Paper No. 002075
An ASAE Meeting Presentation

UILU-ENG 2000-7033

FLOW MEASUREMENT AND CONTROL SYSTEM FOR PRECISION LAND APPLICATION OF LIQUID MANURE FROM VACUUM LOADED SLURRY TANKS

by

Ted L. Funk

Department of Agricultural Engineering
University of Illinois
Urbana-Champaign

Written for Presentation at the
2000 ASAE Annual International Meeting
Sponsored by ASAE
Milwaukee, Wisconsin
July 9-12, 2000

Summary:
An economical and accurate method for variable rate land application of manure slurry via slurry tankers is needed for US livestock farmers. For purposes of developing such a system, the discharge port of a vacuum loaded slurry tank was fitted with a flow measuring and controlling device consisting of a pneumatically operated elastomeric pinch valve and an air bleed pressure sensing circuit. The system was tested with three different applicator devices at flow rates varying from zero to full flow. The pinch valve was treated as a variable area obstruction flow meter and flow v. pressure characteristic functions were determined for a range of operating conditions using water as the test fluid.

Keywords:

Site specific agriculture, liquid manure application, pinch valve

Flow Measurement and Control System for Precision Land Application of Liquid Manure from Vacuum Loaded Slurry Tanks

Ted L. Funk[1]

Abstract

An economical and accurate method for variable rate land application of manure slurry via slurry tankers is needed for US livestock farmers. For purposes of developing such a system, the discharge port of a vacuum loaded slurry tank was fitted with a flow measuring and controlling device consisting of a pneumatically operated elastomeric pinch valve and an air bleed pressure sensing circuit. The system was tested with three different applicator devices at flow rates varying from zero to full flow. The pinch valve was treated as a variable area obstruction flow meter and flow v. pressure characteristic functions were determined for a range of operating conditions using water as the test fluid.

Introduction

The livestock industry's reliance on liquid manure technology has not diminished with the major changes in economic structure. While the rate of construction of new livestock facilities in the US fluctuates rapidly, there is constant pressure from environmental interests forcing producers to do a better job of manure handling.

Variable rate technology in land application, and particularly with vacuum slurry tanks, answers a need for manure nutrient accountability, automation and accurate records (Morris et al, 1999). A reasonable expectation for slurry application is that a producer should be able to drive a tanker to the field, set the appropriate slurry application rate from the tractor seat, and accurately spread one load of slurry, or thirty loads, without having to worry about over- or under-applying nutrients. Slurry tankers with variable rate equipment, incorporating expensive magnetic flow meters and electrically regulated valves, are available from a couple of North American manufacturers, but the hardware for flow metering and interfacing to GPS control is very costly compared to the investment in the tanker alone. Large livestock corporations have demonstrated that they will purchase today's expensive variable rate slurry application systems, while the smaller independent operations do not have access to such luxury. Meanwhile the small operations continue to use unregulated slurry tanks and guess at the application rates being delivered to the field, to the detriment of the industry.

The goal of this research was to make progress toward affordable variable rate slurry application technology by exploring an alternative to the "gold standard" magnetic flow meter and its related hardware.

Objectives

The specific objectives of this phase of the project were:

[1] Extension Specialist and Assistant Professor, Department of Agricultural Engineering, University of Illinois at Urbana-Champaign.

Valve characterization. Measure the pressure v. flow characteristics of a pneumatic pinch valve, to be used as a flow metering and measurement device on vacuum loaded slurry tanks.

Pressure sensor circuit. Develop a pressure sensing circuit suitable for use in slurry measurements.

Procedure

A test apparatus was built incorporating features that ostensibly could be part of a field-ready prototype, and stationary tests were run at the University of Illinois Department of Agricultural Engineering laboratory facilities.

The system consisted of a prototype slurry spreader consisting of a commercially available vacuum slurry tank, pinch valve and pneumatic pressure sensing array, slurry broadcast device with orifice and splash plate, and soil injection toolbar.

Slurry tank. The slurry tank used was a twin-axle unit (Better-Bilt™ Model 2600VT, Top Air Incorporated, Cedar Falls, IA)[2] with rear discharge and a PTO-operated vacuum/pressure air pump capable of maintaining approximately one atmosphere of pressure on the tank during discharge of the tank's contents. A pressure relief valve on the tank prevented over-pressurizing the vessel (Fig. 1).

The rear mounted 15 mm (six inch) discharge was fitted with a hydraulically operated gate valve which was fully open during testing.

Pneumatic pinch valve. The pinch valve has become a common element in wastewater treatment systems because of the valve's inherent non-clogging construction (Fig. 2) and its ease of connection to automatic controls. In this project a pneumatically operated pinch valve was interposed between the slurry tank discharge and the slurry application device (broadcast device for one set of tests, and the soil injection toolbar for another set.) The pinch valve served both as a flow metering and flow measuring device, where the valve acted as a variable-area obstruction flow meter.

Three different pinch valves were tested:

- 102 mm (four-inch) Red Valve™ [Red Valve Company, Inc. Pittsburgh, PA] Type A.
- 102 mm (four-inch) Elasto-Valve™ type AJ-AL [Elasto-Valve Rubber Products Inc., Sudbury, ON],
- 152 mm (six-inch) Red Valve™ Type A).

The smaller diameter valves were useful in early tests because of their smaller bulk, and were evaluated to see how their flow characteristics compared. Since the discharge pipe on the slurry tank was 152 mm (six inches), a reducer between the tank and the four-inch valves had to be used. The reducer may have been the cause of undesirable and confounding flow instabilities at high flow rates, and the research team felt that a six-inch valve should also be tested because of the smaller valves' flow limitations. A 102 mm (four-inch) control valve would unduly restrict the unloading rate of most slurry tanks currently being marketed, which are equipped with larger diameter discharges. Only the 152 mm (six-inch) valve tests are reported here.

---

[2] Use of trade names does not imply product endorsement by the University.

Broadcast slurry device. The tank was supplied with a quick-coupled broadcast device consisting of a 90-degree sweep elbow and detachable orifice with a splash plate (Fig. 3). The 102 mm (4-inch) sweep elbow was reduced from the nominal discharge diameter by a series of two pipe reducers in a welded assembly. Orifice diameter was 51 mm (2 inches).

Flow tests were conducted with the orifice in place and removed.

Soil injection toolbar. A five-shank soil injection toolbar (Top Air™) (Fig. 4) was supplied which was attached to the slurry tank for the final series of tests.

Tank and weigh cells. Flow rates in the first prototype development stage were obtained by time-based weight changes of the total slurry tank system, as measured by an interconnected set of five portable electronic scales (four under the wheels and one under the hitch, Fig. 5) (wheel scales Model PT300™, Intercomp, Minneapolis, MN). The slurry tank and scales served as a portable "hydraulics table."

Test fluid. Using clear water as the fluid, flow rates out of the tank and pressures were measured to characterize the pinch valve and produce a prediction function.

Pressure sensor circuit. Since the pinch valve required regulated air pressure for its flow-control activation, the research team decided to develop a low-cost, reliable pressure sensing circuit connected to the same air supply. (Another phase of the project will incorporate a mobile air supply using 12-volt power supply from the tractor.) To measure liquid differential pressure across the pinch valve being tested, a pneumatic bubbler arrangement was built which incorporated inexpensive differential pressure transducers (Model PX 137-030, 0-90 mV at 0-207 kPa [0-30 psi], 12-v excitation; Omega Engineering™) on the pneumatic supply lines (Fig. 6).

Liquid pressures on either side of the pinch valve were measured as the air pressure in the supply lines between the 0.51 mm (0.020 inch) stainless steel restrictor orifices and the liquid main conduit from the slurry tank. Bourdon-tube pressure gauges were used for data validation. A rotameter in each bubbler line provided a visual check that the air-bleed orifices remained unclogged during the tests. A third pressure sensor measured air activation pressure on the case of the pinch valve.

The test setup is shown in Fig. 7. An electrical analog of the system (Fig. 8) encompasses all components and shows the points of pressure measurement.

Steady state testing. Steady state measurements were obtained by opening the gate valve ahead of the pinch valve and adjusting the air pressure regulator to obtain the desired pinch valve case gauge pressure (indicative of the amount of the pinch valve opening, a higher case pressure causing more restriction of the valve). Once the flow stabilized, the tank weights were read manually and recorded alongside the elapsed time, and at the end of the run the weights were matched up with the automatically recorded pressure readings.

Results

The electrical analog (Fig. 8) shows the principles of the pressure measurements needed for the slurry tank system. Slurry leaving the tank is at a gauge pressure that includes the tank headspace pressure, due to the tank air pump, plus the liquid head. Maximum headspace pressure is on the order of one atmosphere, but a popoff valve at the pump rather loosely regulates headspace air pressure. The slurry encounters a pressure drop across the vena contracta, shown as R1, as it enters the discharge pipe at the tank bulkhead. Next the pinch valve, shown as variable resistance R2, provides a second pressure drop. Finally there is a pressure drop between the outlet of the pinch valve and the point of injection in the soil, R3. The only significant part of R3 is the distribution manifold atop the toolbar (Fig. 4) since the manifold has a plate orifice at the opening of each of the injection sweep supply hoses.

By correctly measuring pressures across the resistances R2 and the sum of R2 and R3 (all non-linear resistances) we can hope to account for the pinch valve restriction and the injection toolbar pressure drop.

Valve characteristics. Since the pneumatic pinch valve was opened and closed for flow control, the pressure v. flow characteristics were measured and recorded as specific to a system, which comprised the tank, valve and slurry discharge attachment.

Three different pneumatic pinch valves and three slurry discharge attachments were evaluated. The results of the 152 mm (six inch) pinch valve tests are given in this paper.

Steady state tests

Each system tested exhibited distinct flow v. pressure characteristics, as expected. Since pressures were measured at four points (including atmospheric pressure) along the flow and between adjacent components, the characteristics of each component in the system could be split out from the others.

The flow v. pressure characteristics of the valves were well behaved functions for all systems where the pinch valves were partially closed. As expected, a fully opened pinch valve displayed no appreciable pressure drop since the cross sectional area of the valve when opened was constant and its diameter was equal to the entrance and exit tubing diameters.

Figures 9 through 11 are compilations of twenty-four steady-state test results, performed with the "broadcast" application devices in place – the 90 degree elbow alone and the elbow with the orifice and splash plate in place.

Two series of pressure drop measurements are significant: (1) the pressure drop across the pinch valve, and (2) the (gauge) pressure upstream of the application device – the 90 degree tube, the tube plus orifice and splash plate, or the soil injection toolbar, depending on the test.

The pressures upstream of the application device are given in Fig. 9. For clarity, only the higher flow ranges are included in the graph, since only in those ranges do the application device pressure drops appear to throttle the flow from the tank. Note the two groups of points, one with the discharge orifice in place and one without the orifice.

Pressure drops across the pinch valve are shown in Fig. 10. All 24 test points – low and high flow rates, with and without orifice -- are included. Note that at the low flow rates the pinch valve pressure drops follow reasonably good prediction curves, the results without the orifice at low flow rates being exceptionally well behaved.

Perhaps the most useful graph is that showing the sum of the pinch valve and application device pressure drops (Fig. 11). For one thing, the devices at low flow rates have fairly linear responses. In addition, the results show that perhaps a single pressure tap, upstream of the pinch valve, could give all the information needed to predict slurry flow from the tank once calibration of the system was performed. At the higher flow rates the flow was apparently controlled by the sum of tank pressure, the vena contracta (fluid entrance to the tank discharge) and the slurry application device. At the higher flow rates the variances are significantly greater, possibly attributable to the limitations of the scales' sampling rate and the rapid manual reading of the weight values.

Temporal response

Analysis of the time based pressure records (Figure 12 as an example) yielded an estimate of the slope of the response rate of the pinch valve, given a supply air pressure of approximately 620 kPa (90 psi) available and using a manual air pressure regulator on the pneumatic pinch valve case.

Response to an increasing step input was approximately 29 to 36 kPa/s (4.2 to 5.2 psi/second); to a decreasing step input, approximately -2.3 to -4.0 kPa/s (–0.34 to –0.58 psi/second).

Pressure sensing circuit. The air bleed pressure sensing circuit performed to expectations, was simple to interface and inexpensive, and used the same supply air pressure as the pneumatic pinch valve actuation.

Discussion

The obstruction flow meter is one of the oldest methods used for fluid flow measurement in pipes. The venturi, nozzle and orifice have all been thoroughly characterized for homogeneous fluids, and standards developed for their construction and use in systems.

Using a pneumatic pinch valve as an obstruction flow meter is different from traditional means because (1) the streamline contour of the pinch valve is not as predictably shaped as the rigid venturi, nozzle, or orifice, and (2) the pinch valve cross section changes as the valve is opened and closed. However, a pinch valve has a major advantage in controlling the flow of slurries because the valve cannot be clogged with slurry solids; depressurizing the case of the pinch valve can easily clear an obstruction as the elastomeric element returns to its relaxed tubular shape.

Precision needed in variable rate application technology. Realistic expectations for the flow measurement do not include the precision required of rigid obstruction flow meters (typically a fractional percent of full flow). However, the guiding function for slurry land application indicates that precision on the order of +/- 10% is adequate (Funk and Campbell 1997).

Temporal response. Given the temporal response of the system evident in the laboratory setup, it is apparent that such a system in the field might require several seconds to fully respond to a step input of any appreciable magnitude. For example, an input flow rate change of 50% necessitates a change in case pressure of about 69 kPa (10 psi). An increasing step input would take about 2 seconds, but a decreasing step input of the same magnitude would require an agonizingly slow 20 seconds. A more rapid response would be needed for satisfactory field operation (Munack 1999). An appropriately sized regulator, tubing and fittings appear to be an immediate need for the system prototype.

Further research needs. Flow tests in the transition regions between valve control and injection tool/tank control must be done to determine flow characteristics at those important flow rates. Once the prototype system is complete, testing with slurries of varying solids content must be done to develop characteristic flow v. pressure curves for manure. System response to transient inputs must be determined and supporting hardware sized to deliver the temporal response required for field operation. Finally the slurry application hardware must be tested with a GPS interface to complete the control system.

Summary

Results of the flow tests of a prototype variable rate slurry applicator system indicate that an alternative to expensive flow meters might be found in a pneumatically actuated elastomeric pinch valve with a simple pressure measuring device. Especially at lower flow rates, the fluid pressure measurements gave good prediction of the fluid flow rate from the slurry tank. Further work is expected to refine the prototype design and culminate in an affordable, reasonably accurate variable rate system adaptable to a large number of US livestock farms.

Acknowledgements

The author gratefully acknowledges funding support by the Illinois Council on Food and Agricultural Research, and the loan of slurry tank equipment by Top Air Incorporated, Cedar Falls, IA.

Appreciation is extended to Mr. Alfonso Guativa and Mr. Jeffrey Dauderman for their diligence in conducting these experiments.

References

Funk, T.L. and W.P. Campbell. 1997. The Illinois manure management plan. In, Proceedings, 1997 Livestock Waste Management Conference, University of Illinois Extension, University of Illinois at Urbana-Champaign, pp. 81-90.

Morris, D.K., D.R. Ess, S.E. Hawkins, and S.D. Parsons. 1999. Development of a site-specific application system for liquid animal manures. Applied Engineering in Agriculture 15(6):633-638.

Munack, A. 1999. High precision control system for spreading of liquid manure. ASAE Paper No. 99-1104. ASAE, St. Joseph, MI.

Figure 1. Vacuum loaded slurry tank used for flow v. pressure testing.

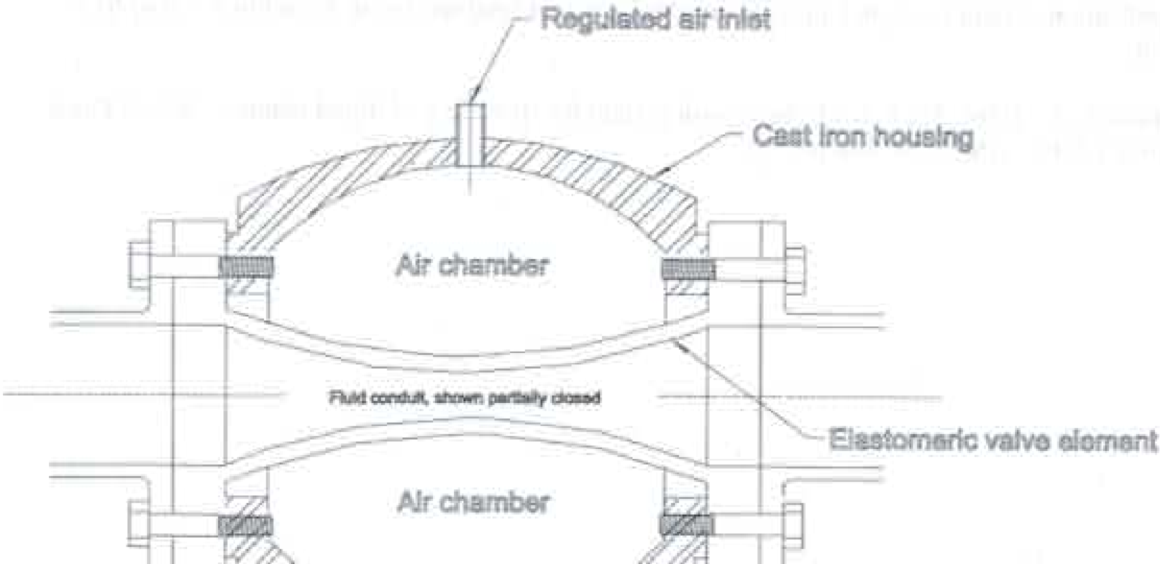

Figure 2. Cross section of elastomeric pinch valve used for slurry flow control and flow measurement.

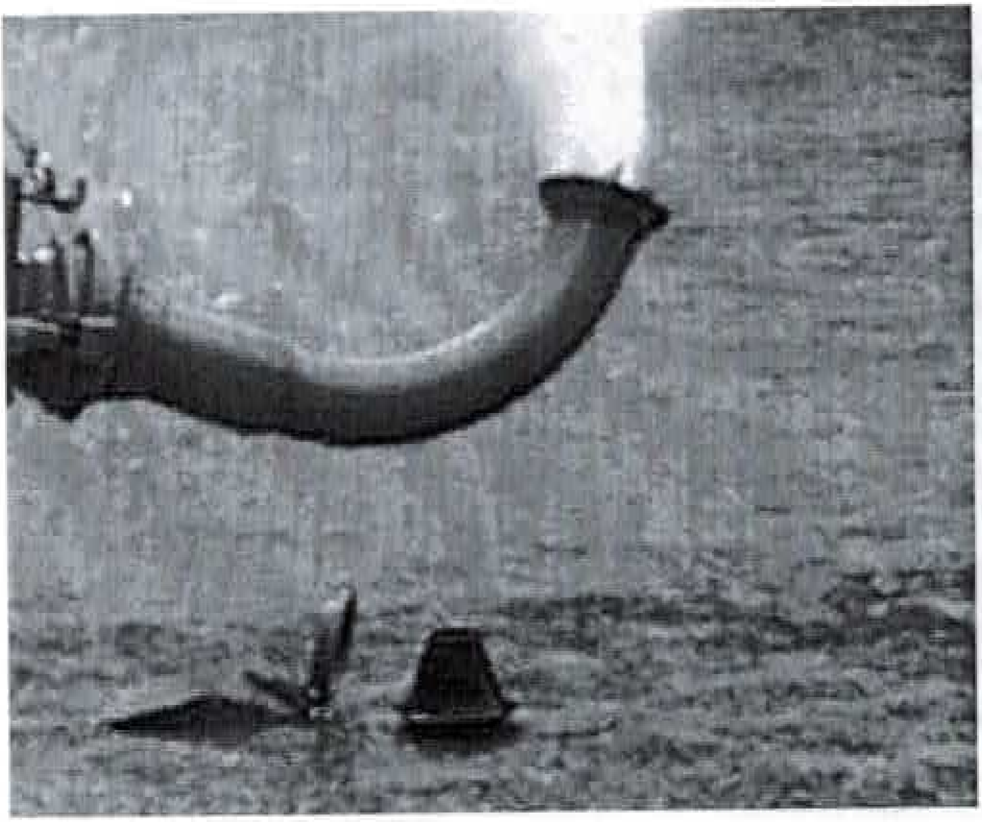

Figure 3. Applicator discharge attachments used. 90 degree elbow, orifice and splash plate (shown removed.)

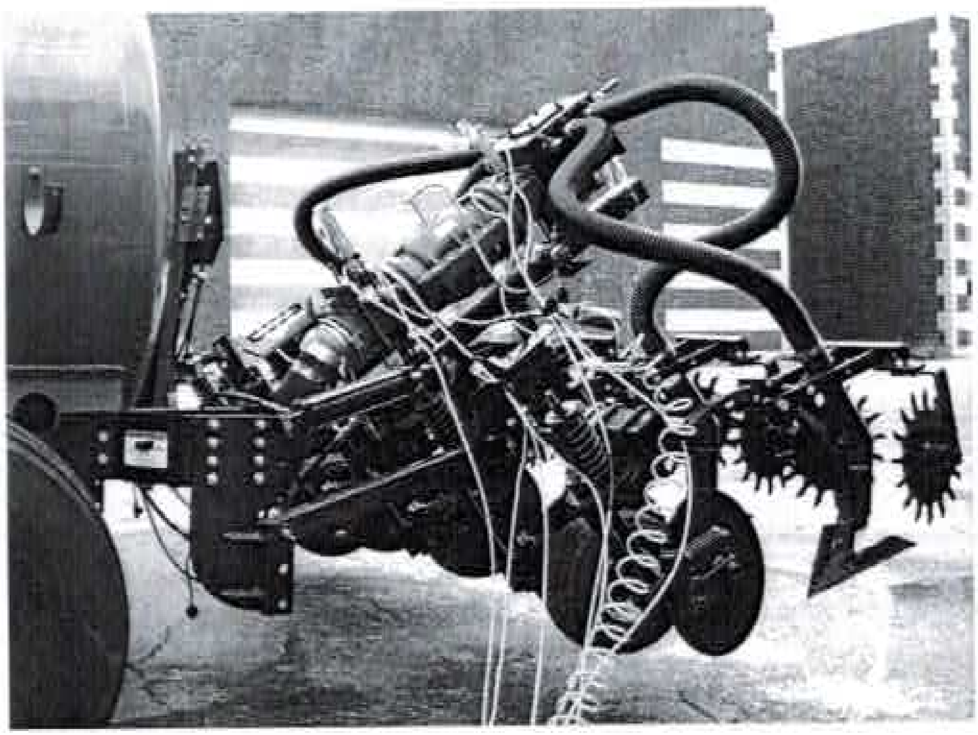

Figure 4. Soil injection toolbar.

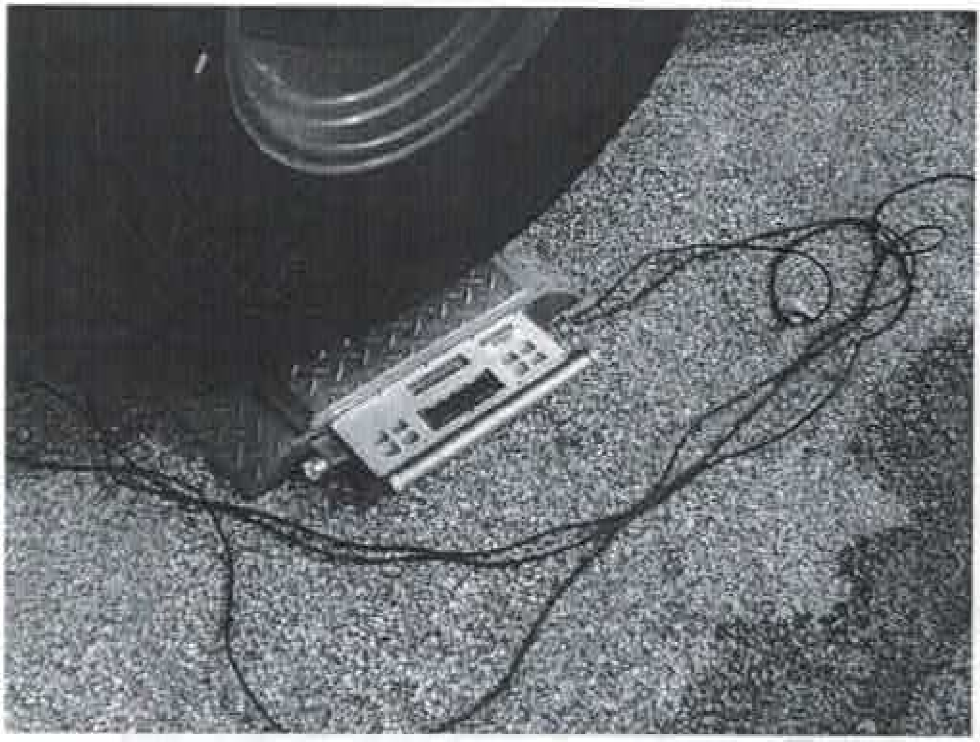

Figure 5. One of five interconnected wheel scales used for monitoring slurry tank weight during flow tests.

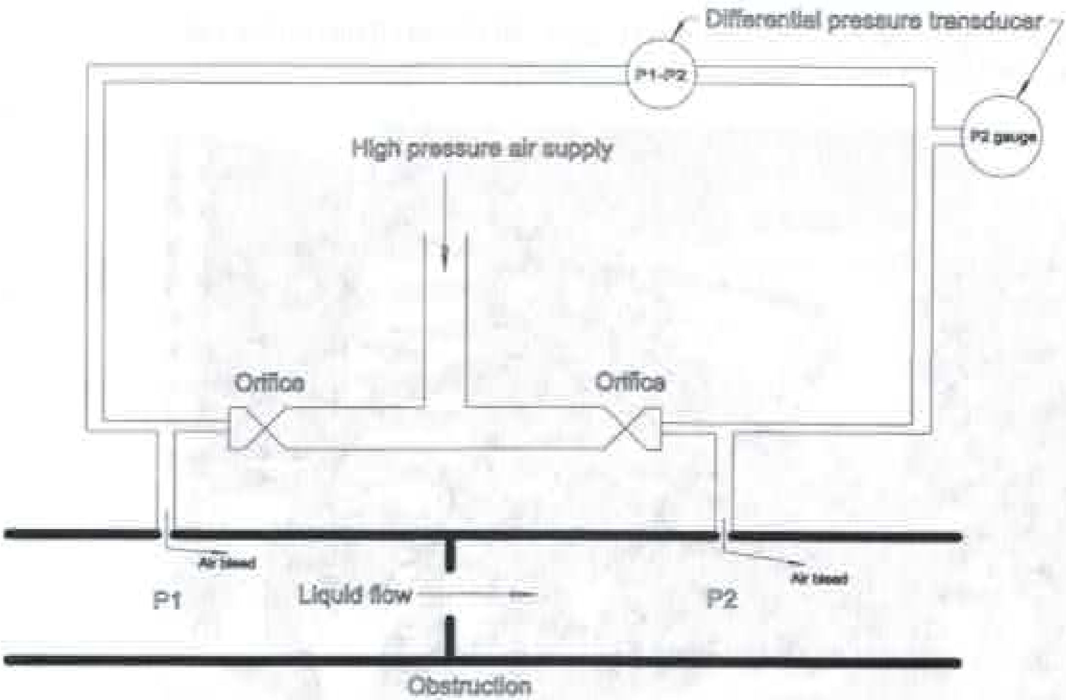

Figure 6. Pressure measuring circuit incorporating orifices and air bleeds.

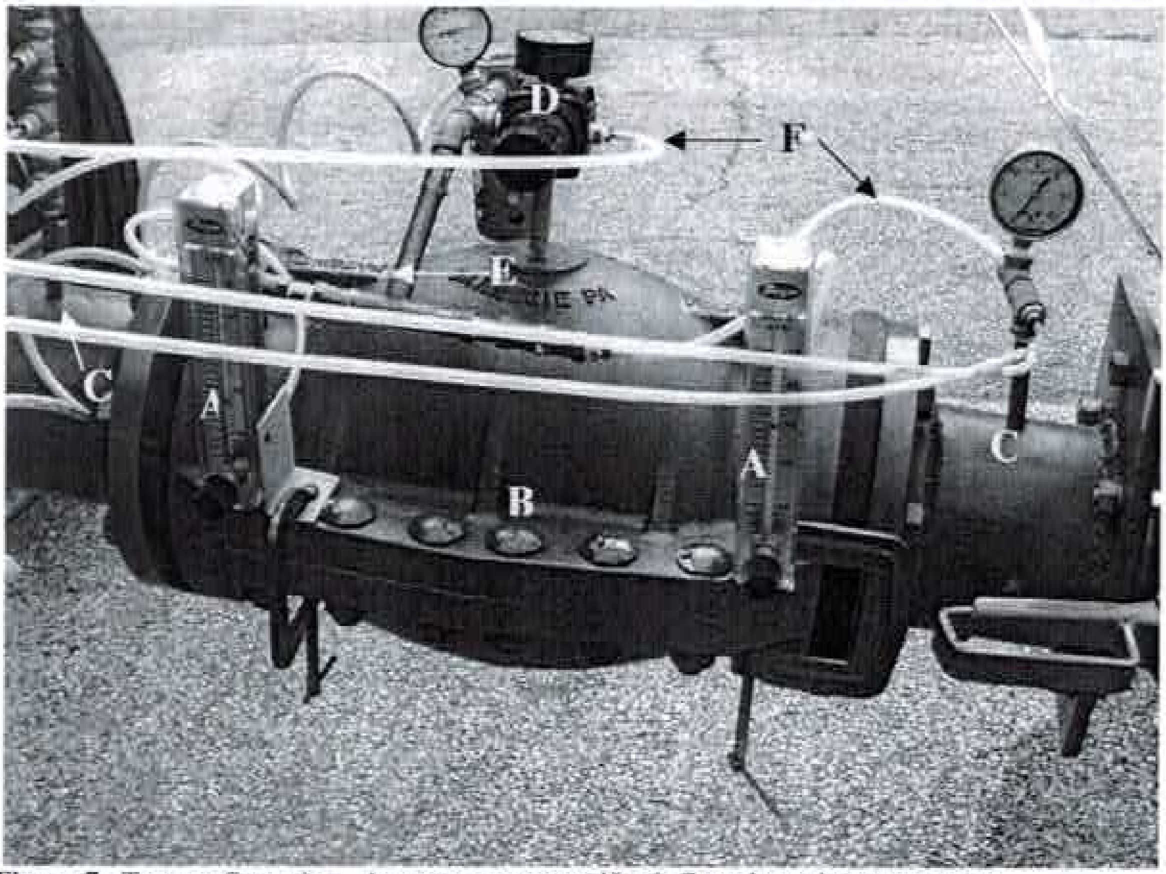

Figure 7. Test configuration. A: rotameters to verify air flow through pressure taps. B:pinch valve under test. C: pressure taps. D:case pressure regulator. E:air bleed orifice assembly. F: pressure sensor tubing.

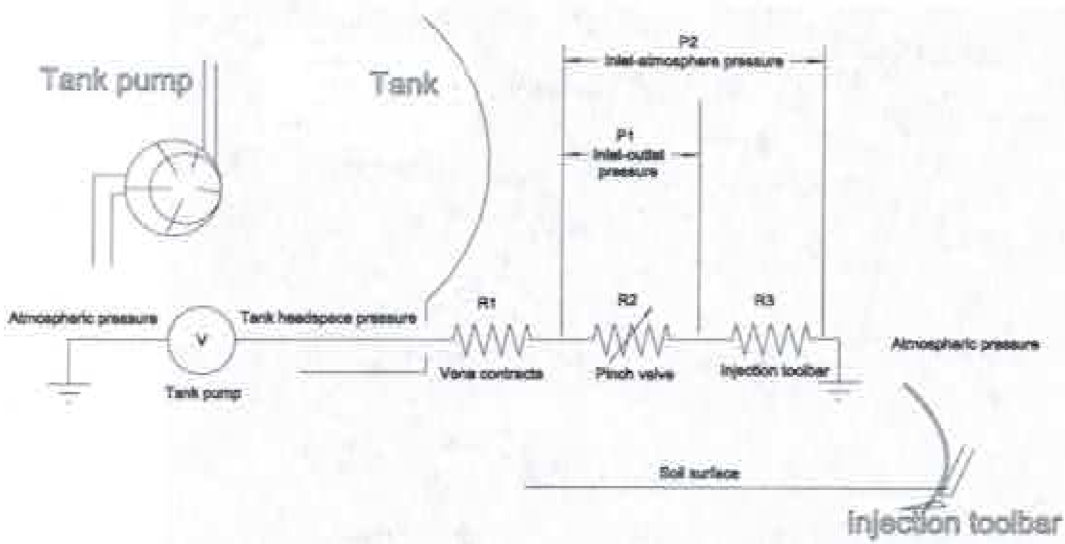

Figure 8. Electrical analog of variable rate slurry tank and soil injection toolbar application system.

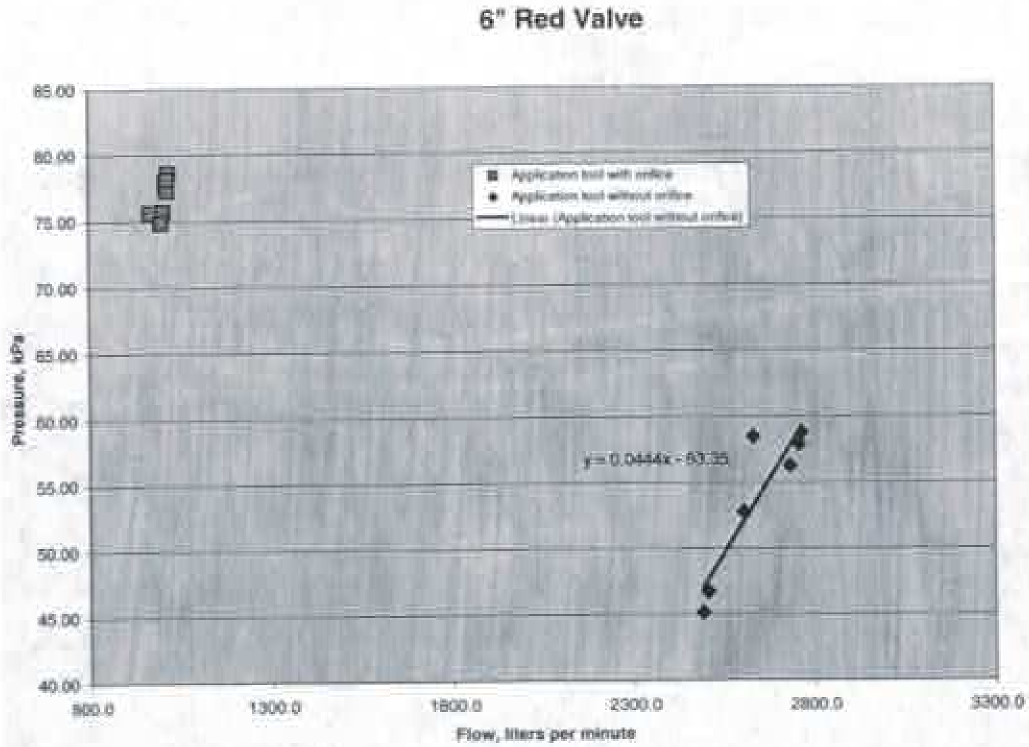

Figure 9. Flow v. pressure across discharge device. 6" Red Valve, with and without discharge orifice in place.

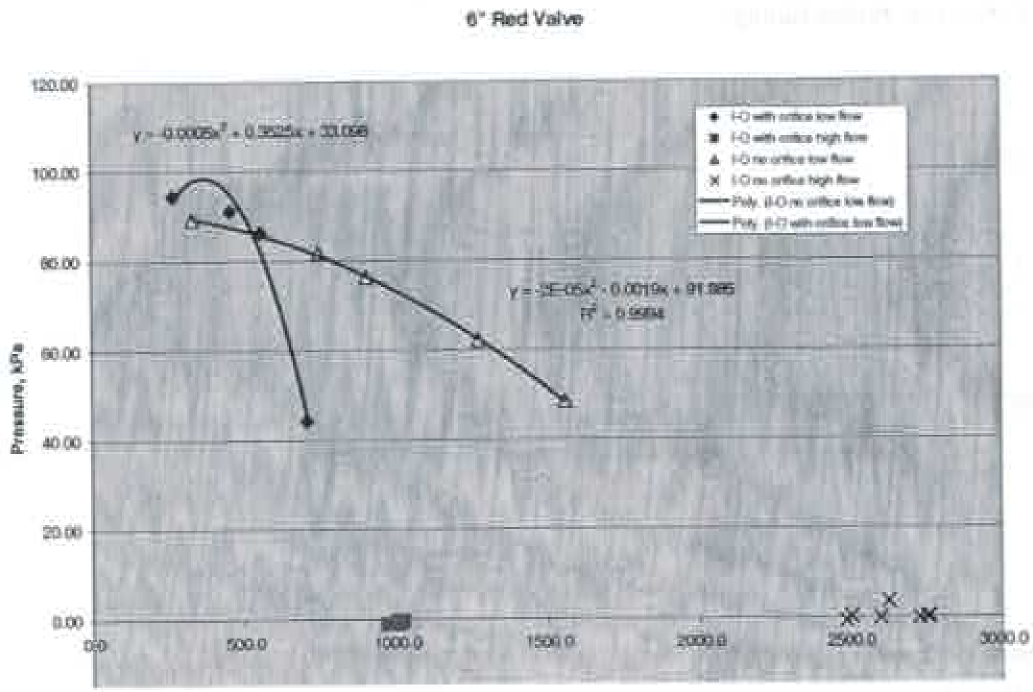

Figure 10. Flow v. pressure across pinch valve. 6" Red Valve, with and without orifice in place on discharge device.

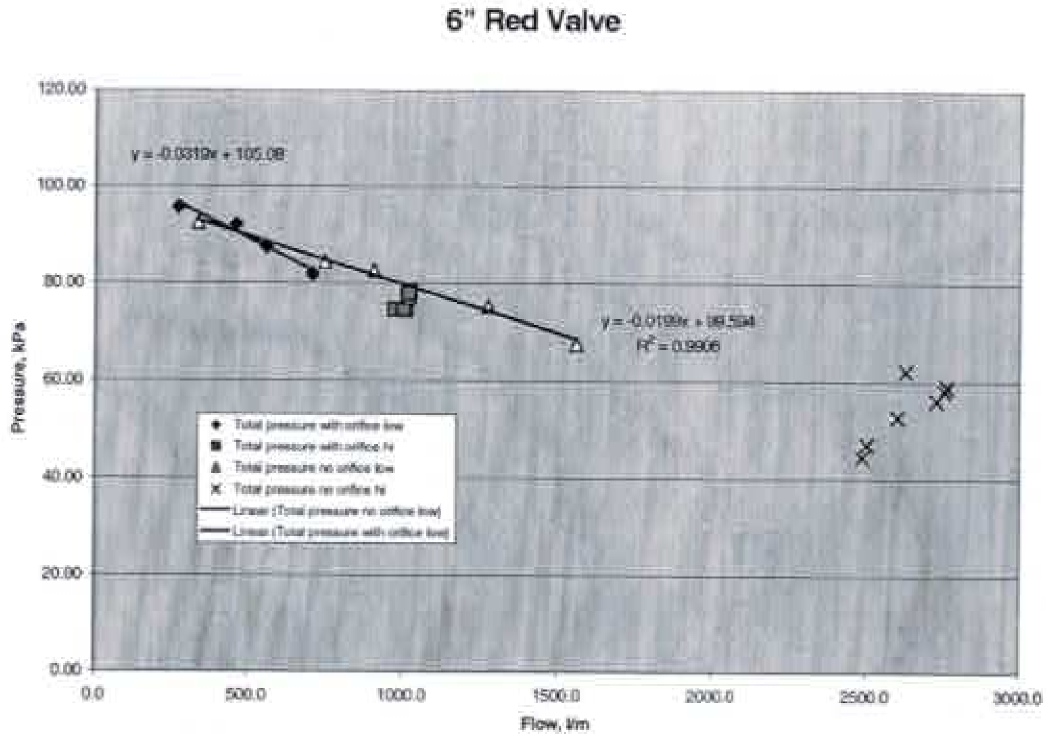

Figure 11. Flow v. pressure, sum of pinch valve and discharge device pressure drops. 6" Red Valve tests, with and without discharge orifice in place.

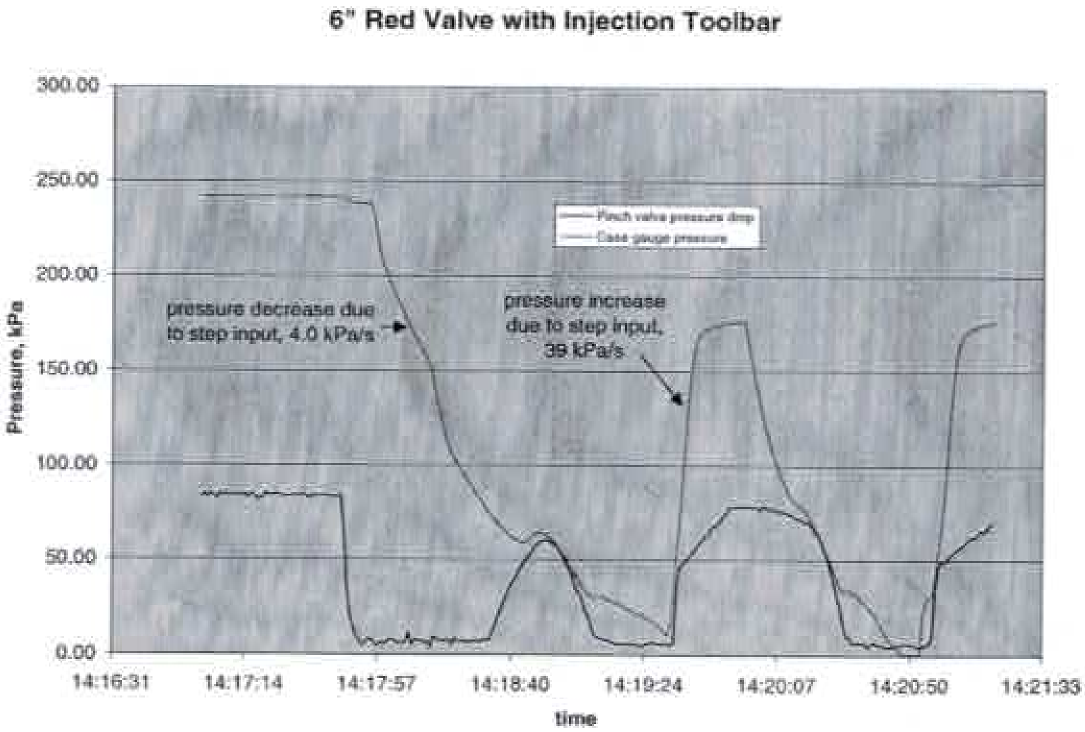

Figure 12. Pressure v. time, pinch valve case and pinch valve fluid pressure drop. 6" Red Valve, soil injection toolbar in place.