The Properties of Combined Horizontal Flows of Air and Farm Livestock Slurries in a Tubular Loop Aerator

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Pig slurries and dairy cattle slurries exhibit shear-thinning characteristics and therefore two-phase horizontal pipeline flows of water and slurries with air were studied in a novel Tubular Loop Aerator (TLA) to determine whether air injection could achieve shear-thinning effects, leading to reduced energy requirements. The TLA incorporated a pipeline of 40.2 mm internal diameter which was 65 m in length. It was found that the pressure gradients resulting from these two-phase flows were described satisfactorily by a correlation based on ratios of single- and two-phase pressure gradients. This technique enabled convenient comparison of the flow characteristics of slurries with different total solids (TS) concentrations at different air injection rates.

Pig slurries containing up to 3-5% TS showed no reductions in pressure loss due to air injection, whereas cattle slurries of 2-3% TS produced some instances of pressure reduction. These reductions occurred at low superficial liquid flow velocity (0.5 m/s) and <2% (vol/vol) air injected, but the results did not provide statistically significant evidence of an energy-saving effect.

1. Introduction

To design efficient pipeline transport systems for farm livestock slurries, the rheological properties, (i.e. relationships between shear stress and shear rate) must be known. Systems for handling and transporting such slurries have been widely used for many years. Nevertheless, designers of these systems are still without a good procedure for deciding these essential property parameters.

Many farm slurries are known to exhibit non-Newtonian flow characteristics (Hashimoto & Chen, 1975). Non-Newtonian properties lead to non-linear relationships between shear stress and shear rate. Previously, it has been found that relationships between shear stress and shear rate for farm livestock slurries can be expressed by a power law (Hashimoto & Chen, 1975):

\[ \tau_w = K\gamma^n \]  

(1)

where: \( \tau_w \) is the shear stress at the pipe wall in Pa; \( \gamma \) is the shear rate in s\(^{-1}\); and \( K \) and \( n \) are characteristic constants for the fluid. Consequently, it may be more energy-efficient, under certain circumstances, to pump at high velocities and thereby to take advantage of the lower viscosity that ensues. Similar effects may be created by injecting air into the flow. To investigate the effects that air injection has on the rheological properties of farm livestock slurries, experiments with pig slurries and dairy cattle slurries were undertaken in a Tubular Loop Aerator apparatus (TLA), of the type previously described by Cumby and Slater (1984). This type of apparatus had already exhibited good aeration performance in other applications (Russell et al., 1974; Ziegler et al., 1980) and offered the advantage of a plug flow reactor, a device that has been used for the treatment of industrial and domestic sewage in pumped mains (Boon et al., 1977; Newcomb et al., 1979; Carne et al., 1982). More importantly, this apparatus permitted the establishment of defined hydrodynamic conditions, and generation of a variety of shear rates. Using the TLA, the objectives of this study were to develop and assess a simple technique for the presentation and
interpretation of multi-phase flow data and to complete a series of experiments to investigate the specific horizontal flow properties of mixtures of air and farm livestock slurries with a view to possible energy saving. As a precursor, experiments were completed with water and air to provide data representing Newtonian fluids with reproducible physical characteristics.

2. Materials and methods

2.1. Construction of the apparatus and instrumentation

The TLA apparatus is shown diagrammatically in Fig. 1. The liquids tested were mixed and stored in one of two similar vessels (A and B) which each had a volume of 2/7 m³. These vessels were mounted on load cells so that their contents could be monitored. Each was fitted with sampling valves and a variable speed mixing impeller (C, D). Liquid could be withdrawn from either vessel via a system of pipes and valves (E), using a variable speed progressing cavity pump (F). The liquid flow was measured by an electromagnetic flow meter (G) before it entered a 65 m long tubular loop made of a 40.2 mm internal diameter galvanized steel tube. Air was supplied from a compressor (H), controlled by valve (I) and measured with a venturi airflow meter (J) and an electronic pressure transducer (K). These items were calibrated by connecting the flowmeter in series with a positive displacement gas flow meter, and then timing the passage of measured volumes of air at various flow rates up to 20 l/min and at pressures between 200 and 600 kPa. The air temperature was measured with a thermistor (L). The air was injected into the liquid in the pipeline through a non-return valve (M). The pressures were measured with ten pressure transducers in locations N1 to N10. These were arranged so that there were two 3.8 m sections of straight pipeline connected with four 90° bends and two tees between successive transducers in the tubular loop. There were seven sections like this and a supply and return line making a total of 65 m of pipeline between the first and the last pressure transducers. Thermistors were also fitted in locations N3, N5, N7, N9 and in both vessels to measure the temperature of the liquid. These thermistors were calibrated before installation using a constant temperature water bath and an electronic thermometer, thus ensuring measurement accuracy within ±0.1 °C between +10 and +25 °C. The pressure transducers were calibrated before installation using a dead-weight pressure gauge calibrator enabling a measurement accuracy of ±0.5% of measured value, between 0 and 600 kPa gauge pressure. The estimated accuracy of the electromagnetic flow meter was within ±2% of maximum flow (135 l/min).

After passing through the tubular loop, fluids were returned to either one of the vessels or to an external storage tank (not shown) via valve (O). Data were recorded on a personal computer (PC) via an analogue to digital converter (P). Proportional–integral–differential (PID) controllers were used to control the system. The set points for these controllers were specified using

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
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<tbody>
<tr>
<td>D</td>
<td>pipe internal diameter, m</td>
</tr>
<tr>
<td>K</td>
<td>fluid consistency coefficient, Ns⁻¹/m²</td>
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<tr>
<td>L</td>
<td>pipe length, m</td>
</tr>
<tr>
<td>n</td>
<td>flow behaviour index, dimensionless</td>
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<td>P</td>
<td>gauge pressure inside the pipe, Pa</td>
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<tr>
<td>Q</td>
<td>flow rate, l/min</td>
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<tr>
<td>Q_sg</td>
<td>flow rate of gas, l/min</td>
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<tr>
<td>Q_sl</td>
<td>flow rate of liquid, l/min</td>
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<tr>
<td>Re</td>
<td>Reynolds number = DVρ/µ, dimensionless</td>
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<tr>
<td>Re_sg</td>
<td>Reynolds number corresponding to the superficial flow velocity of gas, dimensionless</td>
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<tr>
<td>Re_sl</td>
<td>Reynolds number corresponding to the superficial flow velocity of liquid, dimensionless</td>
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<tr>
<td>V</td>
<td>fluid velocity, m/s</td>
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<tr>
<td>V_sg</td>
<td>superficial velocity of the gas in the pipe (at pressure P), m/s</td>
</tr>
<tr>
<td>V_sl</td>
<td>superficial velocity of the liquid in the pipe, m/s</td>
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<tr>
<td>X</td>
<td>single-phase pressure gradient ratio, dimensionless</td>
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<td>ρ</td>
<td>densities of gas at s.t.p., kg/m³</td>
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<tr>
<td>μ</td>
<td>dynamic viscosity of the gas (at s.t.p.), Pa s</td>
</tr>
<tr>
<td>ρ_l</td>
<td>densities of liquid at s.t.p., kg/m³</td>
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<tr>
<td>μ_l</td>
<td>dynamic viscosity of the liquid, Pa s</td>
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<tr>
<td>Δp</td>
<td>differential pressure, Pa</td>
</tr>
<tr>
<td>φ_t</td>
<td>two-phase pressure gradient ratio, dimensionless</td>
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<tr>
<td>γ</td>
<td>shear rate, s⁻¹</td>
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<tr>
<td>τ_w</td>
<td>shear stress at the pipe wall, Pa</td>
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<th>Subscripts</th>
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<td>g</td>
<td>gas</td>
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<td>l</td>
<td>liquid</td>
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<td>sg</td>
<td>superficial gas</td>
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<td>sl</td>
<td>superficial liquid</td>
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<td>tp</td>
<td>two phase</td>
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the computer, which also controlled system operation. The apparatus included a system for calibration of the electromagnetic flow meter by diverting and timing the flow using a calibration valve (Q) into a barrel (R) mounted on a weighing device (S). This enabled calibration at flows up to 135 l/min.

2.2. Liquids tested

Clean water was used as a fluid of known behaviour for comparison with slurries, and to test the equipment. Raw pig slurry was collected from a nearby piggery (fattening pigs fed on concentrates with ad lib water). The slurry collected from the farm had a total solids (TS) concentration of 3.5% (w/w). Untreated cattle slurry was collected from a nearby dairy farm (dairy cows on a diet of grass and maize silage and concentrates). This slurry contained long fibrous material which was removed before the experiments using a roller press separator to reduce the risks of pipe blockage. The TS concentration of the raw cattle slurry was 10.9% (w/w) and after separation it was reduced to 4.9% (w/w). Experiments were undertaken with raw pig and dairy cattle slurries, and with both types diluted with water to various concentrations. The slurries were stored in open-top tanks, thus they were re-sampled in conjunction with each experiment and the TS concentrations of these samples were measured, as reported below. This avoided possible errors due to cumulative rainfall and evaporation.

2.3. Experiments with air

The analytical procedures used to characterise and compare the properties of the two-phase flows created in the TLA required data representing the pressure gradients associated with different rates of single-phase, air-only flow in the apparatus. Air was introduced into the apparatus via the non-return valve (M) shown in Fig. 1. A micro-manometer was incorporated in the apparatus to measure the differential pressure between locations N1 and N10. Pressure gradients were measured with air supplied at several combinations of flow rate and pressure. Specifically, the airflow rates ranged from
1.6 to 19.5 l/min and at gauge pressures from 200 to 600 kPa. These ranges were equivalent to airflow rates ranging from 3.2 to 117 l/min at atmospheric pressure.

2.4. Experiments with water

Water was circulated at four different flow rates: 43, 84, 124 and 145 l/min and pressures and flows were measured as described above. Air was injected into the water at rates between 2 and 12% (v/v), calculated according to the pressures and flows measured at the injection point.

The experiments with air-free and air-injected water were performed sequentially. The pump (F) was set to a certain speed and an air-free experiment was carried out. Subsequently, the tests with different air injection rates were completed from the lowest to the highest air injection rate, without changing the pump speed. Every time the air injection rate was changed, the combined flow was allowed to stabilise for at least 2 min before any data were logged. Data were logged every 10 s for 90 s, and then the airflow was altered. Once the maximum air injection rate had been achieved, the pump speed was changed and the procedure was repeated. The water was returned to a 10 m³ external storage tank for degassing before it was reused. Four hours were allowed for degassing. All logged data were imported to a computer spreadsheet and organised for statistical analysis. Throughout the experiments, the water temperatures were between 10°C and 15°C.

Due to the construction of the TLA, it was not possible to measure pressure gradients in the straight pipeline sections directly. It was therefore necessary to correct the pressure drop for singular losses in bends and fittings to get the real pressure loss in the straight pipeline. The calculations were made for water under a turbulent flow regime and so an equivalent length of pipeline was calculated and used for all the analyses completed for different fluids. Standard procedures were used as described elsewhere (Daugherty et al., 1989). As a result of this analysis, the data could be expressed in terms of measured pressure against position along the length of the pipe (Fig. 2). A straight line was fitted to the data points for each test. The lines fitted in this way provided a very good agreement with the data; most of the coefficients of determination \( r^2 \) were between 0.8 and 0.97.

The operating range of the pressure transducers was from 0 to 600 kPa and this led to bigger variations in the data at low flow rates due to the proportionally larger measurement errors at low pressures. The regression coefficients were therefore lower for low flow rates than for the higher flow rates.

Fig. 2. Conceptual illustration of the pressure losses in the tubular loop aerator apparatus: 1, measured pressure gradient; 2, actual pressure loss in the straight pipeline; and 3, loss due to bends and fittings.

2.5. Long duration pumping tests

Since repeated dilution and re-use of the slurries might have changed their rheological properties, an experiment was completed to determine whether these properties were affected by prolonged pumping. Samples of approximately 1 m³ of each slurry with TS concentrations that were as high as possible (pig TS = 3.5%, cattle TS = 4.3%) were pumped around the TLA for 3 h at a flow rate of 110 l/min (corresponding to a pipeline shear rate of approximately 290 s⁻¹). After 3 h pumping, each slurry had, on average, passed through the pump approximately 20 times. Samples were collected for particle size distribution and TS concentration analysis before the start of the test run. The samples were collected from the vessel, using the sampling valves.

During the first hour of pumping, samples were collected every 10 min. Data were logged every 10 s. After the first hour, the logging time was reset to 30 s and samples were taken every 20 min. The sample volume was 250 ml for analysis of TS concentration and 250 ml for particle size distribution analysis. The TS concentration was calculated by weighing each sample before and after drying in an oven at 105°C for 16 h. The analysis of particle size distribution was achieved by wet sieving using sieve sizes of 600, 425, 300 and 212 μm.

2.6. Experiments with pig slurry and cattle slurry

The procedures for these experiments were similar to those used for water. The slurries were pumped through the TLA at four different nominal flow rates: 41, 84, 124 and 140 l/min. Air was injected into the slurry at rates of approximately 2, 4, 6, 8 and 10% (v/v). Slurry samples for TS analysis were collected during alternate runs.
Throughout the experiments the slurry temperatures remained within a range from 19.8 to 24.1°C for pig slurry and from 8.0 to 9.8°C for cattle slurry.

Different TS concentrations for each slurry type were obtained by dilution with water. The amount of dilution was calculated from the previously measured TS values and the volume of water needed was then pumped into the vessel where it was thoroughly mixed with the slurry using an impellor mixer. The pig slurry was diluted to achieve two different TS concentrations, in the ranges 3–4% and 2–3% (w/w), respectively. The cattle slurry was diluted to give three different TS concentrations in the ranges: 1–2%, 2–3% and 3–4% (w/w).

3. Results and discussion

3.1. Pressure gradients for single-phase airflow

Data representing the measured pressure gradients for single-phase flows of air are shown in Fig. 3 and are grouped according to the pressure at which the air was introduced to the TLA. The airflow rates are all expressed at atmospheric pressure and show that the measured pressure gradients were a function of the air supply pressures. To enable these data to be used in the subsequent interpretation of the two-phase flow data, similar sets of air pressure values were used during the experiments with two-phase flows, although the flow rates were different.

3.2. Long duration pumping tests

The particle-size distribution data from the samples taken during the long duration pumping test were arranged in three groups according to when they were sampled: 0–30, 30–80 and 80–180 min. The data were analysed statistically by simple analysis of variance (F-test). This tested the hypothesis that the mean values of particle size for each group of samples were not significantly different. This showed that there was no reason to reject the hypothesis on a 5% significance level.

The pressure gradient data were organised in the same way as the particle-size data and analysed by the same method. The results from these analysis showed that there were no significant changes in pressure gradient with either pig slurry or cattle slurry. The observations that there were no significant changes in either pressure gradients or particle-size distribution with time indicated that it was acceptable to use the slurries for more than one test run later in the experiment.

3.3. Pressure gradients for single-phase liquid flow

As expected, without air injection, the measured relationships between pressure gradients and liquid flow rate showed non-linear characteristics (Fig. 4). The pressure gradients became proportionally greater with increasing flow rates. Also, the pressure gradients tended to increase with increasing TS concentration. Since variations in the TS concentrations of the samples were found to be negligible at each liquid flow rate, these observed flow properties could be ascribed directly to the presence of solid matter and not to any time-dependent effects. Correlation and comparison of these data were achieved by firstly converting paired measurements of differential pressure \( \Delta p \) and flow rate \( Q \) to corresponding values of wall shear stress \( \tau_w \) and
apparent shear rate $\gamma$, as quoted in Eqn (1), using the following equations:

$$\tau_w = \frac{D\Delta p}{4L}$$  \hspace{1cm} (2)

and

$$\gamma = \frac{32Q \times 10^{-3}}{60\pi D^3}$$  \hspace{1cm} (3)

where: $D$ is the pipe internal diameter in m; $L$ is the pipe length in m; $Q$ is the liquid flow rate in l/min; and $\Delta p$ is the differential pressure in the pipe, expressed in Pa. Secondly, these values of $\tau_w$ and $\gamma$ were plotted in logarithmic form according to the principles described by Metzner and Reed (1955). Results for water, pig slurry and cattle slurry are shown in Figs 5 and 6.

Straight lines were fitted to the sets of data points for each liquid (Figs 5 and 6) and the resulting coefficients of determination $r^2$ showed a high degree of correlation. The slopes of these lines, which are the exponents of $\gamma$ are given in Table 1. Since the slopes for slurries were less than that of water, this indicates, as Hashimoto and Chen (1975) described, that the rheological properties of farm livestock slurries could be described by Eqn (1). Furthermore, the results from pig slurry indicated that higher TS concentrations reduced the slope of the line, as observed by Lord et al. (1967), using bentonite, calcium carbonate, carboxy methyl cellulose and guar gum slurries. However, a similar overall trend was not observed with respect to cattle slurry. The slope of the line for water from Lord et al. (1967) was 1.78, which agreed well with the value of 1.91 calculated from the data in this experiment, considering the different surface roughness of the pipes and fittings used in the present experiments.

3.4. Pressure gradients for flows of liquid and air

The results from the experiments in which air was injected into the flows of water and slurries are shown in Figs 7–12. The percentage values represent the amounts of air included and are expressed as volume fraction at the injection point. Although the results shown in Figs 7–12 indicate general trends, further analyses are required for pipeline design purposes and to determine the effects of air injection on the energy required for pipeline transport of slurries. Therefore, to enable a comparison of data from slurries with different TS concentrations and different air injection rates, the data were transformed into two dimensionless ratios proposed by Lockhart and Martinelli (1949), representing respectively, the two-phase $\phi_l$ and single-phase $X$ pressure gradient ratios:

$$\phi_l = \sqrt{\frac{(\Delta p/L)_{lp}}{(\Delta p/L)_{sl}}}$$  \hspace{1cm} (4)
Fig. 7. Relationship between pressure gradient and flow rate for water and air: ■ no-air; □, 1.8% air; ◆, 2.7% air; ○, 5.0% air; ▲, 10.0% air

Fig. 10. Relationship between pressure gradient and flow rate for dairy cattle slurry of 1–2% total solids content: ■, no-air; □, 3.3% air; ◆, 6.5% air; ○, 10.0% air

Fig. 8. Relationship between pressure gradient and flow rates for pig slurry of 2–3% total solids content: ■, no-air; □, 1.8% air; ◆, 4.0% air; ○, 6.0% air; ▲, 8.0% air

Fig. 11. Relationship between pressure gradient and flow rate for dairy cattle slurry of 2–3% total solids content: ■, no-air; □, 3.6% air; ◆, 6.3% air; ○, 10.0% air

Fig. 9. Relationship between pressure gradient and flow rates for pig slurry of 3–4% total solids content: ■, no-air; □, 1.8% air; ◆, 4.0% air; ○, 6.0% air; ▲, 7.8% air

Fig. 12. Relationship between pressure gradients and flow rate for dairy cattle slurry of 3–4% total solids content: ■, no-air; □, 3.5% air; ◆, 7.0% air; ○, 10.0% air
and

\[ X = \sqrt{\frac{(\Delta p/L)_d}{(\Delta p/L)_{sl}}} \]  

(5)

The terms \((\Delta p/L)_d\) and \((\Delta p/L)_{sl}\) are the pressure gradients that would occur if the liquid and gas, respectively, were flowing alone in a pipe at velocities equal to their superficial velocities, both expressed in \(\text{Pa}/\text{m}\); and \((\Delta p/L)_p\) is the pressure gradient for two-phase flow of liquid and gas in the same pipe, in \(\text{Pa}/\text{m}\). By transforming experimental data into this form, it is possible to use the resulting empirical relationship between \(\phi_l\) and \(X\) to characterise the properties of the two-phase flows. Appropriate values of \((\Delta p/L)_d\) for each measured value of two-phase flow were determined from the relationships shown in Fig. 3. Corresponding values of \((\Delta p/L)_{sl}\) were determined from the data shown in Fig. 5 by interpolation between appropriate pairs of single-phase airflow values selected from the relevant data set representing the same air supply pressure.

Equations (4) and (5) are useful because they provide a convenient way to represent the measured effects of air incorporation on pressure gradient over a range of different internal pipe diameters. However, Lockhart and Martinelli (1949) showed that transition between laminar and turbulent flow must be taken into account to maintain the validity of the approach. Hence, these authors proposed grouping the data according to four flow regimes, depending upon whether the individual phases were either in laminar or turbulent flow, determined by the Reynolds number of the gas \(Re_{sl}\) and the Reynolds number of the liquid \(Re_d\):

1. Laminar–laminar (\(Re_{sl} < 1000\) and \(Re_{sl} < 1000\)),
2. Laminar–turbulent (\(Re_{sl} < 1000\) and \(Re_{sl} > 2000\)),
3. Turbulent–laminar (\(Re_{sl} > 2000\) and \(Re_{sl} < 1000\)), and
4. Turbulent–turbulent (\(Re_{sl} > 2000\) and \(Re_{sl} > 2000\)),

where

\[ Re_{sl} = \frac{\rho_g D V_{sg} P}{\mu_g} \]  

(6)

and

\[ Re_d = \frac{\rho_l D V_{sl} P}{\mu_l} \]  

(7)

and where: \(D\) is the pipe internal diameter in \(\text{m}\); \(P\) is the gauge pressure inside the pipe in \(\text{Pa}\); \(V_{sg}\) is the superficial velocity of the gas in the pipe (at pressure \(P\)) given by \((66-67 \times 10^{-6} \times Q_{sl}/\pi D^2)\), in \(\text{m/s}\); \(V_{sl}\) is the superficial velocity of the liquid in the pipe, given by \((66-67 \times 10^{-6} \times Q_{sl}/\pi D^2)\), in \(\text{m/s}\); \(\mu_g\) is the dynamic viscosity of the gas (at s.t.p.) in \(\text{Pa}\cdot\text{s}\); \(\mu_l\) is the dynamic viscosity of the liquid in \(\text{Pa}\cdot\text{s}\); and \(\rho_g\) and \(\rho_l\) are the densities of the gas and liquid respectively at s.t.p. in \(\text{kg}/\text{m}^3\).

All of the data obtained from the experiments reported here were in either the turbulent–laminar or turbulent–turbulent regimes: no data were obtained for laminar liquid flow.

The results for water and slurries are shown in Fig. 13. In general, the results agreed fairly well with the Lockhart–Martinelli correlations, although there was some divergence at the lower values of \(X\). The values of \(\phi_l\) determined from Eqn (4) were therefore equivalent to the measured ratios of two-phase pressure gradient to the liquid phase pressure gradient. Presentation of the results in this form in Fig. 13 allows three specific zones to be identified:

1. Zone 1 includes data above the Lockhart–Martinelli line for water and air;
2. Zone 2 includes the area below the Lockhart–Martinelli line where \(\phi_l \geq 1\) (i.e. values of \(\phi_l\) lower than those predicted by Lockhart–Martinelli at a given value of \(X\)), and
3. Zone 3 represents the region where \(\phi_l < 1\).

The significance of these zones is as follows: data points in Zones 1 and 2 respectively indicate a general increase or reduction of the two-phase pressure gradients compared with the Lockhart–Martinelli correlation for water and air. Although data in Zone 2 do not amount to a reduction in total pressure gradients compared with liquids flowing alone, these results...
indicate that introduction of air has some shear-thinning effect. Data points in Zone 3 show that the pressure gradient for two-phase flow is less than the pressure gradient for liquid flowing alone.

Figure 13 includes just a few observations in Zone 3: all relating to cattle slurry with 2–3% TS concentration and corresponding to a low superficial flow velocity (0.5 m/s) and less than 2% (vol/vol) air injected. Thus, although these data do not provide conclusive evidence of significant reductions in pressure gradients following the introduction of air, they indicate a tendency towards this effect, thus indicating the possible energy savings, worthy of further investigation, particularly in pipes of larger diameters. For values of X between 60 and 120 (representing air injection up to approximately 4% v/v at injection point) there are several observations in Zone 2. Of these, those relating to cattle slurries showed a bigger reduction in values of $\phi_i$ than pig slurries, indicating that dairy cattle slurries were more shear-thinning than pig slurries.

4. Conclusions

A previously published analytical technique based on dimensionless pressure gradient ratios provided a satisfactory method to describe and compare the pipeline pressure loss characteristics of two-phase flows of water and air and three-phase flows of farm livestock slurries and air.

The injection of air into pig slurries containing less than 3.5% total solids (TS) produced pressure gradients which were consistently higher than those of the slurries flowing alone. Thus, in these dilute slurries, air injection did not improve pumping efficiency. By comparison, similar air injection into cattle slurries containing less than 4% TS usually increased the pressure gradients, but in a few cases, some reductions were observed although the results did not provide statistically significant evidence of an energy-saving effect. Thus, although these data do not provide conclusive evidence of significant reductions in pressure gradients following the introduction of air, they indicate a tendency towards this effect, thus indicating possible energy savings, worthy of further investigation, particularly in pipes of larger diameters. The data showed that dairy cattle slurries were more shear-thinning than pig slurries.

The rheological properties and the particle size distributions of pig slurries containing less than 3.5% TS and cattle slurries containing less than 4.3% TS were found to be independent of time in that they were unaffected by continuous pumping for periods of 3 h using a progressing cavity pump and a 65 m circuit formed from 40.2 mm internal diameter steel pipe line. During this time, the slurries were subject to shear rates of approximately 290 s⁻¹.

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