FLOW PROPERTIES OF DAIRY WASTE SLURRIES

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INTRODUCTION

The return of animal manure to the soil is desirable for the recycling of essential plant nutrients. The use of wheeled transport equipment to accomplish this has been a standard practice but undesirable soil compaction can occur. For this reason there is considerable interest in utilizing pipeline irrigation equipment for conveying and distributing animal manure.

Hart et al. (4) investigated pumping characteristics of swine, poultry, and dairy manure slurries based on short lengths of 2 inches (5 cm) nominal diam galvanized iron pipe. Dougherty and Broughton[a] carried out studies on pumping systems for swine and dairy manures. Their study indicated that for dairy herds in excess of 100 animals, there were economic advantages to pumping systems, particularly when the equipment could also be used for irrigation.

The flow of solid-liquid mixtures (i.e., slurries) in pipes differs from that of common liquids. In addition to laminar, transitional, and turbulent liquid flow there is either homogeneous or heterogeneous slurry flow. Aude et al. (1) define a homogeneous slurry as one in which the solids are uniformly mixed with the liquid fraction and high concentrations of fine particle sizes may be present. These slurries usually exhibit non-Newtonian rheology. Manure slurries are included in this category along with sewage sludge and clay slurries. Heterogeneous slurries tend to have lower solids content and large particle sizes that cause a vertical solids concentration gradient in a horizontal pipe even at high flow rates. Design criteria based on water are inadequate for these slurries. However, very little work has been done with animal manure slurries, and thus their rheological properties are largely unknown. Because knowledge of fluid flow behavior is required to properly design a pipeline system, this study was initiated to provide design data for pumping dairy manure slurries.

[a] Dougherty, R.S. and R.S. Broughton. 1969. Pipeline transport of manure. CSAE Paper, Saskatoon, Saskatchewan.

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EXPERIMENTAL PROCEDURE

Viscometric Experiments

Dairy manure slurry samples were obtained from a local commercial dairy farm presently equipped with a sprinkler irrigation system for distributing animal wastes to the fields. These samples were passed through a #30 U.S. standard sieve (595 μmol openings) to remove hay fibers and wood chips. This procedure was necessary to render the fluid compatible with laboratory viscometers. The material removed by the screen was collected and dried to determine the solids content of the original slurry.

Moisture content of the screened manure slurry was varied by evaporating water from the sample in a vacuum oven at 85° and −20 inches (−50.8 cm) of mercury pressure. The purpose of this concentration procedure was to provide a range of solids content for subsequent viscometric measurements.

Viscous properties of the slurry were measured by a Haake Rotovisko rheometer (8) with narrow-gapped concentric cylinder geometry. An MV1 spindle provided a maximum shear rate of 1,370 s^{-1} with a gap width of 0.96 mm. Standard viscosity oils were used to establish the spindle calibration constants. Output from the dual-range torsion dynamometer was plotted on a 10-inch (25.4-cm) two-channel strip chart recorder to provide a signal proportional to the shear stress in the fluid. Spindle rotational speed was varied to supply a wide range of shear rates. Sample temperature was controlled at 20°C by a water jacket connected to a thermostatically regulated supply. Duplicate tests were made on the slurries at each solids content.

Field Experiments

A series of pumping trials was initiated on a dairy farm equipped with a 100,000-U.S. gal (378,500-liter) storage tank, a below-ground sump, and a 30-hp (22.4-kW) Holz (advancing cavity type) manure slurry pump. Aluminum irrigation pipe in 4-inch (10.2-cm) nominal diam 40-ft (12.2-m) sections, and 3-inch (7.6-cm) nominal diam 20-ft (6.1-m) sections were used in the tests. The first pressure gauge was placed several hundred feet from the pump to minimize the effect of pulsations on the pressure readings. Figure 1 shows a schematic of the pipe layout. There were 602.8 ft (183.7 m) and 806.9 ft (245.9 m) of pipe between gauges P3 and P2 for the 3-inch (7.6-cm) and 4-inch (10.2-cm) pipes, respectively. A contour map of the area indicated less than 2 ft (.61 m) of elevation difference between the pair of gauges. At least 80 ft (24.4 m) of pipe extended beyond the last gauge before connecting to a Holz manure gun with a .875-inch (2.2-cm) rubber nozzle.

The time required to fill the pipeline was noted and this time was allowed to elapse at the start of a pumping trial before pressure readings were recorded. In this way the pressure drops and the solids content of the slurry could be held reasonably constant during a trial.

Pressure drop and sump level readings were taken at 60-s intervals. A slurry

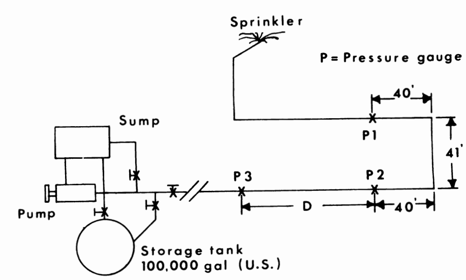

Figure 1. Schematic of system layout showing pump and holding tank, helical pump, control valves, and experimental arrangement of pressure gauges.

sample and its temperature were taken at the beginning and at the end of each test. The samples were subsequently analyzed in the laboratory for total solids content.

RESULTS AND DISCUSSION

Viscometric Experiments

Waste slurries are known to exhibit non-Newtonian flow behavior (5, 7); thus, the familiar power-law model was chosen to interpret the viscometric data. One form of the power law is

$$\tau = m\dot{\gamma}^n \quad \text{. . . . .} \quad (1)$$

where

τ = shear stress;
$\dot{\gamma}$ = shear rate;
m = a parameter, the consistency coefficient;
n = a parameter, the flow-behavior index.

The power-law parameters were computed by the method of least squares using linear regression and the logarithmic transforms of shear stress-shear rate data for each test. As the average coefficient of determination for these fits to the data was 0.984, the power-law model accurately describes viscometric flow of these slurries. Typical rheograms are shown in Figure 2. Differences among the flow curves point out a strong influence of solids content on flow behaviour. Variations of the power-law parameters with solids content (by weight) are presented in Figure 3. This graph can be used to evaluate m and n for slurries of intermediate solids content.

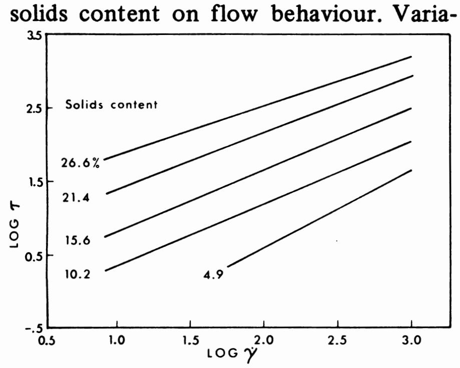

Figure 2. Viscometric flow curves for dairy waste slurries.

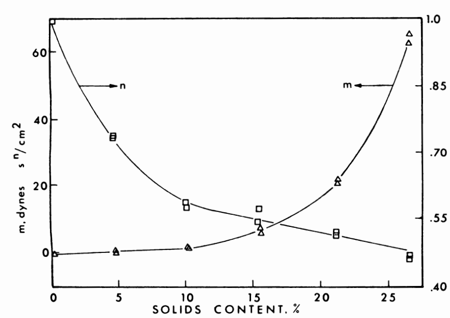

Figure 3. Variation of power-law parameters with solids content of dairy waste slurries.

Laboratory viscometric data thus determined should be useful for the design of dairy slurry pipeline systems. To test this hypothesis, a procedure was developed to calculate pressure drops in a pipeline for a given flow rate and slurry solids content. Although Newtonian pipeline flow has been extensively studied, theories for non-Newtonian flow are not as well advanced. Some theoretical procedures using modified Newtonian parameters are available and correlate reasonably well with experimental data on power-law fluids (2, 3, 6, 9).

Dodge and Metzner (3) have defined a generalized flow-behaviour index (n') and consistency coefficient (m') by the equations

$$n' = n \quad \text{. . . . .} \quad (2)$$

and

$$m' = m \left(\frac{3n+1}{4n}\right)^n \quad \text{. . . . .} \quad (3)$$

for a power-law fluid flowing in round tubes. They have also defined a generalized Reynolds number as

$$N'_{Re} = \frac{D^{n'} V^{2-n'} \rho}{g m' 8^{n'-1}} \quad \text{. . . . .} \quad (4)$$

where

D = inside pipe diam;
V = average fluid velocity;
g = acceleration of gravity;
ρ = fluid density.

This equation reduces to the conventional Reynolds number for Newtonian fluids. Fluid density was taken as 1 g/cm^3 since it was assumed that for the range of solids content pumped, the slurry density would not differ appreciably from that of water.

The Fanning friction factor (f) may be evaluated using an expression relating f to N'_{Re} (3, 9):

$$\frac{1}{f} = \frac{4.0}{(n')^{0.75}} \log \left[N'_{Re} (f)^{1-\frac{n'}{2}}\right] - \frac{0.40}{(n')^{1.2}} \quad \text{. . . .} \quad (5)$$

Because equation (5) cannot be solved explicitly for f, a trial-and-error solution may be used with the aid of a computer.

The pressure drop can then be calculated from the Darcy formula

$$P_c = 4 f \left(\frac{L}{D}\right) \frac{V^2}{2g} \quad \text{. . . . .} \quad (6)$$

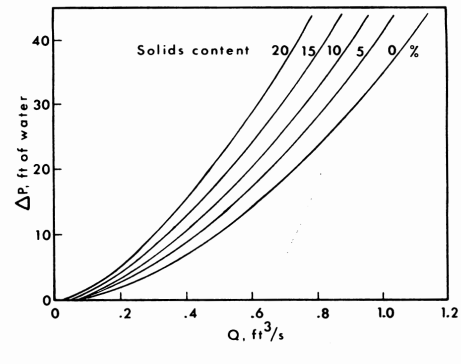

Figure 4. Predicted flow curves for 3-inch (7.6-cm) pipe.

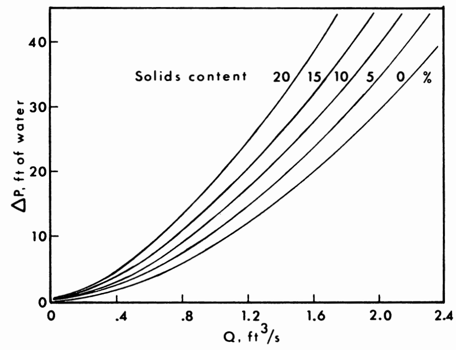

Figure 5. Predicted flow curves for 4-inch (10.2-cm) pipe.

Using the data of Figure 3 along with equations (2) to (6), pipeline pressure drop at a given flow rate for a slurry of specified solids content was computed. This procedure was carried out for 3- and 4-inch (7.6- and 10.2-cm) aluminum pipe for slurry solids contents of 0, 5, 10, 15, and 20% using a wide range of flow rates. The resulting curves are shown in Figure 4 and 5. The curves apply to smooth pipes and allowance would have to be made for couplers, elbows, and other fittings common in a practical piping system. The suitability of this proposed method was then tested by comparison with pipeline experiments.

Field Experiments

Volume flow rates for the field trials were calculated from the known sump size and the measured drawdown per unit of time. Because measured pressure drops included the effect of pipe couplers, and viscometric measurements apply only to liquid-wall shear stresses for smooth pipe, it was necessary to estimate the effect of pipe couplers on pressure drops. The effect of pipe couplers on pressure drop for water was assumed to have the same relative effect on manure slurries. Data for irrigation system design indicated that an additional 15% pressure loss per 100 ft (30.5 m) of pipe occurs for couplers at 40 ft (12.2 m) spacing and an additional 30% pressure loss occurs for couplers at 20 ft (6.1 m) spacing.[b] These data were used to plot a calibration curve of pressure reduction per 100 ft (30.5 m) of pipe for 3 and 4 in (7.6 and 10.2 cm) diameter aluminum pipe over the range of flow rates used in the field (Figure 6). Experimental pressure drops were then adjusted by the pressure reduction per 100 ft (30.5 m) of pipe caused by the couplers between the pressure gauges. These values were then compared with predicted values from the viscometry study.

Comparison of Viscometric and Field Results

The measured pressure drops from the field experiments (ΔP_m) were then compared with the predicted pressure drops (ΔP_c) calculated from viscometric data. Table I contains field data (Q, % solids, ΔP_m) as well as the data derived by the method previously described (m', n', N'_{Re}, f, ΔP_c). Measured and calculated pressure drops have further been compared by correlation methods and are plotted in Figure 7. The correlation coefficient was found to be 0.813 for the pooled data ($n = 29$) of 3- and 4-inch (7.6- and 10.2-cm) pipeline tests. The average deviation between measured and calculated pressure drops was ±26% for the 3-inch (7.6-cm) pipe trials.

In view of the sources of error encountered in obtaining field data on a commercial dairy farm, this deviation is not considered excessive. Some of the more significant sources of error in this experiment would be composition variations in the slurry being pumped during a trial, temperature differences of the viscometric tests (20°C) compared with field trials (12-18°C), the use of screened samples for viscometric study, and inaccuracies encountered in measuring flow rate. Because there were no facilities to maintain agitation in the sump during pumping, settling of solids would likely take place. The samples collected from the sump near the beginning and the end of a test may therefore not have been a true measure of actual solids content in the pipe line. Liquid levels in the sump could only be measured to the nearest 1/4 inch (0.63 cm) and for some mixes of high solids content special care was required to obtain reliable levels. Variations in pressure readings also occurred that were probably due to variations in back pressure at the nozzle as hay and wood chips had some influence on flow rate through the nozzle. These factors were considered to be the major sources of error in field data. Furthermore, the slurries were assumed to be time-independent power-law fluids when in fact they may exhibit a more complex rheology, for example, viscoelasticity.

Within the limitations discussed above, the method outlined has reduced the design of dairy waste slurry systems to a procedure similar to that used for Newtonian fluids. To extend this method to other homogeneous slurries, viscometric tests at varying solids content are required. Families of flow curves may then be constructed to relate pressure drop, flow rate, and solids content for selected pipe sizes.

TABLE I PIPELINE FLOW PARAMETERS FOR 3- AND 4-INCH (7.6- AND 10.2-CM) ALUMINUM PIPE

Flow, ft³/s	Solids, %	n and n'	m', dynes s^n cm^{-2}	N'_{Re}	f	Pressure drop, ft/100 ft pipe: Predicted	Experimental
3-inch (7.6-cm)							
0.235	10.5	0.614	1.901	4300	0.00728	4.79	5.09
0.284	3.3	0.831	0.084	40400	0.00479	4.61	2.73
0.248	2.0	0.882	0.043	52100	0.00472	3.46	2.73
0.273	5.8	0.744	0.277	18400	0.00539	4.79	2.37
0.235	2.4	0.866	0.053	43100	0.00486	3.20	2.41
0.262	1.4	0.906	0.031	67300	0.00454	3.72	1.69
0.258	0.90	0.927	0.024	78000	0.00448	3.56	2.31
0.290	5.8	0.744	0.277	19900	0.00528	5.30	2.86
0.235	5.8	0.744	0.277	15300	0.00567	3.73	2.02
0.338	0.10	0.961	0.015	135100	0.00410	5.59	4.81
0.139	0.10	0.961	0.015	53600	0.00499	1.15	1.16
0.302	2.0	0.882	0.043	65000	0.00449	4.88	4.84
0.145	2.5	0.862	0.056	24100	0.00558	1.40	1.50
0.302	6.7	0.716	0.414	16300	0.00542	5.89	4.20
0.290	4.9	0.774	0.183	25700	0.00509	5.10	5.34
0.163	3.8	0.813	0.107	18000	0.00577	1.83	2.55
0.290	1.4	0.906	0.031	75200	0.00443	4.44	5.34
0.181	1.5	0.902	0.033	43400	0.00500	1.95	2.82
0.290	8.6	0.662	0.919	9300	0.00601	6.03	4.00
0.290	6.1	0.735	0.318	18300	0.00535	5.37	6.14
0.338	0.40	0.948	0.018	122500	0.00414	5.64	6.33
4-inch (10.2-cm)							
0.145	3.9	0.809	0.113	9600	0.00682	0.40	0.67
0.133	2.2	0.874	0.048	16200	0.00623	0.30	0.16
0.145	1.0	0.922	0.025	28300	0.00563	0.33	0.73
0.048	0.20	0.956	0.016	12200	0.00711	0.05	0.63
0.398	2.6	0.858	0.059	48600	0.00470	2.05	1.44
0.097	2.0	0.882	0.043	12300	0.00674	0.17	2.26
0.417	0.7	0.935	0.021	98000	0.00429	2.06	2.24
0.410	0.10	0.961	0.015	119000	0.00421	1.95	2.14

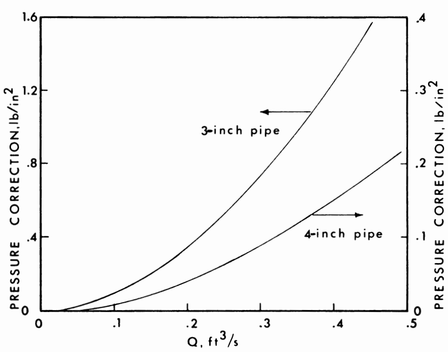

Figure 6. Pressure correction for pipeline couplings per 100 ft (30.48 m) of pipe.

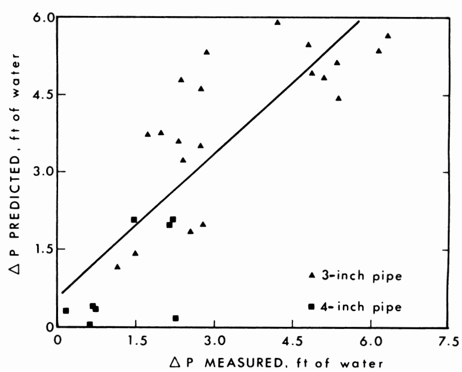

Figure 7. Comparison of predicted and measured head loss per 100 ft (30.48 m) of pipe.

[b] Miller, R.J. 1971. Data manual for sprinkler irrigation system design in British Columbia. Agricultural Engineering Division, B.C.D.A., Victoria, B.C.

CONCLUSIONS

It has been shown that dairy manure slurries are non-Newtonian pseudoplastic fluids that can be characterized by a power-law flow model. Viscometric tests on screened manure slurries resulted in power-law parameters that were then used in equations applicable to non-Newtonian fluids in pipeline flow to develop a family of flow curves relating pressure drop, flow rate, and solids content. These curves were constructed for 3- and 4-inch (7.6- and 10.2-cm) aluminum pipe for a range of conditions encountered in the practice of distributing animal wastes on farmland by sprinkler-irrigation methods. It was shown that pressure drops calculated from viscometric tests correlate well ($r = 0.813$) with pressure drops obtained from field experiments. For a series of 21 trials using 3-inch (7.6-cm) pipe, the average deviation of ±26% between the calculated and measured pressure drops was considered adequate for design of these pipeline systems. The potential for extending this method to the design of pipeline transport facilities for other agricultural slurries should be more fully explored.

SUMMARY

Dairy manure slurries of varying solids content were tested in a Haake Rotovisko rheometer over a wide range of shear rates. The resulting data accurately fitted a power-law model for which the flow parameters were determined. These parameters were used to calculate a generalized Reynold's number and Fanning friction factor. Darcy's equation then gave pressure drops for selected pipe sizes and flow rates.

Field experiments were conducted by pumping dairy manure through 3- and 4-inch (7.6- and 10.2-centimeter) diameter irrigation pipe. Flow rates, solids content, and pressure drops were measured. After applying corrections for the effect of pipe couplers, measured and calculated pressure drops were compared and found to be in good agreement. The method of applying viscometric data to predict pipeline flow appears to have good potential in the design of distribution systems for dairy waste slurries.

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