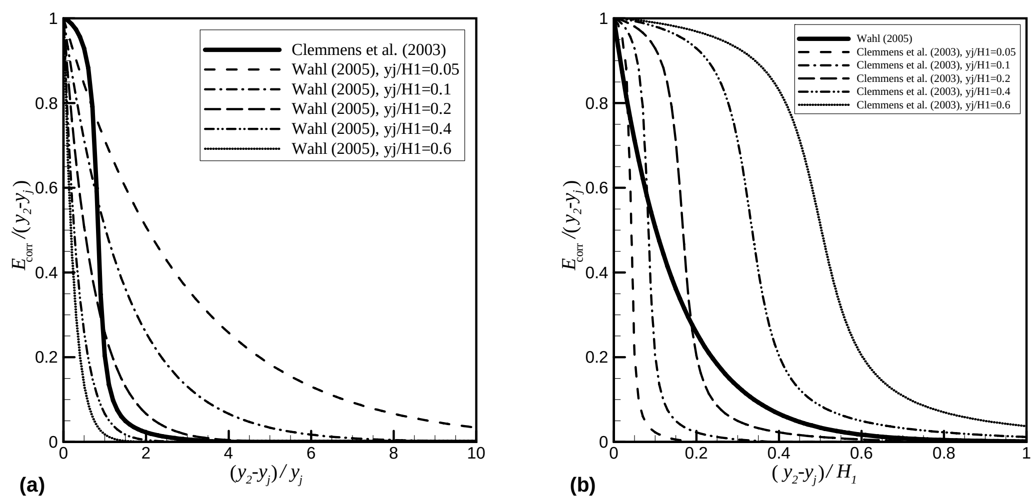

Figure 2. — Comparison of E_{corr} relationships developed by Clemmens et al. (2003) and Wahl (2005).

The difference in the energy correction models is illustrated in Figure 2. The relation developed by Clemmens et al. (2003) produces a single curve relating $E_{corr}/(y_2-y_j)$ to $(y_2-y_j)/y_j$, the increase in jet thickness nondimensionalized by the jet thickness itself. The relation developed by Wahl (2005) produces a family of curves for different values of the relative jet thickness, as shown in Figure 2(a). In Figure 2(b) the situation is reversed when we relate $E_{corr}/(y_2-y_j)$ to $(y_2-y_j)/H_1$, the increase in jet thickness nondimensionalized by the upstream energy head. Wahl's relation produces a single curve, while the Clemmens et al. equation would yield a family of curves. Moreover, in areas where the curves overlap one another, their basic forms are different, and this is a point that we hope additional testing will resolve.

In late 2004 a new series of laboratory tests were initiated at the U.S. Water Conservation Laboratory in Phoenix, Arizona. This work is being performed primarily by ARS personnel, with technical assistance from Reclamation. In addition, the Salt River Project is simultaneously funding work by Reclamation on the development of a user-friendly computer program for calibrating radial gates for discharge measurement. The initial software development will be focused on a stand-alone Windows-based program, with other implementations possible in the future.

The new tests utilize the same gate originally supplied by SRP for testing by ARS (Tel 2000). For the previous testing the gate was installed with a tailwater channel about 2 times wider than the gate; in the new tests the tailwater channel will initially match the gate width (eliminating F_w from the momentum equation), and then in later tests the channel will be widened to about twice the gate width.

The radial gate being tested is constructed from aluminum with a sharp-edged leaf (no seal on the lower lip). The gate is 1.5 ft (0.4572 m) wide, and the gate-arm radius is also 1.5 ft (0.4572 m). The gate is set between two side walls that are 4 ft (1.219 m) long. The trunnion pin height is 1.2 ft (0.3658 m), and is located 0.3 ft (0.091 m) upstream from the downstream end of the side walls, which, if scaled, is typical of SRP installations. Entrance transitions with a 1.28 ft (0.39 m) radius were constructed to avoid a blunt entry into the gate structure. The flume in which the gate is installed is 4 ft (1.22 m) wide, 2 ft (0.61 m) high, and 50 ft (15.2 m) long. The upstream and downstream water levels are measured 11.5 ft (3.5 m) upstream and 16 ft (4.88 m) downstream from the gate trunnion pin, respectively.

Tests are being performed at gate openings ranging from 5 cm to 20 cm, and at upstream and downstream water levels that produce relative gate openings, w/H_1, of 0.1 to 0.9. For w/H_1 ratios less than 0.667, tests include both free and submerged flow conditions; at larger w/H_1 ratios, only submerged flow is possible.

Experimental Procedure

Tests are being performed initially with a set of false walls installed downstream from the gate so that the downstream channel matches the gate chamber width. The gate position is set using a machined block and fixed for each series of tests. Flow to the test flume is provided from a constant head tank, so discharges are the same for all tests in a sequence, although independent measurements of discharge are made at each flow condition. Two types of tests are being run. In the first type, we start with free flow controlled by the gate and increase the tailwater incrementally to produce desired submerged flow conditions. In the second series of tests, we start with a flow that is free, but not controlled by the gate (the gate is out of the water), and the tailwater is then increased to bring the gate into contact with the flow and incrementally increase the upstream and downstream water levels.

In free flow conditions, the upstream (y_1) and downstream (y_3) water levels are measured using static tubes connected to stilling wells equipped with point gages. The upstream water level is also verified by a point gage reading on the upstream pool. The flow depth at the vena contracta (y_j=y_2 in free flow) is measured using two methods, a point gage lowered to the surface of the jet, and a Prandtl tube that senses the pressure in the jet. During shakedown testing, to determine the location of the vena contracta, point gage and pressure measurements were made at several distances downstream from the gate lip, and pressure measurements were made at different depths within the jet.

RESULTS

Our plan for analysis of the collected data is to:

- use the free-flow measurements of gate opening and jet depth/thickness at the vena contracta, y_j, to confirm the previously established relationship (Tel 2000; Clemmens et al. 2003) for the contraction coefficient, δ,

- use eq. (1) and the free-flow measurements of discharge, head, and jet thickness to confirm the existing relationship (Clemmens et al. 2003) for the upstream energy loss and velocity distribution factor, 1+ξ,

- use eq. (2), the relationship for 1+ξ, and the measurements of discharge, head, and y_2 depth at the submerged vena contracta to solve for values of E_{corr}.

For those submerged flow tests that had a preceding free flow test at the same discharge, the last task could make use of either the measured jet thickness ($y_j=\delta w$) from the free flow test, or a value of δw computed from established relationships. An alternative method for computing E_{corr} is to use the momentum equation (eq. 3) to solve for y_2 using the measured y_3 and discharge (assuming a drag coefficient or neglecting the drag). The energy equation can then be used to solve for E_{corr}. Iteration is required because the value of E_{corr} affects the value of the effective velocity, v_e, which appears in the momentum equation (see Clemmens et al. 2003).

This approach to the analysis depends of course, on being able to locate the vena contracta and measure the free flow jet thickness. We initially intended to determine the free flow jet thickness primarily by using the Prandtl tube to measure the pressure in the jet. This would allow the use of the same measurement technique in both free and submerged flow, since a point gage could not be used to measure the y_2-depth in submerged flow due to excessive turbulence and water surface unsteadiness.

Many previous studies have measured the jet thickness at two gate openings (2w) downstream from the gate lip. Our initial measurements showed that the pressure distribution at this location is not hydrostatic. Prandtl tube measurements made near the floor of the channel indicated a significantly greater depth than that indicated by a point gage. As the Prandtl tube was moved toward the surface of the jet, the pressure measurements and corresponding point gage measurements converged. Subsequent measurements have been somewhat contradictory, and we are still working to resolve this issue. For now, we have collected most of the jet pressure data at a distance of 3*w* downstream from the gate lip.

Data collection and analysis are continuing at this time. With the data collected thus far, we have made a preliminary analysis of the values of the energy correction. E_{corr} values have been computed using the two different approaches outlined earlier. The calculations shown here have utilized existing relations for δ and $1+\xi$.

Using the y_2 values determined from the Prandtl tube measurements, E_{corr} can be computed directly from the energy equation (eq. 2). Figure 3 shows the results. Clearly there is a better fit of the data to the Clemmens et al. (2003) equation than to the Wahl (2005) equation. Furthermore, in Figure 3(a) there appears to be little dependence on the relative jet thickness.

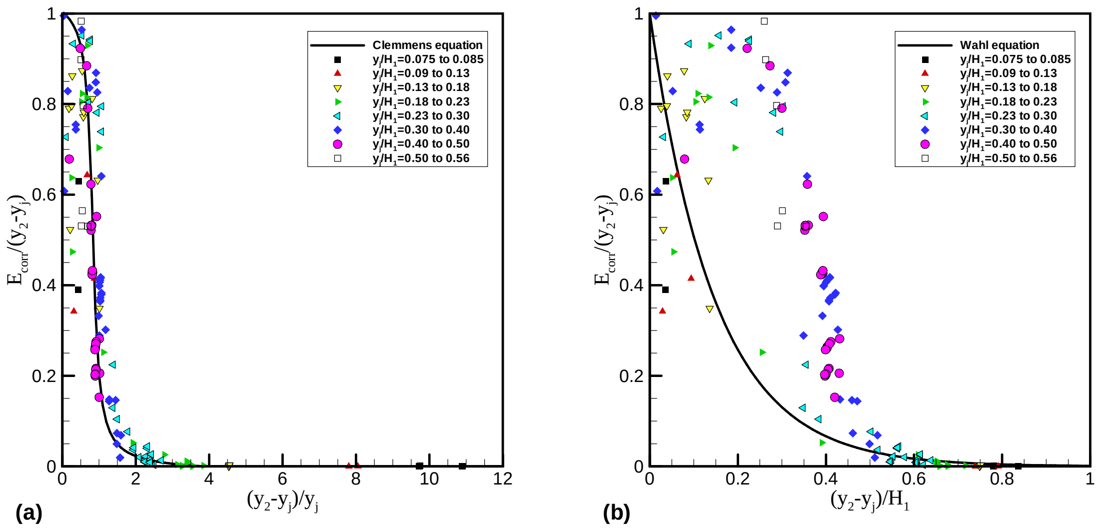

Figure 3. — E_{corr} values computed from the measured values of y_2.

The second approach to computation of E_{corr} is the iterative solution of the energy and momentum equations. A drag coefficient of 0.00235 was assumed for fully developed turbulent flow (Clemmens et al. 2001b). Including the drag coefficient provided some stability to the numerical solution technique. Without any drag force included, the iterative solution did not converge in a significant number of cases, but with the drag force included, convergence was achieved on every test. Figure 4 shows the energy correction values computed by this technique. The comparison in Figure 4(a) to the Clemmens et al. (2003) equation is poor compared to that in Figure 3(a), whereas the comparison in Figure 4(b) to the Wahl (2005) equation is better than that in Figure 3(b), although it appears there is still some deviation from the curve, perhaps due to the value chosen for the drag coefficient. Figure 4(a) suggests that perhaps the best model to fit the E_{corr} values computed in this manner would be a relation having the form of the Clemmens et al. (2003) equation, but modified to produce a family of curves when $E_{corr}/(y_2-y_j)$ is plotted versus $(y_2-y_j)/y_j$.

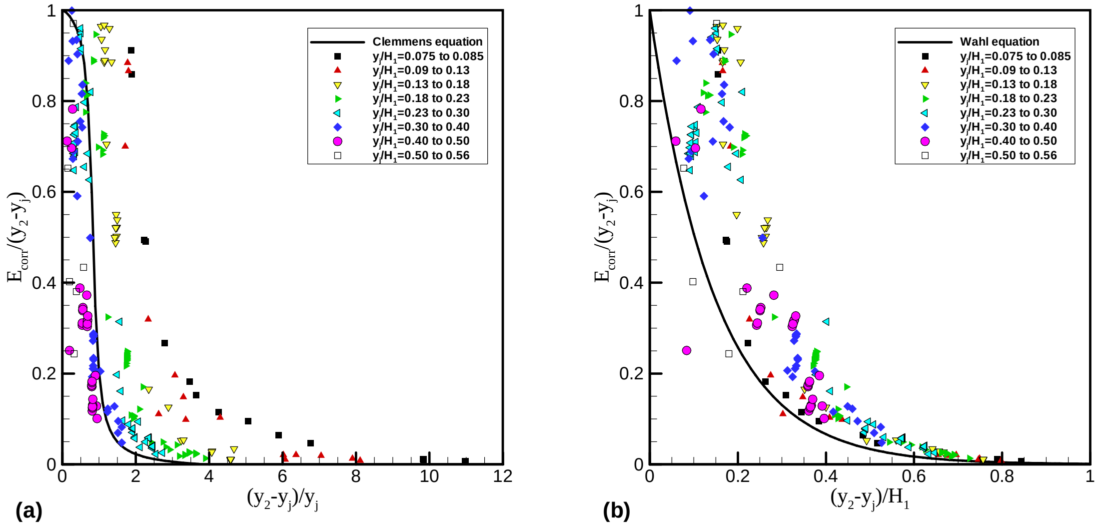

Figure 4. — E_{corr} values computed from the measured values of y_3, by iterative solution of the energy and momentum equations.

DISCUSSION

Measurement of flow using radial gates in field applications could be accomplished by two different approaches. The data we have collected thus far show that the application approach selected should determine which energy correction model is most appropriate. The energy corrections we compute from measured values of y_2 and those computed from measured values of y_3 are not equivalent. Possible explanations for this are nonhydrostatic pressure distribution and/or nonuniform velocity distribution downstream from the gate.

With a suitable method for measuring the y_2-depth downstream from the gate, discharge can be calculated using the energy equation and empirical relations for the contraction coefficient and the energy loss and velocity distribution factor, $1+\xi$. This approach could alleviate difficulties anticipated with side-by-side gates operating at different gate settings (and possibly in different flow regimes). It also would avoid the need to estimate forces on downstream channel boundaries, since the momentum equation would not be used. The challenge will be to develop durable instrumentation that can effectively measure y_2 over a range of gate openings and flow conditions. For this application approach it appears that the Clemmens et al. (2003) equation is the best method presently available for computing the energy correction.

If adequate means of measuring y_2 in the field cannot be developed, then gate calibration will require the use of the energy and momentum equations and a measurement of y_3 downstream from the gate. For this type of application, the energy correction should be computed by a method that is itself developed from similar measurements of y_3 and iterative solution of the energy and momentum equations. At this time it appears that the Wahl (2005) equation, which was developed in this manner, is superior to the Clemmens et al. (2003) equation, which was developed from measurements of the y_2-depth. However, the data suggest that a modified form of the Clemmens et al. (2003) equation might be superior to both. This possibility will be pursued as the experimental program and data analysis continue. Computer software presently under development will be designed with the flexibility to use different algorithms suitable to alternative methods of field application.

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