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Agricultural University of Norway

DOCTOR SCIENTIARUM THESES 1996:7

Pipeline Transportation of Livestock Waste Slurries - Rheological Properties and Effects of Air Injection

Rørtransport av husdyrgjødsel - Reologiske egenskaper og virkninger av luftinjeksjon

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Abstract

The return of livestock waste to the soil is desirable for the recycling of essential plant nutrients. There is considerable interest in utilising pipelines and irrigation equipment for transporting and distributing livestock waste as slurries. Pipeline systems allow a clean and low-cost removal, transport and distribution of the waste, particularly when the equipment can also be used for irrigation.

To design efficient pipeline transport systems for animal waste slurries, the rheological properties, (i.e. relationships between shear stress and shear rate) must be known. Systems for handling and transporting animal waste slurries have been widely used for many years. Despite these facts, 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. The main objectives of the work reported here were to determine flow properties of pig and cattle slurries, and measure the effects that injection of air into the fluid flow had on the flow properties.

Experiments were done with water, pig slurries (< 4.4% Total Solids (TS)) and cow slurries (< 5.5% TS) with and without injection of air in a Tubular Loop Aerator apparatus, and in a large-scale pipeline viscometer. The tests with water were undertaken to investigate the hydrodynamic characteristics of the apparatuses and to compare results to those of slurries. The flow speed for all fluids tested were between 0.5 m/s and 6 m/s. The air injection rates tested were between 1% and 10% volume by volume at the point of injection.

Overall, the key findings arising from the work were:

1. that air injection did not reduce pressure gradients with the slurries tested, although there were indications of a tendency towards this effect at high values of TS;
2. the Lockhart-Martinelli and modified Lin analysis provided useful techniques to express and assess the effects of air injection;
3. the principles of the Lord et al. scale-up procedure were developed for the design of slurry pipelines.

Key words: pig slurry, cow slurry, pipeline transportation, pipeline viscometer, tubular loop aerator, rheological properties, air injection, two-phase flow.

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Preface

This thesis covers investigations of general interest to the design of pipelines conveying non-Newtonian fluids, and in particular pipelines for transportation of animal waste slurries. The primary aim throughout this work has been to determine flow properties of pig and cattle slurries, and measure the effects that injection of air into the fluid flow had on the flow properties.

Sincere gratitude is extended to the Norwegian Research Council (Norges forskningsråd) whose sponsorship made this work possible.

The main part of the work reported here was carried out at Silsoe Research Institute (SRI) in England. I wish to express my appreciations to Professor Brian Legg, Director of SRI, who allowed me to work for 14 months in a very inspiring environment. I also wish to thank Professor Bill Day, Head of Process Engineering Division, for his support, and especially Dr Trevor Cumby, Leader of Biochemical Engineering Group, for his enthusiastic help and valuable suggestions. I received comments of a highly constructive nature from Trevor, which were very important for the progress of the work.

I also wish to recognise those of the technical staff at SRI who have contributed materially to the construction of the research equipment and to the gathering of data. However, there is one person in the technical staff that deserves a special thank - Mr Ian Scotford. Ian was a key person in getting the research equipment to run properly. He also introduced me to the "SRI-system" and used a great deal of his spear time helping my wife and me with practical problems during our stay in England.

I wish to express my gratefulness to Professor Vidar Thue-Hansen, Head of Department of Agricultural Engineering at the Agricultural University of Norway, for being my supervisor for the Norwegian Doctor Scientiarum-degree.

Finally, I wish to thank my wife, Bjørg for her support and for cheering me up during periods of the work when I needed it.

Agricultural University of Norway
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Ås, March, 1996

Jarle T. Bjerkholt

Sammendrag

Hovedmålet med det forskningsarbeidet som presenteres her var å bestemme strømningsegenskapene til bløtgjødsel fra gris og storfe. Videre har hensikten vært å bestemme hvilken virkning injeksjon av luft i væskestrømmen hadde på strømningsegenskapene til disse gjødseltypene. Forhåpentligvis er dette et bidrag til forbedring av dimensjoneringsgrunnlaget for rørledninger til transport av flytende husdyrgjødsel.

Under gjennomgangen av tidligere forskning innenfor området "strømnings-egenskaper til husdyrgjødsel" ble det klart at det var tildels store uovensstemmelser mellom resultatene til de forskjellige forskerne. Disse uoverensstemmelsene kan forklares med at de gjødseltypene som sammenlignes bare tilsynelatende er sammnelignbare. Dette fordi forsøksmetode og forsøksutstyr er mangelfult beskrevet.

Første del av mitt arbeide hadde som hovedhensikt å bidra til den grunnleggende forståelsen av de reologiske egenskapene til bløtgjødsel fra gris og storfe. Resultatene hadde betydning for den strategi som ble valgt for det videre arbeidet. To-fase strøm av husdyrgjødsel og luft ble undersøkt for å finne ut om luftinjeksjon i væskestrømmen kunne ha samme skjærtynnende virkning som hastighetsøkning.

Det ble utført eksperimenter med vann, grisegjødsel (< 3,5% TS (Tørrstoff)) og storfe-gjødsel (< 3,5% TS) med og uten injeksjon av luft i et apparat kalt "Tubular Loop Aerator" (TLA). TLA kan kort beskrives som en lang rørledning med pumpe, gassinjeksjonsutstyr og et væskereservoar. Væsken pumpes rundt i rørledningen og trykket måles i fler punkter. Eksperimentene med vann ble gjort for å skjekke at utstyret fungeret som det skulle, og for å sammenligne resultater fra en væske med kjente egenskaper med resultatene fra husdyrgjødselforsøkene. Det ble konstatert at Lockhart-Martinellis ligninger beskriver trykkgradienten for to-fase strøm av vann og luft på en tilfredsstillende måte.

Lockhart-Martinelli transformasjonen ble også brukt til å sammenligne trykktap ved pumping av husdyrgjødsel med forskjellig TS-innhold, og ulike mengder luftinn-blanding. Det ble gjort noen få observasjoner (ikke statistisk signifikante) hvor trykktapet til to-fase strøm var mindre enn der gjødsla strømmet alene. Alle disse observasjonene ble gjort for storfegjødsel (2-3% TS) ved lav strømningshastighet (0,5 m/s), og mindre enn 2% luftinnblanding (vol./vol.). For grisegjødsel med mindre enn 3.5% TS ble det ikke gjort noen observasjoner hvor trykktapet for to-fase strøm var lavere enn trykktapet hvor gjødsla strømmet alene.

Resultatene fra eksperimentene i TLA apparatet viste at de reologiske egenskapene til husdyrgjødsel lett kan undersøkes ved å måle trykktapet i en rørledning når gjødsla strømmer gjennom. Siden TLA apparatet bare hadde ett rør, og dette ikke var mer enn 40,2 mm i diameter, var det ikke mulig å gjøre eksperimenter med gjødsel som inneholdt mer enn ca. 4% TS. Det var også problemer med å bruke disse resultaten til å beregne trykktapet i rørledinger med andre dimensjoner.

For å undersøke strømningsegenskapene til husdyrgjødsel nermere ble det bygget et storskala rørviskosimenter. Viskosimeteret ble utformet for å måle trykkgradienter til

væsker med forholdsvis høyt innhold av suspendert materiale. Det var nødvendig å kunne prøve mange strømningshastigheter i flere rørdimnsjoner. Viskosimeterets målestrekninger besto av rette, horisontale plastrør (PVC, Polyvinylchloride). Også i andre deler av viskosimeteret, som ventiler, tilførselsledinger etc. ble det brukt PVC. De dimensjonene som ble brukt ble ansett for å være typiske for anlegg til transport av husdyrgjødsel. Viskosimeteret besto av fire rør med følgende innerdiametere: 38,1 mm, 50,8 mm, 76,2 mm og 101,6 mm. Det ble også montert utsyr som gjorde det mulig å injisere luft i væskestrømmen.

For å skjekke at viskosimeteret fungerte tilfredsstillende ble det utført forsøk med vann, tilsvarende testene av TLA apparatet. Videre var det nødvendig å ha data fra en væske med kjente egenskaper til sammenligning av resultatene av forsøkene med husdyrgjødsel. Trykktapet for vann ved ulike strømningshastigheter ble målt i de fire rørene som viskosimeteret besto av, og resultatene ble ansett for å være i god overens-stemmels med det som produsenten oppgav.

Det ble foretatt trykktapsmålinger for følgende væsker: vann, grisegjødsel (< 4,4% TS) og storfegjødsel (< 5,5% TS), med og uten injeksjon av luft. Eksperimetene ble utført med volumstrømmer som variert i intervallet fra 120 l/min til 700 l/min. Det ble injisert luft i væskestrømen som tilsvarte omtrent 1%, 2%, 4% og 6% volum luft per volum væske, beregnet ved injeksjonspunktet.

Skjærspenningen ved rørveggen og nominell skjærrate ble beregnet på bakgrunn av sammenhørende verdier av trykkgradient og volumstrøm. Strømningskurvene for alle væskene ble tegnet (et diagram hvor skjærspenning er inntegnet som en funksjon av skjærrate kalles et reogram, eller en strømningskurve). Strømningskurvene for husdyr-gjødslene ble slakere ettehvert som TS-innholdet øket. Resultatene av disse målingene viser at det er en sterk sammenheng mellom gjødslas TS-innhold og strømningsegenskaper. De væskene som ble undersøkt her, gir alle en kaskade av strømningskurver, som er en av kriteriene for å bruke Lord et al. sin modell for trykktapsberegninger. Det ble vist at Lord et al. prodedyren for å skalere opp trykktapsmålinger for en ikke-Newtonsk væske, også kan benyttes for husdyrgjødsel.

For å sammenligne trykktap for to-fase strøm av væske og luft ble det brukt en modifisert utgave av Lins modell. Denne modellen bygger på den metoden som Lockhart og Martinelli utledet og viste seg å være egnet til formålet og gi akseptable resultater. Det bør imidlertid understrekes at de antagelsene som modellen bygger på er diskutable.

Med bakgrunn i hele det arbeidet som er gjort kan man trekke følgende konklusjoner:

1. Det er ingen signifikante bevis for at injeksjon av luft i væskestrømmen reduserer trykktapet for de husdyrgjødseltypene som er prøvet, selv om det er indikasjoner på at man får en slik effekt for høye innhold av TS.
2. Lockhart-Martinelli og en modifisert utgave av Lins modell er egnede metoder til å uttrykke virkningene av luft injeksjon i væskestrømmen.
3. Det er vist at Lord et al. sin oppskalerings prosedyre også kan brukes til å beregne røranlegg for husdyrgjødseltransport.

Summary

The main objectives of the work reported here were to determine flow properties of pig and cattle slurries, and measure the effects that injection of air into the flowing fluid had on the flow properties. This will hopefully contribute to the refinement of design procedures for pipeline transportation of slurries, taking into account the range of rheological characteristics usually encountered with pig and cattle slurries.

A study of research literature, covering the flow properties of slurries, revealed considerable disagreements between the findings of the various researchers. These disagreements may be explained by the fact that the slurries compared are only apparently comparable. It is essential to view and use data from different investigations with caution, particularly where complete details of their test procedures and equipment are not available.

The first part of the work reported here, describes work whose objective was to gain some understanding of pig and cattle slurries' rheological properties. The results of this work had importance for the selection of strategy for further investigations into the matter. Two-phase flow of slurry and air was investigated to find out whether air injected in the pipework could possibly give the same shear-thinning effects as pumping at higher speed.

Experiments were done with water, pig slurries (< 3.5% TS (Total Solids)) and cow slurries (< 3.5% TS) with and without air injection in a Tubular Loop Aerator (TLA) apparatus. Tests with water were undertaken to check the apparatus and to compare results to those of slurries. The pressure gradients for two-phase flow of water and air is described satisfactorily by the Lockhart-Martinelli correlations.

The Lockhart-Martinelli transformation was also used to compare slurries of different TS-content and different air injection rates. There were a few observations (but no significant evidence) for two-phase pressure drop being less than the pressure drop for single-phase flow of slurry. These observations were related to cow slurry (2-3% TS) at low flow speed (0.5 m/s) and less than 2% air (vol./vol.) injected. Pig slurry containing less than 3.5% TS showed no reduction in pressure loss due to air injection. All observations showed increased pressure losses for two-phase flow of pig slurry and air.

The results of the work in the TLA apparatus showed that the rheological properties of animal waste slurries easily could be investigated measuring the pressure drop in a pipeline section when the slurry flows through it. Anyway, the TLA had only the option of one pipe diameter and that pipe was only 40.2 mm (ID). This made it impossible to investigate slurries containing more than 4% TS or unseparated slurries containing long fibrous material. There are also problems involved in scaling-up the results to make useful predictions for larger pipes.

To make further investigations, a large-scale pipeline (capillary) viscometer was developed. The viscometer was designed to measure pressure gradients of fluids with a relatively high concentration of suspended solids at various flow rates, in pipes of

different diameters. The viscometric test sections (capillaries) and other parts of the pipeline were constructed from PVC (Polyvinylchloride) plastic pipes. The material and sizes used were considered typical of those found in many commercial slurry transport systems both for internal transport in farm buildings and for long distance transport. The internal diameters of the viscometric pipes were 38.1 mm, 50.8 mm 76.2 mm and 101.6 mm. Equipment for injection of air into the fluid flow was also fitted to the viscometer.

To investigate the hydrodynamic characteristics of the viscometer, and get data from a fluid with known behaviour for comparison to the results of slurries, ordinary tap water was used. Pressure gradients were measured in the four viscometric capillaries at various flow rates. The results obtained were found to be in reasonable agreement with those published by the manufacturers.

The work reported here includes experiments with water, pig slurries (< 4.4% TS) and cow slurries (< 5.5% TS) with and without air injection. Pressure gradients were measured in the four viscometric capillaries at a range of flow rates from 120 l/min to 700 l/min. Air was injected into the fluids at rates of approximately 1%, 2%, 4%, and 6% (vol./vol.) calculated at the point of injection.

Corresponding values of differential pressure and flow rate were converted into values of wall shear stress and nominal shear rate and the flow curves for the fluids were plotted. All slurries tested had more gently sloped flow curves than water. The flow curves for slurries got more gently sloped as the TS-content increased. The results point out a strong influence of TS-content on flow behaviour. The fluids studied here produced a diameter family of curves, being one of the criteria for using the model of Lord et al. The principles of the Lord et al. scale-up procedure were developed for the design of slurry pipelines.

A modified version of the model first suggested by Lin, which is a development of the method suggested by Lockhart and Martinelli, has been shown to be useful for comparison of pressure drops for combined flows of liquid and air. However, the assumptions behind the model are questionable.

Overall, the key findings arising from the work were:

1. that air injection did not reduce pressure gradients with the slurries tested, although there were indications of a tendency towards this effect at high values of TS;
2. the Lockhart-Martinelli and modified Lin analysis provided useful techniques to express and assess the effects of air injection;
3. the principles of the Lord et al. scale-up procedure were developed for the design of slurry pipelines.

Contents

1. Pipeline transportation of livestock waste slurries – Rheological properties and effects of air injection

1.1 Introduction

The main objectives of the work reported here were to determine flow properties of pig and cattle slurries, and measure the effects that injection of air into the fluid flow had on the flow properties. This will hopefully contribute to the refinement of design procedures for pipeline transportation of slurries, taking into account the range of rheological characteristics usually encountered with pig and cattle slurries.

The return of livestock waste 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. The tractors and tankers used are usually very heavy and undesirable soil compaction can occur. Soil compaction leads to a closer packing arrangement of the soil particles, and thereby a reduction of the fractional volume of air. Traffic associated with field operations in wet conditions causes deep rutting, smearing, and compaction, which can also inhibit drainage. As shown by Wiersum (1957) and Cannell (1977), roots are unable to decrease in diameter to enter pores narrower than their root caps. Thus, if they are to grow through compacted soil they must displace soil particles to widen the pores by exerting a pressure greater than the soil's mechanical strength. In addition to this mechanical constraint, the soil compaction also impedes the movement of water and air through the soil by reducing the number of large pores. The resulting restriction of aeration and drainage thus exposes roots to several simultaneous stresses. A reduced volume fraction of large pores also reduces the infiltration capacity, with an increased risk of surface runoff and erosion as a result.

A large proportion of the livestock waste produced is stored on the farms for some months and the removal of it is concentrated to a short period of time during spring, at least in Scandinavia. The greater part of the waste is removed as slurries. Wheeled transports have a steeply declining efficiency rate as the distance of transport increases, and when the content of total solids (TS) decreases. The cost of handling has to be balanced against the ease of handling, the flexibility of the handling system, the environmental advantages and the value of the waste.

For these reasons there is considerable interest in utilising pipelines and irrigation equipment for transporting and distributing livestock waste as slurries. Pipeline systems allow a clean and low-cost removal, transport and distribution of livestock waste, particularly when the equipment can also be used for irrigation. A pipeline system also permits an extensive use of automation and therefore needs less attention.

1.2 Thesis outline

In addition to this introductory chapter, this thesis consists of three individual chapters, each containing a separate phase of the research work. However, each new chapter is a natural consequence and follow-up of the experience gained in the previous one.

Chapter 2 is a brief summary of some of the theories and empirical findings valid for non-Newtonian fluids in general and for livestock waste slurries in particular. Chapter 2 presents the classification of single-phase and pseudo-homogeneous multi-phase mixtures and covers some of the basic theories for the work reported in Chapter 3 and Chapter 4. It also focuses on some of the factors that can affect the flow properties of livestock waste slurries from production through storage, treatment and disposal. The chapter also includes a discussion of some of the methods used for measuring the rheological properties of slurries and the interpretation of the data.

In Chapter 3 the results of experiments carried out in a Tubular Loop Aerator (TLA) apparatus, are presented. The objective of this work was to gain some understanding of the rheological properties of pig and cattle slurries, or their flow characteristics. Two-phase flow of liquid and air was investigated to determine the effects that had on the flow properties. The effects of long duration pumping have also been investigated. The pig and cow slurries used in these experiments had a content of total solids (TS) from about 1.5% to 3.5%. Air was injected into the liquids at rates between 2% and 13% (volume by volume).

For the work presented in Chapter 4 a large-scale pipeline viscometer, with four different pipe diameters, was developed. The flow properties of pig slurries containing up to 5% TS, and cow slurries containing up to 6% TS, were investigated and are presented here. The flow behaviour of a combined flow of liquid and air up to 6% volume of air to the volume of slurry at the point of injection, was investigated. A theoretical analysis and a discussion of how the equipment and the techniques used for analysing pressure loss data, are included.

The thesis covers investigations of general interest for the design of pipelines conveying non-Newtonian fluids, and in particular pipelines for transportation of animal waste slurries. The results from the investigations of combined flow of liquid and air are of interest for the design of systems that can aerate the slurry during transport. More efficient design and utilisation of transport systems and treatment plants for slurries, do not only give a positive economic effect, but can also have environmental advantages.

2. General theories for flow of non-Newtonian fluids and previous work on flow properties of livestock waste slurries

2.1 Introduction

The flow of solid-liquid mixtures, i.e. slurries, in pipes differ from that of common liquids. In addition to laminar, transitional and turbulent liquid flow there is homogeneous, pseudo-homogeneous or heterogeneous slurry flow. Govier and Aziz (1972) introduced the term "complex mixtures" referring to all single-phase fluids that are non-Newtonian in their behaviour, and to all multi-phase mixtures involving two or more fluids, or a fluid and a solid, which are capable of flowing in a pipe. The term is used for convenience only and refers to fluid or fluid/solid systems for which the conventional fluid mechanics of single-phase Newtonian fluids does not apply.

Multiphase mixtures where solid particles, gas bubbles or droplets of immiscible liquid of sufficient "fineness" are uniformly dispersed in the continuous phase can be considered being pseudo-homogeneous (Govier & Aziz, 1972). Their flow behaviour can be included with that of single-phase liquids (for some fluids this is only true for highly turbulent flow). Manure slurries are included in this category along with sewage sludge and clay slurries. Heterogeneous slurries tend to have lower contents of solids and higher proportion of large sized particles. This causes a vertical solids concentration gradient in a horizontal pipe even when the flow is highly turbulent (Stalley et al., 1973).

The designer of a fluid-conveying pipeline needs to know the relationship between pressure losses and flow rates as an aid to choosing pipes of suitable diameters. This information is most reliably obtained by making direct measurements in a full-scale simulation plant. Since this approach is seldom feasible, other techniques involving small-scale or laboratory experiments are commonly used to determine fluid properties. By applying these to theoretical or empirically based equations, pressure losses in a full-size pipeline system can be estimated. Several researchers have investigated the rheological properties of agricultural slurries (e.g. Stalley et al., 1973, Chen & Hashimoto 1976, Cumby, 1980, Hauge & Berthelsen, 1988). However, more data are needed on the flow properties of livestock slurries for the satisfactory design of pipelines and other handling equipment.

2.2 Classification of single-phase and pseudohomogeneous, multiphase mixtures

Purely viscous, single-phase fluids and pseudo-homogeneous, multi-phase fluid mixtures that are stable even in the absence of turbulence may be classified in accordance with their response to shearing stresses under conditions resulting in unidirectional, laminar flow. Govier & Aziz (1972) reviewed many of these, and these reviews are recommended for further information. This chapter includes a brief discussion of time-independent viscous fluids only. However, the flow properties of Newtonian fluids are also briefly discussed for comparison.

2.2.1 Viscosity

The viscosity of a fluid is a measure of its resistance to shear or angular deformation. The friction forces in fluid flow result from the cohesion and momentum interchange between molecules in the fluid (Daugherty et al., 1985).

Consider the system of two parallel plates separated by the fluid of interest as shown in Figure 1.

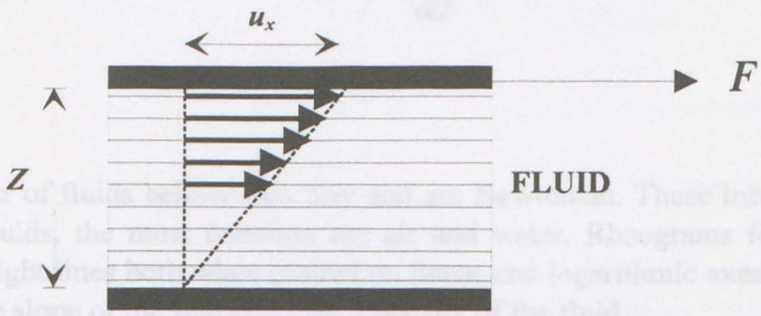

Figure 1: Illustration sketch of basis for Equation 1

The plates can both be moving, but it is the relative velocity of the plates that is of interest, and for simplicity the lower surface is assumed to be stationary. The upper plate is moved parallel to the lower plate at velocity u_x by a force F corresponding to some area A of the moving plate. In Figure 1, x and z are the Cartesian coordinates in the direction of the flow and perpendicular to the plates, respectively. The shearing stress imposed on the fluid is $F/A = \tau_{zx}$, or simply τ. Particles in contact with each plate will adhere to it, and therefore have the same velocity as the plates. The fluid is subjected to strain at the rate du_x/dz ($du_x/dz = \gamma$), which is the velocity gradient or the rate of shear. Experiment has shown that shear stress and shear rate are related, although differently for different fluids, and also differently for the same fluid under different temperature and/or pressure conditions. Equation 1 is known as the constitutive or rheological equation for a fluid. This equation is characteristic of a given fluid or fluid system at any given pressure or temperature.

$$\tau = f(\frac{du_x}{dz})$$

Equation 1

Equation 1 describes the rheological equation for purely viscous fluids, discussed in the next section. The graphical representation of Equation 1 is known as the rheogram, or the flow curve for the fluid.

2.2.2 Newtonian fluids

Newtonian fluids are so called because they follow the rheological equation postulated by Newton (Equation 2). The constant of proportionality, μ, is the viscosity of a fluid, at any given temperature.

$$\tau = \mu \frac{du_x}{dz}$$

Equation 2

A vast number of fluids behave this way and are Newtonian. These include all gases and many liquids, the most common are air and water. Rheograms for Newtonian fluids are straight lines both when plotted on linear and logarithmic axes. For plots on linear axes the slope of the line gives the viscosity of the fluid.

2.2.3 Non-Newtonian fluids

There are certain fluids that do not obey Newton's law of viscosity, Equation 2. For these fluids the shear stress does not vary proportionally to the shear rate. These types of fluids are named "non-Newtonian" fluids. There is no single or simple form of constitutive equation, as for Newtonian fluids, that accurately describes the rheological behaviour of non-Newtonian fluids. Several equations, both theoretically and empirically based, have been developed to describe the various types of non-Newtonian fluids. Even the simplest and also most limited one of these involves two or more constants to characterise the fluid, as compared with the single property of Newtonians. One of these equations (Equation 3), that in its general form probably describes the majority of non-Newtonians, will be briefly discussed here, owing to the fact that many of the other equations are highly complex and can be difficult to use for pipeline design, and the fact that most agricultural slurries, including livestock waste slurries, are well described by Equation 3.

$$\tau = K\gamma^n + \tau_y$$

Equation 3

where:

τ = shear stress (N/m^2)

K = consistency coefficient (N*s^n/m^2)

n = flow behaviour index (dimensionless)

τ_y = yield stress (N/m^2)

The rheological indices, consistency coefficient (K) and the flow behaviour index (n), are used for classification of fluids into categories (Metzner & Reed, 1955 and Dodge & Metzner, 1959). Figure 2 shows generalised rheograms for fluids covered by Equation 3.

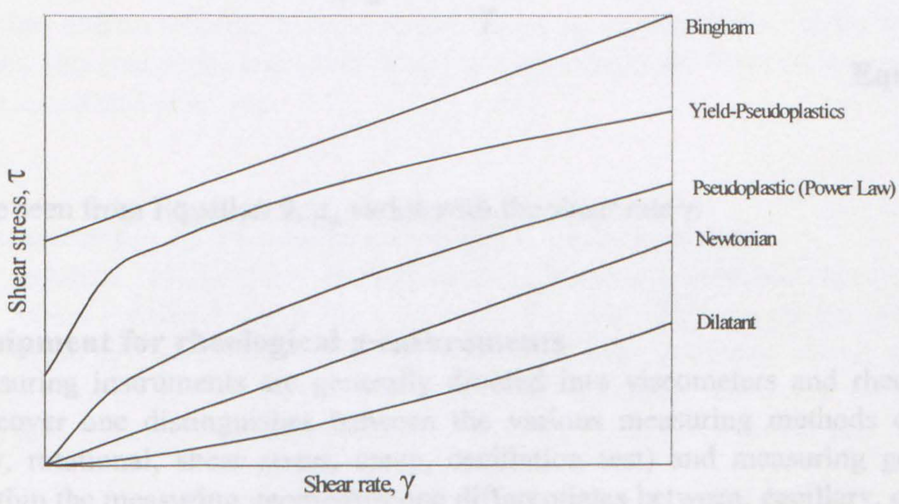

Figure 2: Generalised rheograms for some categories of non-Newtonian fluids

The constitutive equations for the fluids shown in Figure 2 are as follows:

Bingham: $\tau = K\gamma^n + \tau_y, \quad n = 1$ **Equation 4**

Yield-Pseudoplastic: $\tau = K\gamma^n + \tau_y, \quad n < 1$ **Equation 5**

Pseudoplastic (Power Law): $\tau = K\gamma^n, \quad n < 1$ **Equation 6**

Newtonian: $\tau = K\gamma^n, \quad n = 1 \text{ and } K = \mu$ **Equation 7**

Dilatant: $\tau = K\gamma^n, \quad n > 1$ **Equation 8**

The rheological indices K and n, for a fluid can be determined by measuring the shear stress for a range of shear rates and plot their rheograms on log-log paper. The rheogram are straight lines where n are the slopes of the lines, and K is found as the value of shear stress when the shear rate is equal to one.

Although only Newtonian fluids possess a property which strictly may be called viscosity, it is still possible to use the term for non-Newtonians if one states the shear rate for which it was determined. This has been assigned the expression "apparent viscosity" with the symbol, μ_a. The apparent viscosity is defined by Equation 9.

$$\mu_a = \frac{\tau}{\gamma}$$

Equation 9

As can be seen from Equation 9, μ_a varies with the shear rate γ.

2.3 Equipment for rheological measurements

The measuring instruments are generally divided into viscometers and rheometers, and moreover one distinguishes between the various measuring methods or types (capillary, rotational, shear stress, creep, oscillation test) and measuring geometry used. Within the measuring geometries one differentiates between: capillary, co-axial, cone/plate, plate/plate. Three main types of apparatus are in common use for measurement of viscosity or other rheological properties. All these are designed to create laminar shear conditions and have sensors for measurement of quantities that allow the shear rate and shear stress to be determined. Falling, rolling and sliding spheres viscometers will not be discussed here since these are instruments more for comparative measurements and not for absolute viscosity determination. A brief outline of the principles of the three main types of viscometers is given below.

2.3.1 The capillary viscometer

In the capillary viscometer the pressure drop is measured when the fluid sample flows through a tube with known diameter and length. The shear rate can be determined from the measured flow rate and the shear stress from the measured pressure drop and the geometry of the pipe. Precautions are taken to maintain constant temperature conditions, and corrections are applied for entrance and kinetic energy effects (Hashimoto & Chen, 1975a). The capillary viscometer has its advantage in being mechanically simple and having the possibility of providing high shear rates.

2.3.2 The rotary viscometer

There are two main types of rotary viscometers. The first type is also called concentric cylinder viscometer. The fluid sample is placed in the gap between a stationary and a rotating cylinder, and the torque acting upon the stationary cylinder is measured. The other type of rotary viscometer uses a single rotating cylinder that can be immersed into in a fluid sample in any container. The shear rate can be determined from the geometry of the device and the speed of the rotating cylinder. The shear stress can be determined from the measured torque.

2.3.3 The cone-and-plate viscometer and the parallel-plate viscometer

The cone-and-plate viscometer and the parallel-plate viscometer are designed to subject a sample of fluid maintained in the narrow space between a rotating, flat, circular plate and an inverted cone or parallel plate to laminar shear. As for the rotary viscometer, the shear rate and shear stress can be calculated from measurements of rotational speed and of torque.

2.4 Interpretation of data from rheological measurements

The interpretation of laboratory measurement data usually involves calculations of points to define the rheogram or flow curve for the fluid. This means the calculation of shear stress and shear rate from the measured data described above after any appropriate corrections are made. The following is a brief summary of how the measured data from the viscometers are related to the rheological properties.

2.4.1 Shear stress

When a capillary viscometer is used the following parameters are either measured or known:

Q = volumetric flow rate

D = the internal diameter of the capillary

L = length of capillary over which pressure loss is measured

Δp = pressure drop over the length L

The average fluid velocity can be calculated applying Equation 10.

$$V = \frac{4 * Q}{\pi * D^2}$$

Equation 10

The shear stress at the pipe wall, τ_w, is determined by the force balance in Equation 11.

$$\frac{\pi * D^2}{4} * \Delta p = \pi * D * L * \tau_w$$

Equation 11

Equation 11 can be rearranged to:

$$\tau_w = \frac{D * \Delta p}{4 * L}$$

Equation 12

These equations can be used for laminar and turbulent flow of both Newtonian and non-Newtonian fluids.

For a rotational viscometer the shear stress is calculated from a simple force balance by Equation 13.

$$\tau = \frac{2 * M}{{D_c}^2 * \pi * L_c}$$

Equation 13

where

D_c = diameter of the rotational cylinder
L_c = length of the rotational cylinder
M = torque

2.4.2 Shear rate

Rabinowitsch (1929) and Moony (1931) developed an expression for the rate of shear of a fluid which is entirely independent of the fluid properties (Equations 14).

$$\gamma = \left(\frac{1+3n'}{4n'}\right)\frac{8*V}{D}$$

Equation 14

where

$$n' = \frac{d \ln \frac{D*\Delta p}{4*L}}{d \ln \frac{8*V}{D}}$$

Equation 15

n' is the slope of the logarithmic plot of $(D\Delta p/4L)$ versus $(8V/D)$.

For a rotary viscometer the calculation of shear rate depends on the type of instrument used. The calculations including corrections can be very complex, and Equation 16 is an example for a rotating cylinder viscometer that is one of the easiest.

$$\gamma = \frac{4*\pi*N}{n''}$$

Equation 16

where:

N = speed of rotating cylinder

$n'' = d \ln T/d \ln N$ is the slope of a logarithmic plot of T versus N

T = torque measured on the cylinder

No further discussion of the use of these instruments will be made here. Further information on theory, techniques and instruments can be found in the book by Scott Blair (1969) and in manuals from manufacturers of viscometers.

2.5 Flow properties of livestock waste slurries – previous work

Several researchers have investigated the flow properties of livestock waste slurries and other agricultural slurries with similar flow behaviour (e.g. Stalley et al., 1973, Chen & Hashimoto 1976, Cumby, 1980, Hauge & Berthelsen, 1988). Hauge & Berthelsen (1988) have investigated the flow properties of cattle slurries as part of their work on rotational heat exchangers. Hashimoto & Chen (1975b), Chen & Hashimoto (1976), and others have investigated rheological properties of a variety of animal waste slurries. Cumby (1980, 1981) has investigated the flow of liquid animal feedstuff and discussed various methods of pipeline design for non-Newtonian fluids.

Agricultural slurries have by these researchers been shown to exhibit non-Newtonian yeld pseudoplastic behaviour or generalised Bingham fluid behaviour, described by Equation 5. Animal waste slurries in particular do not require a finite shearing stress to initiate motion and are described as power-law fluids, Equation 6.

Hauge & Berthelsen (1988) have compared their results to the results of other researchers (e.g. Chen & Hashimoto, 1975, 1976) and found large differences between the rheological indices. This is explained by the fact that they used raw slurry that contained long, fibrous material and larger sized particles than Chen & Hashimoto, that used screened slurries in their experiments. Hauge & Berthelsen also questioned the small range of TS values used by Chen & Hashimoto, which was limited by the diameter of the capillary (9.5 mm). A large-scale capillary viscometer, similar to that described by Cumby (1980), is considered to be more suitable for measurements on agricultural slurries. This type of viscometer is capable of measuring flow properties of slurries with high solid concentrations and gives more realistic results. A large-scale capillary viscometer can have test sections of pipe several meters long, with no restrictions in the selection of diameters. It is also possible to connect several different diameters in series, allowing fluids with time-dependent flow properties to be simultaneously subjected to many different shear rates. This type of viscometer is limited in use only by the type of pump used for circulation.

2.6 Physical parameters influencing the flow properties of slurries – previous work

Several researchers have carried out investigations into physical parameters that influence on the flow properties of animal waste slurries. The reason for investigating these has been to identify those parameters that are of importance to the determination of the flow properties of the slurries. Further it has been important to identify parameters which would mathematically describe the rheological properties of the slurries and that easily and precisely could be measured experimentally. Some of the factors investigated and reported in different papers are presented here.

2.6.1 Total solids content

The total solids contents have by many researchers been shown to have a significant effect on the rheological indices or apparent viscosity of slurries. However, the TS-content is no reliable indicator of the flow properties of the slurry since there is considerable variation in the results. For example, Frost and Owens (1982) showed that the viscosity of sewage sludge can vary more than one hundred-fold for one TS value. Chen et al. (1982a and 1982b) showed that the flow behaviour index, *n*, for cattle slurry was dependent only on the TS-content and independent of the temperature. They derived a functional relationship of TS for *n*. This function was tested by Hauge & Berthelsen (1988), and they found considerable discrepancies between their results and the result of Chen et al. The *n* value of Hauge & Berthelsen decreased faster with increasing TS-content than the *n* value estimated by Chen et al. This was by Hauge & Berthelsen explained by the fact that they used raw slurry and Chen et al. used screened slurry. It is essential to view and use data from other researchers with caution, particularly where complete details of their test procedures and equipment are not available. Even when a capillary viscometer has been used, it is advisable to look carefully at the equipment and test procedures. One should remember that most of the capillary viscometers are short, closed-loop systems of small volume, using short pumping periods to pass samples through small-bore tubes. In addition to this, the samples have usually been screened and are therefore not directly representative of a real, agricultural situation.

2.6.2 Effects of temperature

The viscosity or apparent viscosity has for most fluids been shown to increase as temperature decreases. The apparent viscosity for cattle slurry was found by Chen et al. (1982a) to be dependent on temperature, and they derived a mathematical model for that relationship. As mentioned above, Chen et al. (1982a and 1982b) showed that the flow behaviour index, *n*, for cattle slurry was dependent only on the TS-content and independent of the temperature. Hauge & Berthelsen (1988) also found that the apparent viscosity for cattle slurry was dependent on temperature, but their results did not agree with those of the model of Chen et al. (1982a). It appears from both these works that the effects of temperature are generally small under normal conditions of between 10°C and 25°C.

2.6.3 Effects of particle size

Particle size and particle size distribution affect the rheological properties of slurries. No complete investigations into these effects are known to the author. However, Hashimoto & Chen (1975b) found that slurries with relatively large volumes of loosely aggregated particles presented a higher apparent viscosity than single-particle slurries.

3. Mesurement of pressure loss in a Tubular Loop Aerator

3.1 Introduction

To design efficient pipeline transport systems for animal waste slurries, the rheological properties, (ie. relationships between shear stress and shear rate) must be known. Systems for handling and transporting animal waste slurries have been widely used for many years. Despite these facts, 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, 1975b). Non-Newtonian properties lead to non-linear relationships between shear stress and shear rate. Shear stress vs shear rate relationships for farm slurries have been expressed by the power law, Equation 17, (Hashimoto & Chen, 1975b).

$$\tau_w = K\gamma^n$$

Equation 17

Consequently, it may be more efficient sometimes in energy terms, to pump at high velocities and thereby to take advantage of the lower viscosity which ensues. Similar effects may be created by injecting air into the flow. To investigate the effects air injection have on the rheological properties of animal waste slurries, experiments with pig slurries and cow slurries were undertaken in a tubular loop aerator apparatus (TLA), of the type previously described by Cumby and Slater (1989). Experiments with water and air were done in the TLA to provide data describing Newtonian fluids with reproducible physical characteristics. The results from these experiments were compared with the results from slurries because it was believed that the flow properties for slurries with low concentration of total solids (TS) approach those of water.

3.2 Materials and methods

3.2.1 Construction of the TLA and instrumentation

The TLA apparatus is shown diagrammatically in Figure 3. The TLA was constructed to investigate oxygen transfer and therefore many of the components were not relevant to the experiments described in this report and their function will therefore not be explained.

The liquid tested was mixed and stored in vessel (B) which had a volume of 2.7 m^3. Vessels A and B are mounted on load cells and the volume calculated from their individual weights. The progressing cavity pump (Mono-pump[1]) (E) was driven by an electric motor (G) via a variable speed transmission. The flow was measured by an electro-magnetic flowmeter (D) before it went to the 65 m long tubular loop made of a 40.2 mm internal diameter galvanised steel pipeline. Air was supplied from a compressor (M). The airflow was controlled by valve (AA) and the flow measured with airflow meter (N) and air pressure with pressure transducer (Q). The air temperature was measured with a thermistor (P). The air was injected to the liquid in the pipeline through a non-return valve (L). The pressures were measured with ten pressure transducers in locations R1 to R10. These transducers were placed at the end of a 3.8 m straight section of pipe. Thus, there were two sections of 3.8 m straight pipeline, four 90^o bends, two tees, and two transducer housings. There were seven sections like this. Thermistors were also located in R3, R5, R7, R9 and in both vessels to measure the temperature of the liquid. After passing through the tubular loop, fluids were returned to either one of the vessels or to an external storage tank (Figure 4). A PC collected the data from an analogue to digital converter (X). Three-term (PID) controllers were used to control the system. The controllers, were set from a computer which also controlled the system while it was running. The apparatus also included a system for calibration of the flowmeter by diverting the flow with calibration valve (GG) into a barrel (BB) mounted on scales (BB).

[1] Mention of proprietary products does not imply endorsement by the author.

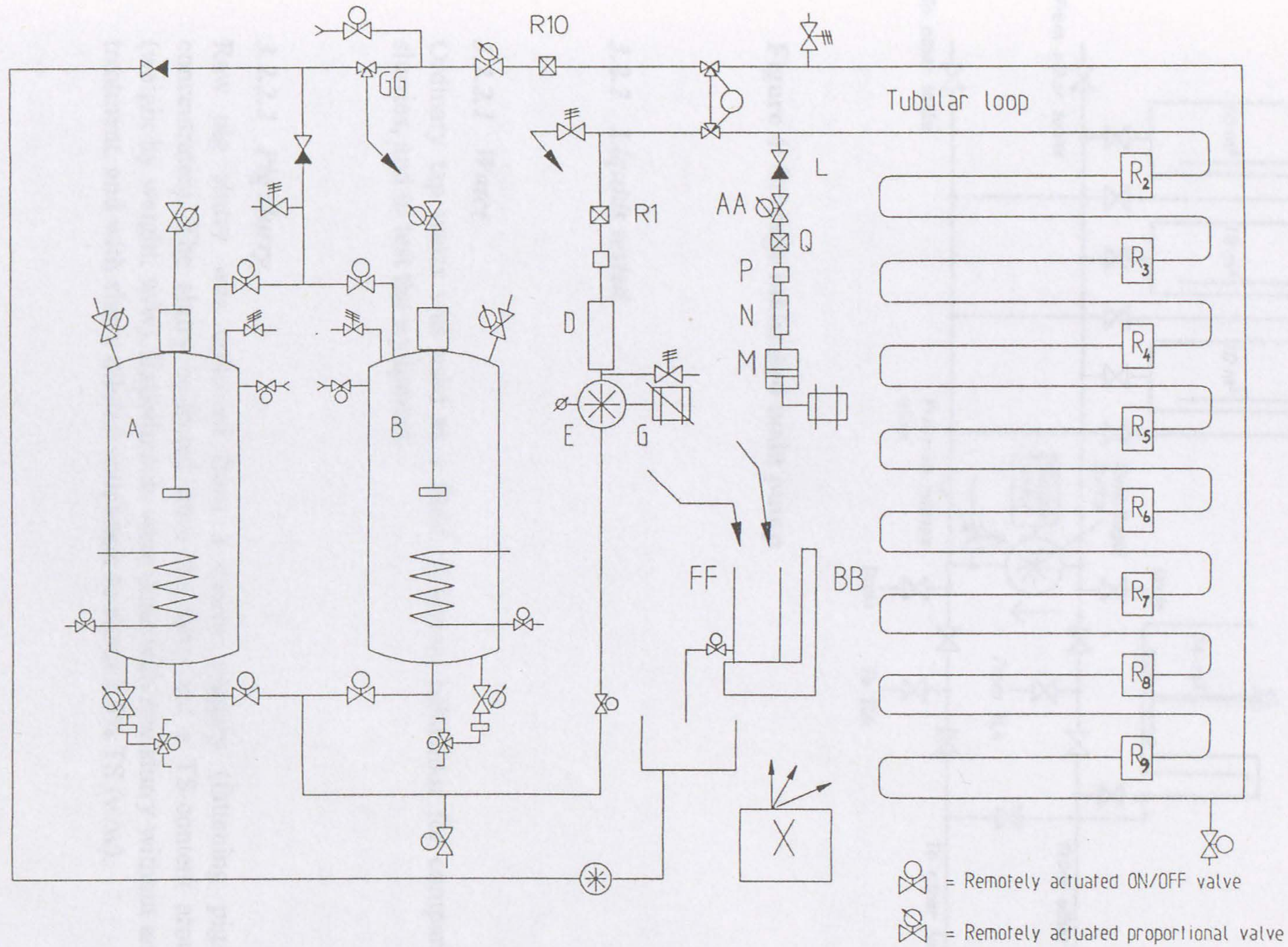

Figure 3: Hydraulic circuit of the tubular loop aerator (TLA) apparatus

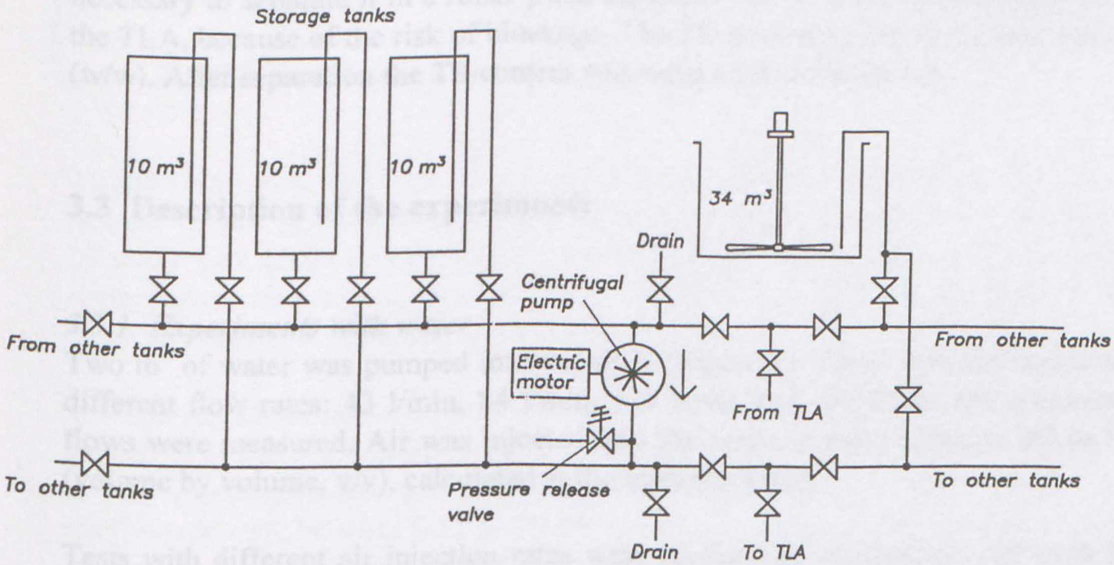

Figure 4: Storage tanks and main pump

3.2.2 Liquids tested

3.2.2.1 Water

Ordinary tap water was used as a fluid of known behaviour for comparison with slurries, and to test the equipment.

3.2.2.2 Pig slurry

Raw pig slurry was collected from a nearby piggery (fattening pigs fed on concentrates). The slurry collected from the farm had a TS-content around 3.5% (weight by weight, w/w). Experiments were done with raw slurry without any kind of treatment, and with slurry diluted with water to about 2.5% TS (w/w).

3.2.2.3 Cow slurry

Untreated cow slurry was collected from a nearby dairy farm (dairy cows on a diet of grass silage and concentrates). The slurry contained long fibrous material and it was necessary to separate it in a roller press separator before doing experiments with it in the TLA, because of the risk of blockage. The TS-content of the raw slurry was 10.9% (w/w). After separation the TS-content was reduced to 4.9% (w/w).

3.3 Description of the experiments

3.3.1 Experiments with water

Two m^3 of water was pumped into vessel B (Figure 3). Water was circulated at four different flow rates: 43 l/min, 84 l/min, 124 l/min and 145 l/min and pressures and flows were measured. Air was injected into the water at rates between 2% and 12% (volume by volume, v/v), calculated at the injection point.

Tests with different air injection rates were carried out successively for each liquid flow rate. Following every change of air flow rate the flow was allowed to stabilise for at least two minutes before any data were logged.

3.3.2 Experiments with pig slurry

Slurry was transferred from the main storage tank to one of the TLA vessels with a centrifugal pump (Figure 4). For each different TS-content tested it was necessary to use three vessels of slurry which is a total volume of 7.5 m^3. Slurry was pumped through the TLA at four different flow rates: 41 l/min, 84 l/min, 124 l/min, 140 l/min. Air was injected into the slurry at rates of approximately 2%, 4%, 6%, 8% and 10% (v/v) calculated at the injection point.

The experiments with air-free and air-injected slurry were done successively. The pump was set to one speed and the air-free test was done. Then the tests with different air injection rates were completed from the lowest to the highest air injection rate. Every time the air injection rate was changed the flow was allowed to stabilise for at least two minutes before any data were logged. Data were logged every 10 seconds for 90 seconds, then the air and liquid flows were changed again. The slurry was returned to a 10 m^3 storage tank (Figure 4) for degassing before it was reused. Time allowed for degasing was four hours. Samples for TS-analysis were collected during alternate runs. The TS-content was stable throughout the run of the tests with each liquid speed. The pig slurries used in the experimets are shown in Table 1, the standard deviation for the samples in the group are also shown.

Table 1: TS-concentration and st. dev. for the pig slurries used in the experiments

Group	Average TS-content (%)	Standard deviation (%)
2-3%	2.29	0.35
3-4%	3.33	0.16

To get slurry with different TS-concentrations the necessary dilution was calculated and the volume of water needed was then pumped into the vessel. The required weight of slurry was added and thoroughly mixed with the mixer in the vessel before new experiments were started. The slurry was diluted from a maximum TS-concentration of approximately 3.5% to a minimum of 2.2% (w/w).

All data were then imported to a spreadsheet and organised for statistical analysis. A straight line was fitted to the pressure data from each test (as illustrated by Figure 5). A very good agreement with the straight line was obtained; most of the regression coefficients were between 0.88 and 0.99. This indicated, amongst other things, that the equipment was working to a satisfactory standard.

3.3.3 Experiments with cow slurry

Cow slurry was transferred from the main storage tank to one of the TLA vessels with a centrifugal pump. The small size of the TLA vessels made it necessary to use three vessels of slurry for each TS content, amounting to a total volume of 7.5 m^3 to complete all the flow rates of liquid and air. Cow slurry was pumped through the TLA at the same flow rates as for water and pig slurry. Air was injected into the slurry at rates between 2% and 13% (v/v) calculated at the injection point. The experimental procedure was the same for cow slurry as for pig slurry. The data for cow slurry are presented in three groups depending on TS concentration. 1 to 2%, 2 to 3% and 3 to 4% TS. The average TS-concentrations and the standard deviations in all groups are shown in .

Table 2: TS-concentration and st. dev. for the cow slurries used in the experiments

Group	Average TS-content (%)	Standard deviation (%)
1-2%	1.60	0.38
2-3%	2.51	0.32
3-4%	3.30	0.05

As for pig slurry, a straight line was fitted to the data points for each test. The pressure drop showed a very good agreement with the straight line; most of the regression coefficients were between 0.8 and 0.97. The range of the pressure transducers was from 0 to 6 bar and that caused bigger variation in the data for low flow rates due to low pressures. The regression coefficients were therefore lower for low flow rates than for the higher flow rates.

3.3.4 Long duration pumping tests

It was necessary to investigate the effect of TS-concentration upon pressure gradient. The easiest way to get slurry with different TS-concentrations without needing vast quantities of slurry, was by successive dilution of an initially concentrated sample. To investigate whether the rheological properties of the slurry remained unchanged during pumping, a long duration pumping test was undertaken. One m^3 of each slurry with a TS-concentration as high as possible (pig TS = 3.5%, cow TS = 4.3%) was pumped around the TLA for three hours at flow rate of 110 l/min. After three hours pumping the slurry had on average, passed through the pump 18 times. Samples for particle size distribution and TS-content analysis were collected before the start of the test run. The samples were collected from the vessel, through the sampling tubes fitted at three different levels (only the lowest one was used here).

During the first hour of pumping, samples were collected every 10 minutes. Data were logged every 10 seconds. After the first hour, the logging-time was reset to 30 seconds and samples were taken every 20 minutes. The sample volume was 250 ml for TS-content and 250 ml for particle size distribution analysis. The TS-content was calculated by weighing before and after drying in an oven at 105°C for 16 hours.

The analysis of particle size distribution were done by wet sieving using sieves sizes:

- 600 mm
- 425 mm
- 300 mm
- 212 mm.

The plan was to do further analysis of the fraction of particles smaller than 212 mm in an electronic particle size counter equipment. Due to the high number of samples (25) and the low capacity of the counter equipment (2 per day) it was decided to freeze the samples to stop biological activity. However, the freezing and defrosting processes made the particles aggregate. The integrity of the samples were therefore dubious and the analyses were not carried out.

3.4 Determination of correction factors

3.4.1 Corrections for bends and fittings

Due to the construction of the TLA it was not possible to measure pressure gradients in the straight pipeline sections directly. As described, the pipeline between successive pressure transducers comprised two 3.8 m sections of straight pipeline connected with four 90° bends and two tees. There were seven sections like this and a supply and return line making a total of 65 m pipeline between the first and the last pressure transducers. 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 turbulent flow regime and an equivalent length of pipeline was calculated and used for all the analysis done for different fluids.

Both theoretical calculations based upon Bernoulli's equation and empirical calculations based upon the manufacturer's data for head-loss in straight pipeline were undertaken.

3.4.2 Measured pressure gradients

Due to the localised pressure losses caused by bends and fittings, overall pressure gradients calculated from measured pressure losses and the total geometrical length of the pipeline would have been too large. Examples of pressure gradients calculated in this way are included in row 1 below the heading of Table 3. The effect of the localised losses is illustrated in Figure 5. Two alternative methods of corrections were devised and compared, based on experimental data for water.

Table 3: Measured pressure gradients and calculated pressure gradients for water at four different flow rates in the TLA

Flow rate of water (l/s)	0.73	1.38	2.10	2.46
All pressure gradients in (kPa/m)				
1. Measured pressure gradients	0.232	0.774	1.736	2.363
2. Corrected pressure gradients (Method 1)	0.198	0.673	1.506	2.060
3. Measured pressure - manufacturers data for pressure loss in stright pipelins	0.121	0.404	0.906	1.233
4. Manufacturer's data (nomogram)	0.120	0.408	0.900	1.230

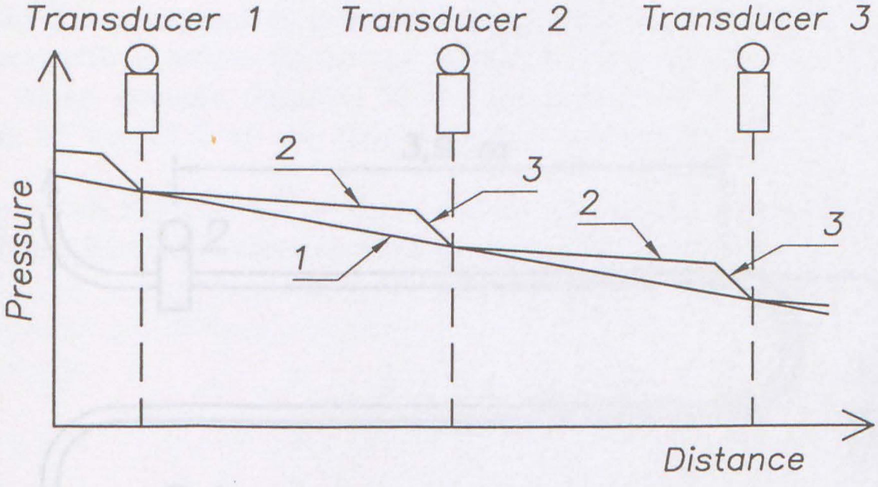

Figure 5: Conceptual illustration of the pressure losses in the TLA: (1) Measured pressure gradient; (2) Real pressure loss in the straight pipeline; (3) Loss due to bends and fittings

3.4.2.1 Method 1: Energy considerations for steady flow of incompressible fluid

Bernoulli's equation was applied to calculate the different forms of energy present in fluid flow. The equation was applied to the flow between pairs of pressure transducers for various flow rates. Based on these calculations a modified pressure gradient and an equivalent length of pipe to represent the bends and fittings was calculated.

If we assume no heat is gained or lost between locations 1 and 2 (Figure 6) Bernoulli's equation for an incompressible fluid becomes:

$$\frac{p_1}{\gamma} + Z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + Z_2 + \frac{V_2^2}{2g} + h_L$$

Equation 19

where: p = pressure (Pa)
Z = elevation (m)
V = velocity (m/s)
g = acceleration of gravity = 9.81 m/s^2
γ = specific weight (kg m^{-2}s^{-2})
h_L = energy loss per unit weight (m)
subscripts 1 and 2 refer to locations 1 and 2.

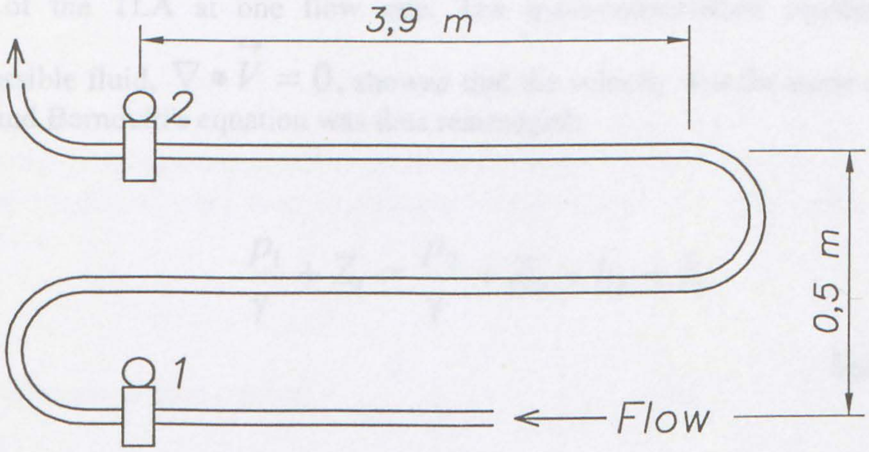

Figure 6: Section of the TLA

The energy loss per unit weight of fluid, h_L, can be divided into friction loss in the pipe, h_f, and minor losses in bends and fittings, h_s.

$$h_s = C\frac{V^2}{2g}$$

Equation 20

$$h_f = f\frac{L}{D}\frac{V^2}{2g}$$

Equation 21

where: f = friction factor (dimensionless)
D = pipe diameter (m)
L = length of pipe (m)
C = loss factor (dimensionless)

f may be found from a Moody diagram. The Moody diagram is a logarithmic diagram in which f is expressed as a function of the Reynolds number and the relative roughness ε/D. C values for various accessories is given in tables (eg. Lencastre, 1987). As an example, Equation 20 and Equation 21 were applied to one of the sections of the TLA at one flow rate. The mass-conservation equation for an incompressible fluid, $\nabla \bullet \vec{V} = 0$, showed that the velocity was the same at location 1 and 2, and Bernoulli's equation was thus rearranged:

$$\frac{p_1}{\gamma} + Z_1 = \frac{p_2}{\gamma} + Z_2 + h_f + h_s$$

Equation 22

The coefficients used in these calculations were taken from Lencastre (1987), and from the details of the experimental apparatus:

Pipe diameter:	D	= 40.2 mm
Pipe wall roughness:	ε	= 0.15 mm¨
Relative pipe roughness:	ε/D	= 0.15/40.21 = $3.7 * 10^{-3}$
Friction factor:	f	= 0.029
Liquid speed:	V	= 1.658 m/s

Friction loss (m of water): $h_f = 0.029 * \dfrac{7.8}{0.0402} * \dfrac{1.658^2}{2 * 9.81} = 0.79$

Minor losses (m of water): $h_s = C\dfrac{V^2}{2g}$, as follows

- four 90° bends, $C = 0.50$ gives $h_{f(bends)} = 4*0.50*(1.658^2/(2*9.81)) = \underline{0.28}$
- two Tees, $C = 0.37$ gives $h_{s(tees)} = 2*0.37*(1.658^2/(2*9.81)) = \underline{0.10}$
- transducer housings, modelled by four threaded unions, $C = 0.07$ gives $h_{f(housings)} = 4*0.07*(1.658^2/(2*9.81)) = \underline{0.04}$

Thus: total pressure loss due to bends and fittings, $h_s = 0.28 + 0.10 + 0.04 = \underline{\underline{0.42\ m}}$

Hence the expected pressure at location 2 was calculated and compared with the measured pressure.

Measured pressure at location 1, $p_1 = 1.39*10^5$ Pa. Calculated, or expected pressure at location 2 is given by Equation 23.

$$p_2 = \left(\frac{p_1}{\gamma} + Z_1 - Z_2 - h_f - h_s \right) \gamma$$

Equation 23

which gives a pressure of 121.4 kPa or 1.21 bar. The measured pressure at p_2 was 1.25 bar, showing good agreement between prediction and the measured result. Thus, the equivalent length of pipe was calculated, which would have produced the same pressure loss:

$$\text{Equivalent length of pipe (meter)} = \frac{h_s}{h_f / L} \Rightarrow \frac{0.42}{0.79} * 7.88 = 4.15$$

When the equivalent pipe length is added to the real pipe length and the regression is done we get the corrected pressure gradients, shown in Table 3, line 2 below the heading.

3.4.2.2 Method 2: Manufacturer's data

In Method 2 the pressure loss due to bends and fittings was calculated as the difference between measured pressure loss and the pressure loss in the straight pipe sections given in table by the manufacturer (British Steel, 1971). As in Method 1, an equivalent length of pipe was calculated, added to the real pipe length and the pressure gradient was calculated by regression. This should ideally have given the same pressure gradient as the gradient given by the manufacturer. Discrepancies were caused by measurement errors in transducers, the data being scattered and thereby not lying exactly on a straight line.

The manufacturer's pressure gradient data for flow of water in galvanised steel pipes were based on the formula:

$$i = \frac{0.00219 * G^{1.92}}{d^{5.13}}$$

Equation 24

$$p_2 = \left(\frac{p_1}{\gamma} + Z_1 - Z_2 - h_f - h_s\right)\gamma$$

Equation 23

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$$i = \frac{0.00219 * G^{1.92}}{d^{5.13}}$$

Equation 24

where: i = pressure gradient (Dimensionless ratio of h_f/L)

G = rate of discharge (gallons/minute)

d = bore of tube (inches)

The data from the manufacturer are presented in a nomogram (British Steel, 1971).

By subtracting the pressure gradients predicted by calculations based on Equation (8), from the measured pressures, an equivalent length of pipe was estimated and new pressure gradients were calculated by regression. An example of these calculations is given below, results from these calculations are shown in Table 3, line 3 below heading.

Example: Calculation of equivalent pipe length.

Flow rate:	1.38 (l/s)
Pressure gradient as calculated in row 1, Table 1:	0.774 (kPa/m)
Manufacturer's pressure gradient data:	0.408 (kPa/m)
Total geometrical pipe length:	65 m

$$\text{Equivalent pipe length} = \frac{\text{Total gometrical pipe length(Measured pressure grad - Manufact. press. grad)}}{\text{Manufact. pressure grad}}$$

$$\text{Equivalent pipe length} = \frac{65(0.774 - 0.408)}{0.408} = 58.30 \text{ m}$$

Similar calculations were done for four flow rates representing a total of 240 pressure observations. The average equivalent pipe length was 59.54 m with a standard deviation of 0.88 m.

The values of pressure gradient expressed in line 3 in Table 3 were calculated as follows: $\text{Overall pressure gradient} = \frac{\text{(measured pressure gradient) * (pipe length)}}{\text{(pipe length) + (average equivalent length)}}$

$$\text{eg } 0.404 = \frac{0.774 * 65}{(65 + 59.54)}$$

The differential pressure, (Δp), versus flow rate, (Q), data were converted to corresponding values of wall shear stress, ($\tau_w = D\Delta p/4L$) and nominal shear rate, ($\gamma = 8V/D$), (Metzner and Reed, 1955). A logarithmic plot of τ_w and γ showed a linear relationship between τ_w and γ. Similar plots were prepared using manufacturer's data (British Steel, 1971).

Figure 7 through Figure 10 show the flow curves calculated for the different methods of corrections from Table 1. The slope of the lines varies from 1.90 to 1.93.

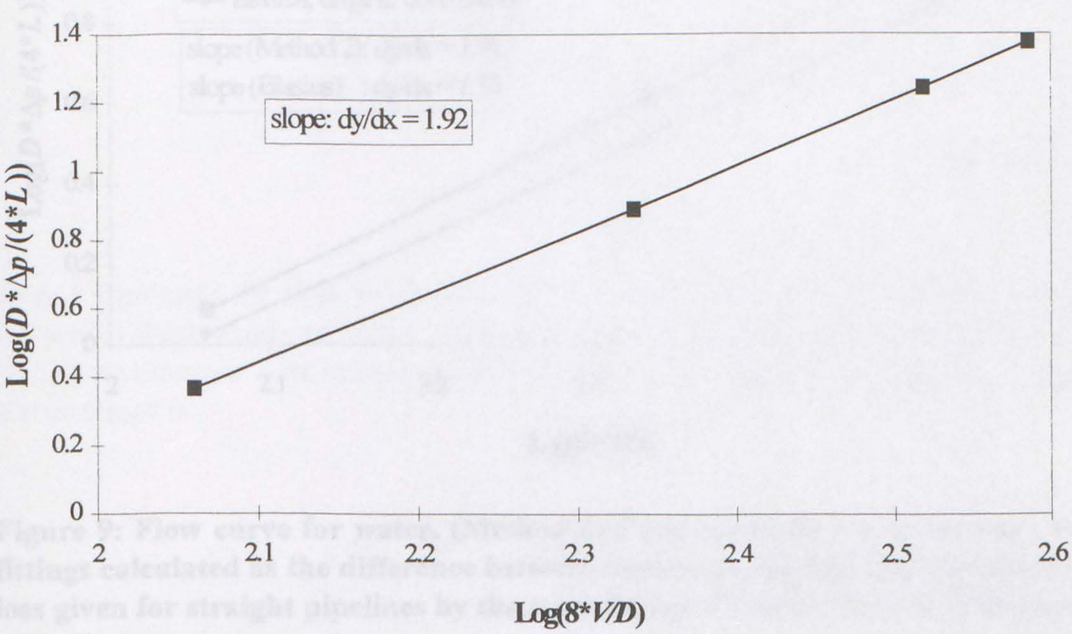

Figure 7: Flow curve for water calculated from the measured data

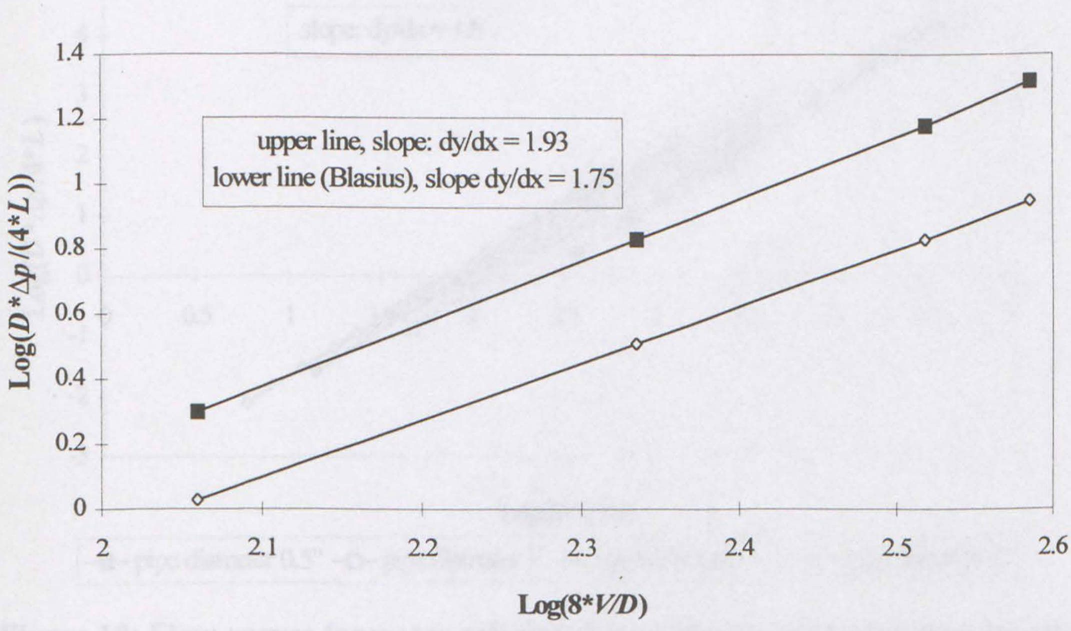

Figure 8: Flow curve for water calculated with data obtained with Bernoulli's equation (Method 1)

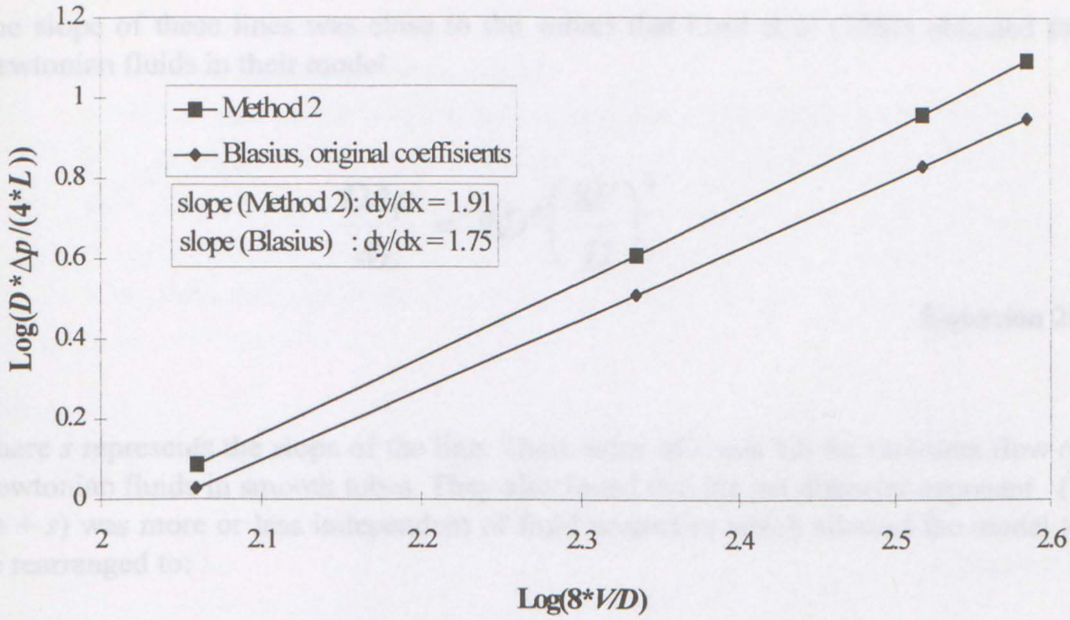

Figure 9: Flow curve for water. (Method 2) Corrections for losses in bends and fittings calculated as the difference between measured pressure loss and pressure loss given for straight pipelines by the manufacturer's table. (Blasius) Calculated with Blasius

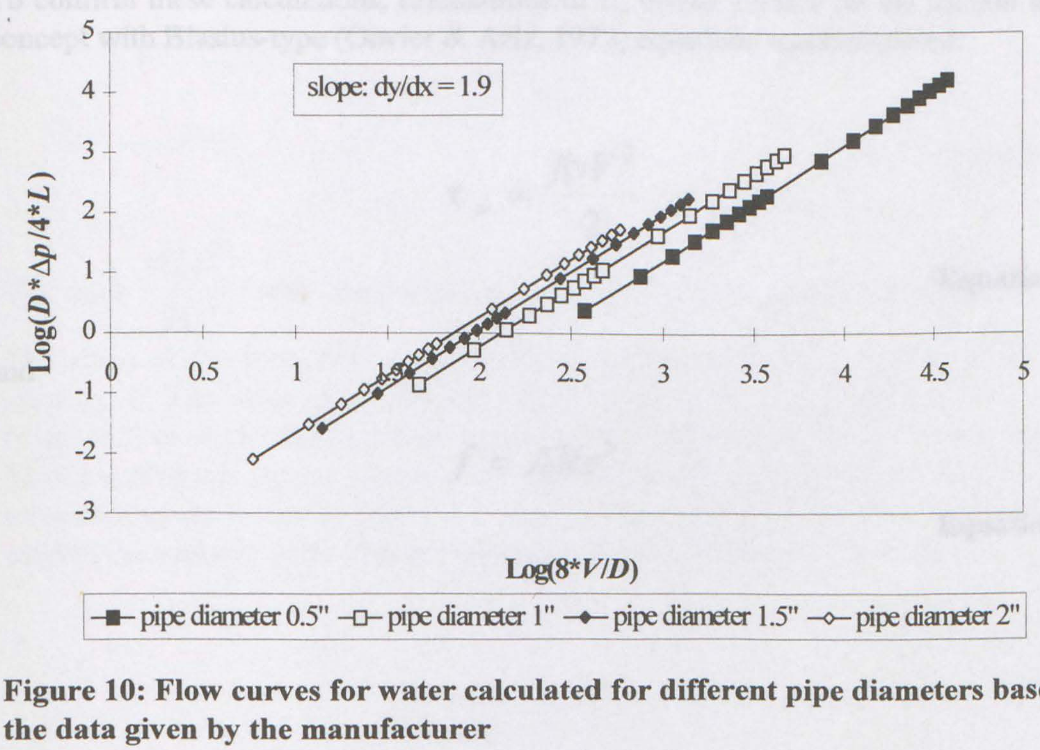

Figure 10: Flow curves for water calculated for different pipe diameters based on the data given by the manufacturer

The slope of these lines was close to the values that Lord et al (1967) obtained for Newtonian fluids in their model

$$\frac{D\Delta p}{4L} = AD^{e}\left(\frac{8V}{D}\right)^{s}$$

Equation 25

where s represents the slope of the line. Their value of s was 1.8 for turbulent flow of Newtonian fluids in smooth tubes. They also found that the net diameter exponent (1 - e + s) was more or less independent of fluid properties which allowed the model to be rearranged to:

$$\frac{D^{1.2}\Delta p}{4L} = A(8V)^{s}$$

Equation 26

To confirm these calculations, calculations of τ_w versus γ based on the friction factor concept with Blasius-type (Govier & Aziz, 1972) equations was completed:

$$\tau_w = \frac{f\rho V^2}{2}$$

Equation 27

and

$$f = ARe^{b}$$

Equation 28

where:

τ_w = wall shear stress (N/m^2)

f = friction factor (dimensionless)

A = constant (in the original Blasius equation = 0.079) (dimensionless)

b = constant (in the original Blasius equation = -0.25) (dimensionless)

Re = Reynolds number (dimensionless)

ρ = fluid density (kg/m^3)

V = fluid velocity (m/s).

Since:

$$Re = \frac{D * V}{\nu}$$

Equation 29

where:

ν = kinematic viscosity (m^2/s)

D = pipe diameter (m)

Equation 27, Equation 28 and Equation 29 were rearranged:

$$\tau_w = \frac{AD^b \rho V^{(2+b)}}{2\nu^b}$$

Equation 30

The term $\frac{AD^{b\rho}}{2\nu^b}$ was therefore a constant for each pipe diameter and type of fluid.

The slope of the line (flow curve) therefore varied with the power, *b*, of the fluid velocity, *V*. The value of *b*, calculated by other researchers (eg. Blasius, 1913) varies from -0.32 to -0.18 which gave a slope of 1.68 to 1.82 for t_w vs g. The results from the TLA experiments agreed closely with this (Figure 7). An equivalent length of pipe representing the losses in bends and fittings was calculated based on Method 2, and used in the analysis of the data for water and slurries with and without air.

3.5 Results and discussion

3.5.1 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 minutes, 30-80 minutes and 80-180 minutes. The data were analysed statistically by simple analysis of variance, F-test. This tested the hypothesis that means from several samples are equal, and showed that there was no reason to reject the hypothesis on a 5% significance level.

The development of particle size by time of pumping is shown in Figure 11 and Figure 12 for pig slurry and cow slurry respectively.

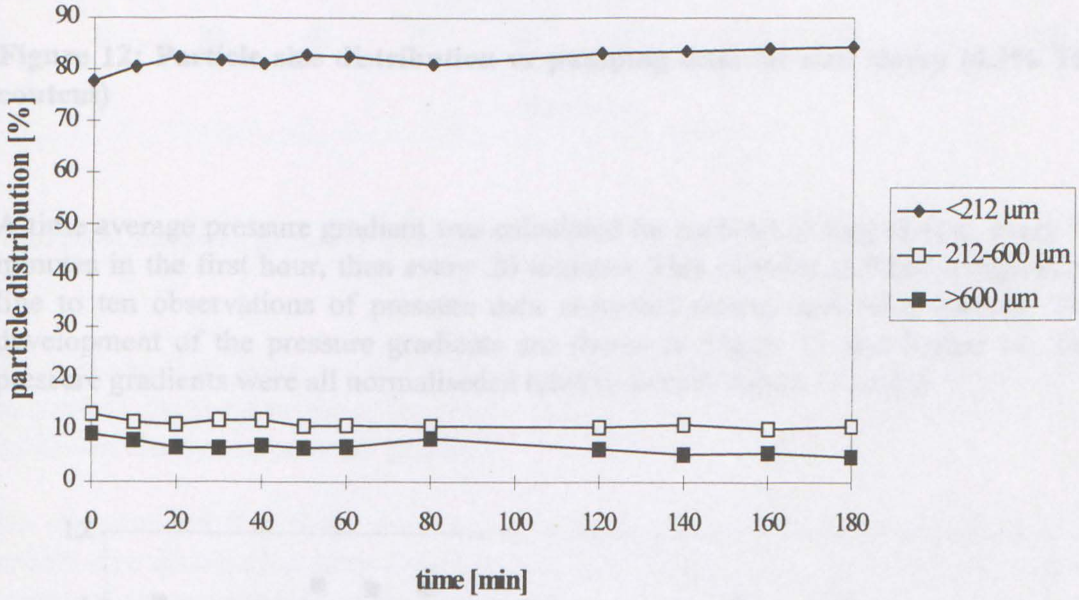

Figure 11: Particle size distribution vs pumping time for pig slurry (3.5% TS-content)

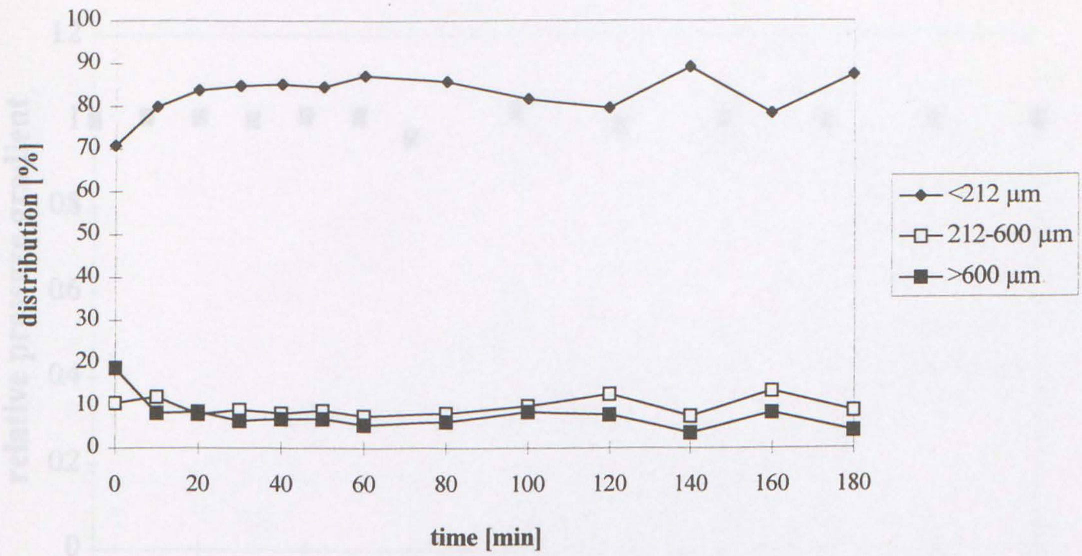

Figure 12: Particle size distribution vs pumping time for cow slurry (4.3% TS-content)

A time average pressure gradient was calculated for each set of logged data, every 10 minutes in the first hour, then every 20 minutes. This calculation fitted a regression line to ten observations of pressure data measured during each time interval. The development of the pressure gradients are shown in Figure 13 and Figure 14. The pressure gradients were all normaliseded relative to their values at time 0.

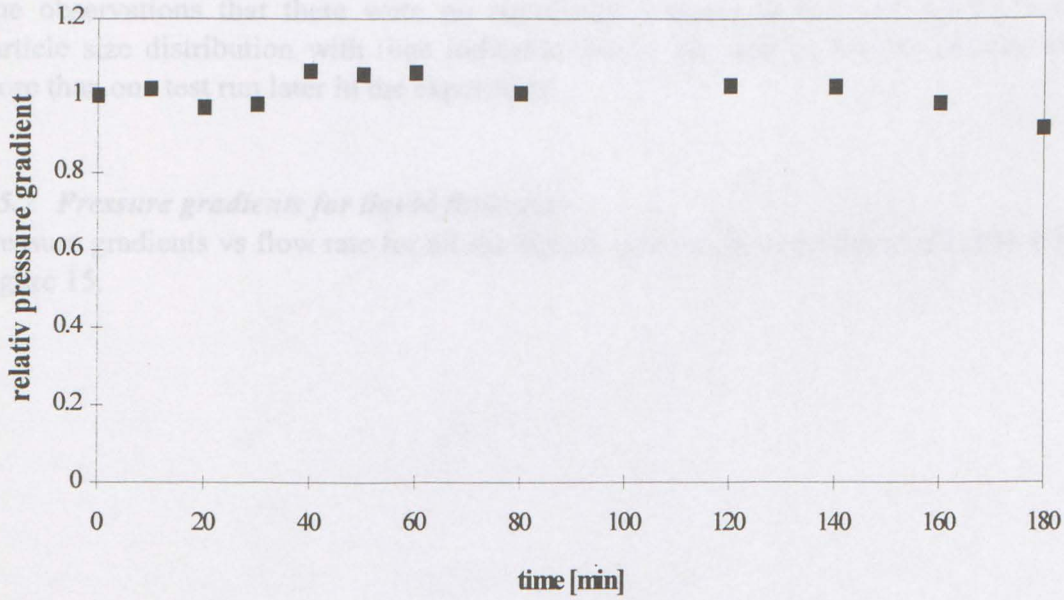

Figure 13: Relative pressure gradient for pig slurry vs pumping time

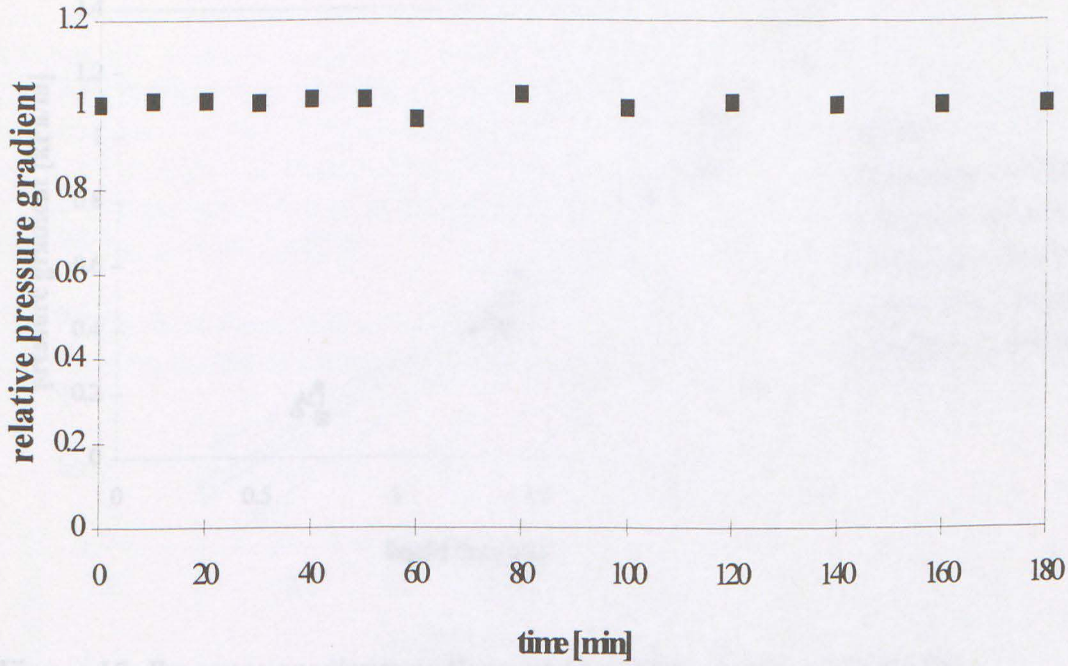

Figure 14: Relative pressure gradients for cow slurry vs pumping time

The pressure data were organised in the same way as the particle size data and analysed by the same method. The results from these analysis show that there were no significant changes in pressure gradient.

The observations that there were no significant changes in pressure gradients or particle size distribution with time indicated that it was safe to use the slurries for more than one test run later in the experiment.

3.5.2 Pressure gradients for liquid flow only

Pressure gradients vs flow rate for all the liquids used in the experiment are shown in Figure 15.

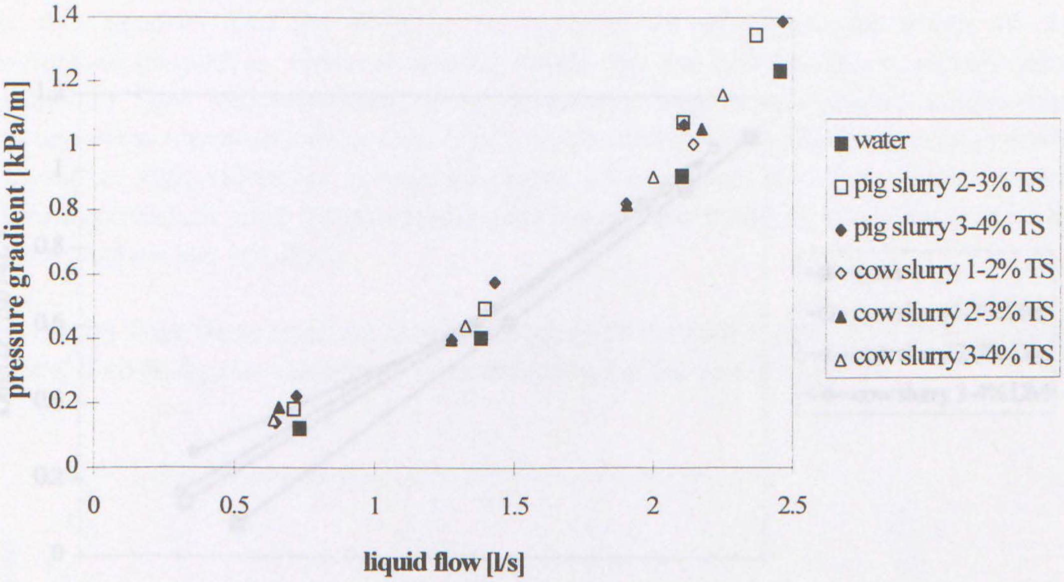

Figure 15: Pressure gradients vs flow rate for different fluids in the TLA

As expected, the pressure gradients became greater with increasing flow rate and increasing TS-content.

Plots of wall shear stress, τ_w, versus nominal shear rate, γ, for water, pig slurry and cow slurry are shown in Figure 16 and Figure 17.

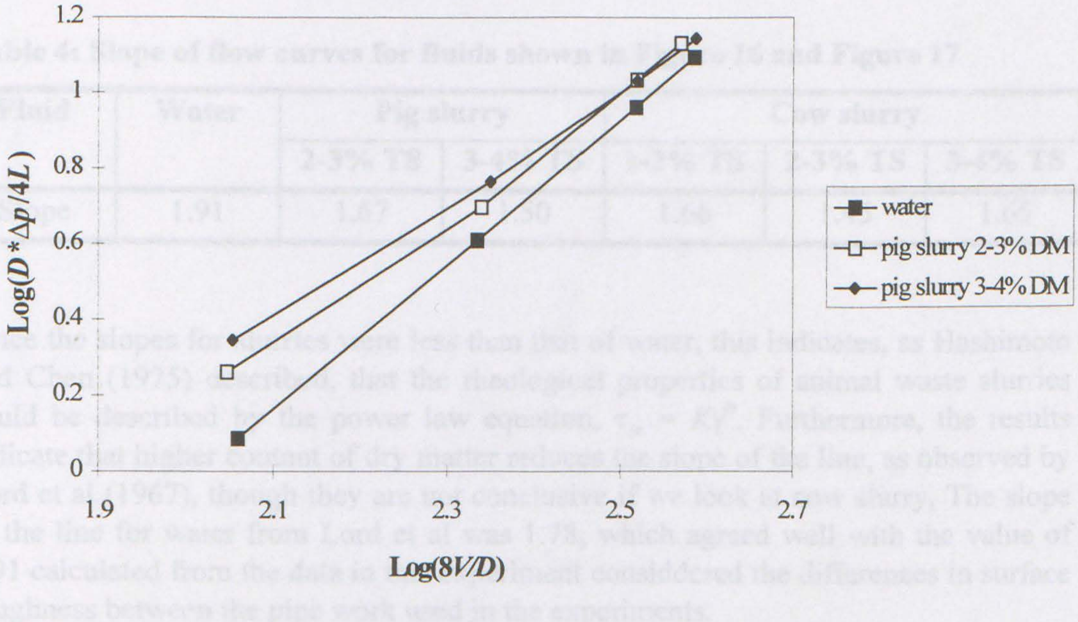

Figure 16: Flow curve for water and pig slurries

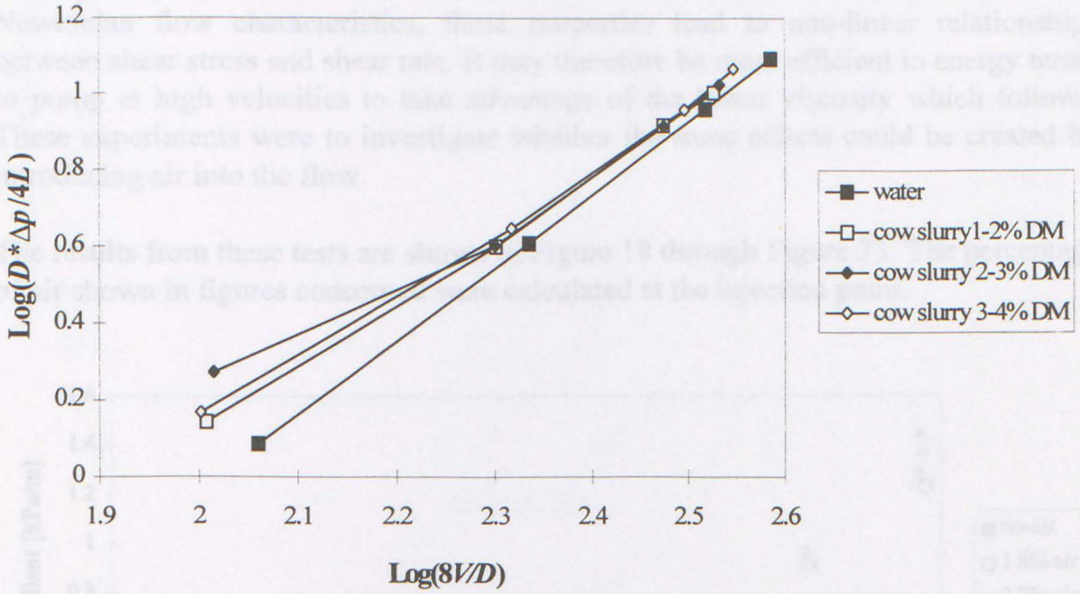

Figure 17: Flow curve for water and cow slurries

A line was fitted to the data points for each fluid and the coefficients of correlation were as good as 0.99. The slope of these lines, which are the exponents of $8V/D$ are given in Table 4.

Table 4: Slope of flow curves for fluids shown in Figure 16 and Figure 17

Fluid	Water	Pig slurry		Cow slurry		
		2-3% TS	3-4% TS	1-2% TS	2-3% TS	3-4% TS
Slope	1.91	1.67	1.50	1.66	1.45	1.65

Since the slopes for slurries were less than that of water, this indicates, as Hashimoto and Chen (1975) described, that the rheological properties of animal waste slurries could be described by the power law equation, $\tau_w = K\gamma^n$. Furthermore, the results indicate that higher content of dry matter reduces the slope of the line, as observed by Lord et al (1967), though they are not conclusive if we look at cow slurry. The slope of the line for water from Lord et al was 1.78, which agreed well with the value of 1.91 calculated from the data in this experiment considdered the differences in surface roughness between the pipe work used in the experiments.

3.5.3 Pressure gradients for flow of liquid and air

Air was injected into the fluid in the pipeline to investigate the effect on the rheological properties. Because animal waste slurries are known to exhibit non-Newtonian flow characteristics, these properties lead to non-linear relationships between shear stress and shear rate. It may therefore be more efficient in energy terms to pump at high velocities to take advantage of the lower viscosity which follows. These experiments were to investigate whether the same effects could be created by introducing air into the flow.

The results from these tests are shown in Figure 18 through Figure 23. The percentage of air shown in figures concerned were calculated at the injection point.

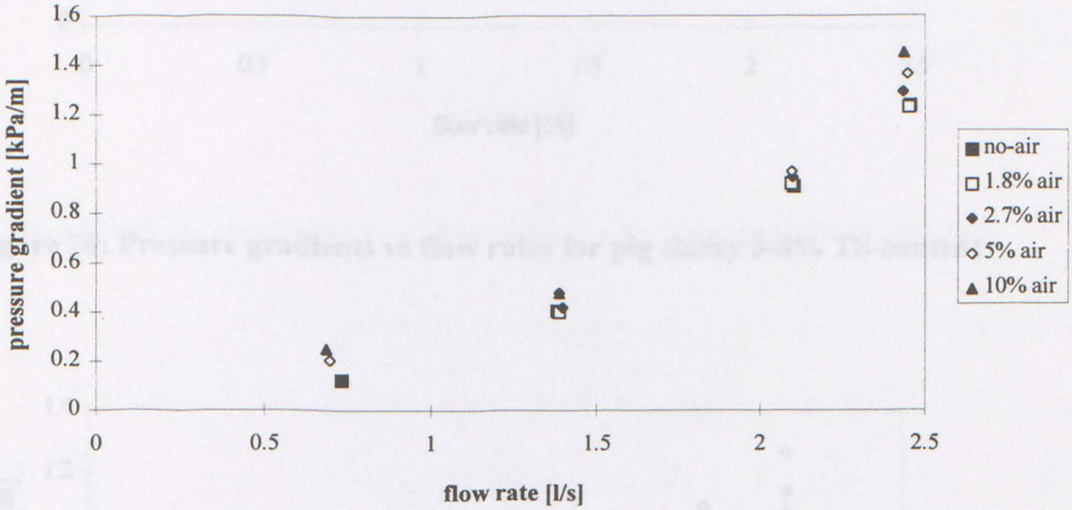

Figure 18: Pressure gradients vs flow rate for water and air

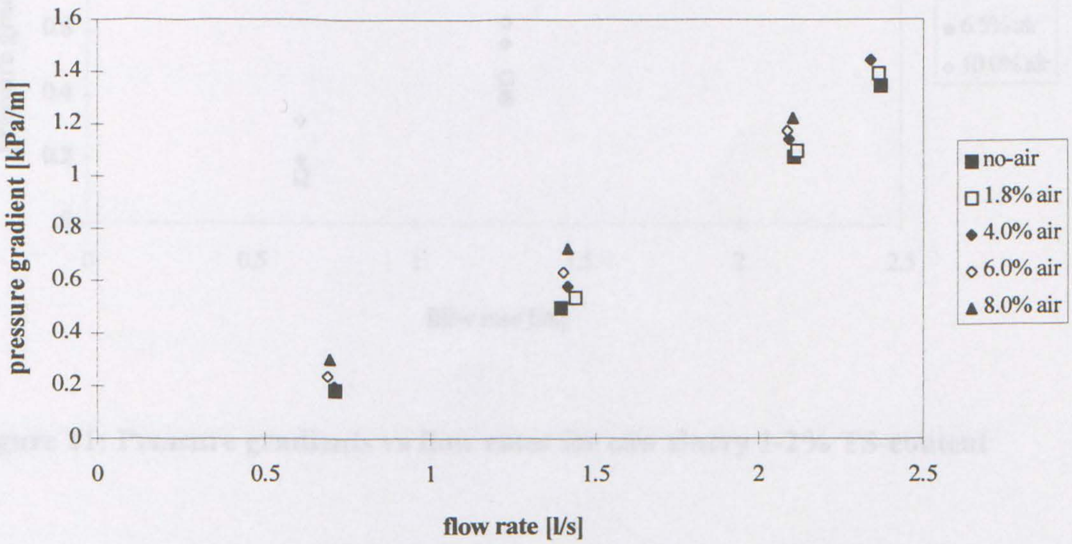

Figure 19: Pressure gradient vs flow rates for pig slurry 2-3% TS-content

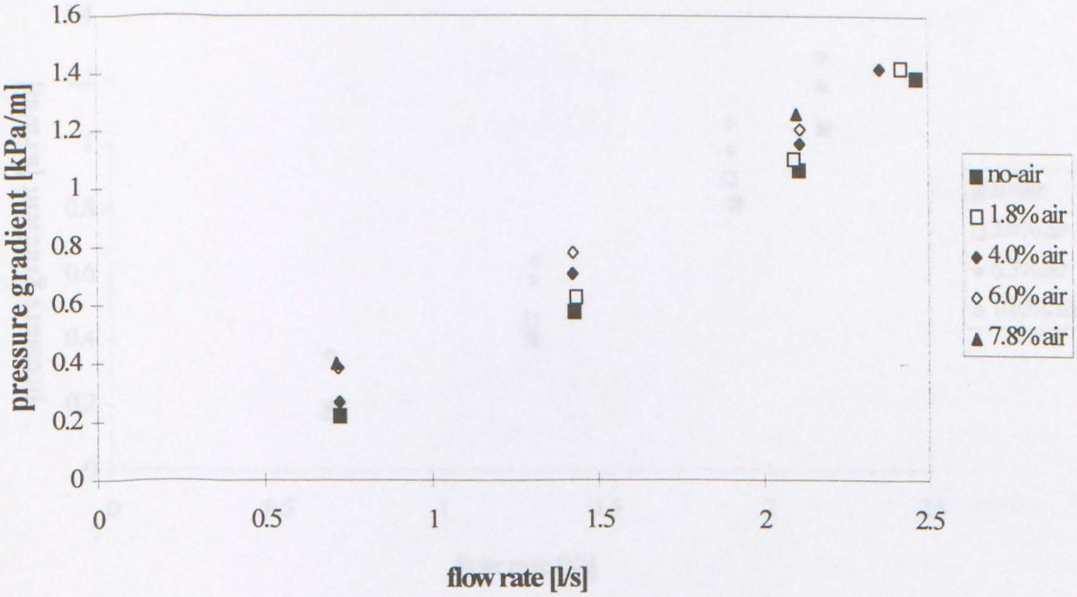

Figure 20: Pressure gradients vs flow rates for pig slurry 3-4% TS-content

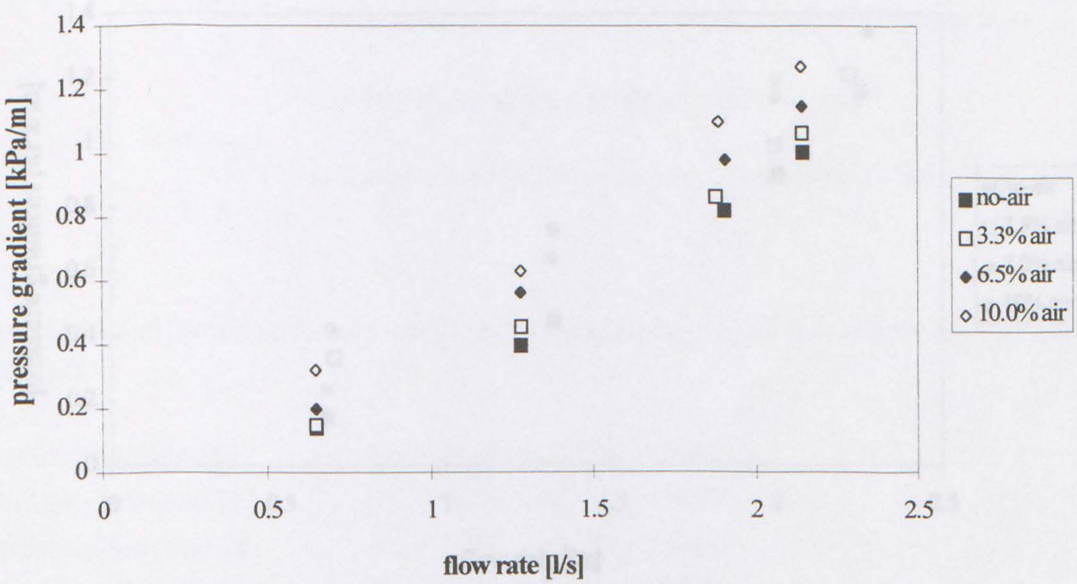

Figure 21: Pressure gradients vs flow rates for cow slurry 1-2% TS-content

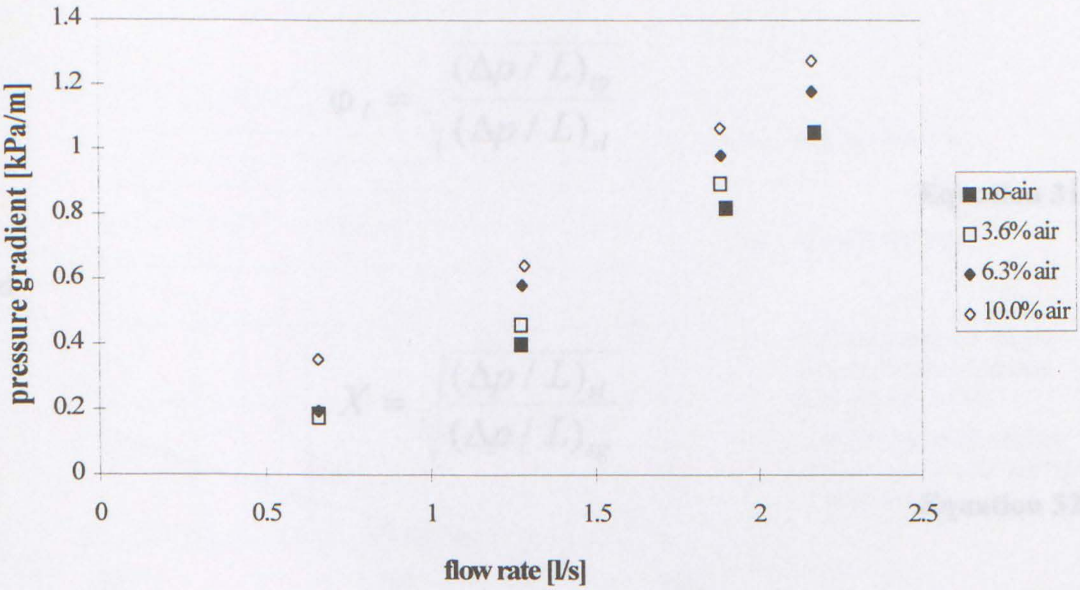

Figure 22: Pressure gradients vs flow rates for cow slurry 2-3% TS-content

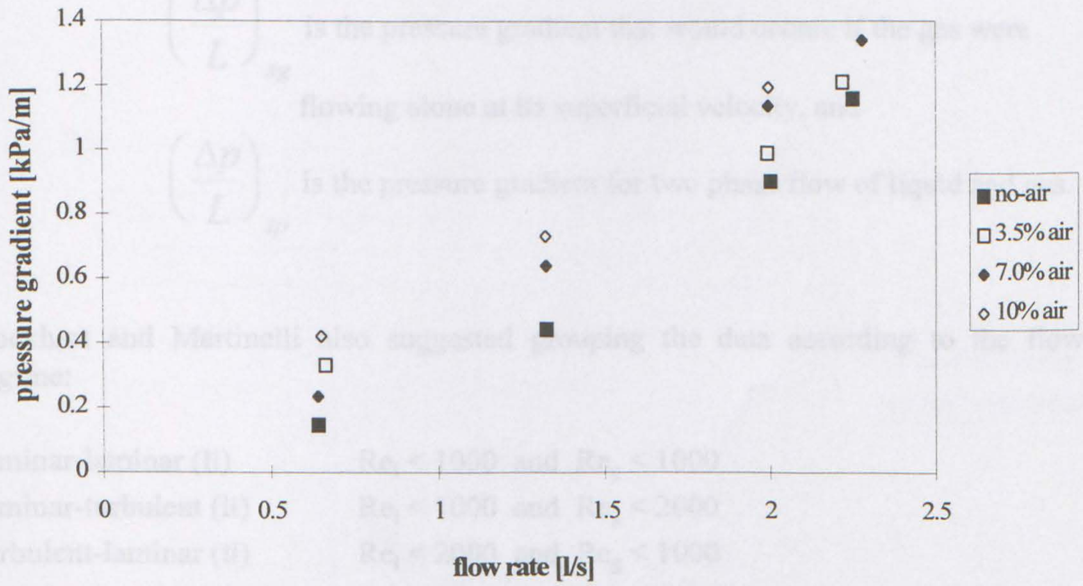

Figure 23: Pressure gradients vs flow rates for cow slurry 3-4% TS-content

To enable a comparison of data from slurries with different TS-contents and different air injection rates the data were transformed into two dimensionless ratios proposed by Lockhart and Martinelli (1949).

$$\varphi_l = \sqrt{\frac{(\Delta p / L)_{tp}}{(\Delta p / L)_{sl}}}$$

Equation 31

and

$$X = \sqrt{\frac{(\Delta p / L)_{sl}}{(\Delta p / L)_{sg}}}$$

Equation 32

where:

$\left(\frac{\Delta p}{L}\right)_{sl}$ is the pressure gradient that would occure if the liquid were flowing alone at a velocity equal to its superficial velocity,

$\left(\frac{\Delta p}{L}\right)_{sg}$ is the pressure gradient that would occure if the gas were flowing alone at its superficial velocity, and

$\left(\frac{\Delta p}{L}\right)_{tp}$ is the pressure gradient for two phase flow of liquid and gas.

Lockhart and Martinelli also suggested grouping the data according to the flow regime:

laminar-laminar (ll)	$Re_l < 1000$ and $Re_g < 1000$
laminar-turbulent (lt)	$Re_l < 1000$ and $Re_g < 2000$
turbulent-laminar (tl)	$Re_l < 2000$ and $Re_g < 1000$
turbulent-turbulent (tt)	$Re_l < 2000$ and $Re_g < 2000$.

The data obtained from the tests in the TLA fell in the groups turbulent-laminar or turbulent-turbulent: no data for laminar liquid flow were obtained. The results for water and air are shown in Figure 24, and agreed fairly well with the Lockhart-Martinelli correlations, although there was some divergence at the lower values of *X*. The same transformations were carried out for the data from the different slurries. The results from these calculations are shown in Figure 25 trough Figure 29.

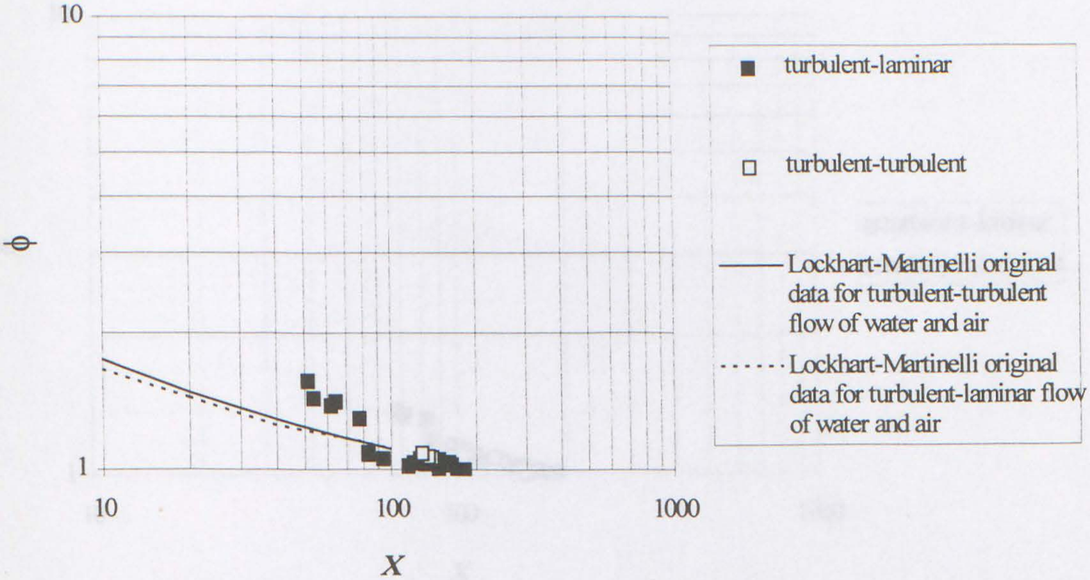

Figure 24: Lockhart-Martinelli transformed data for water and air and curves for the original Lockhart-Martinelli correlations

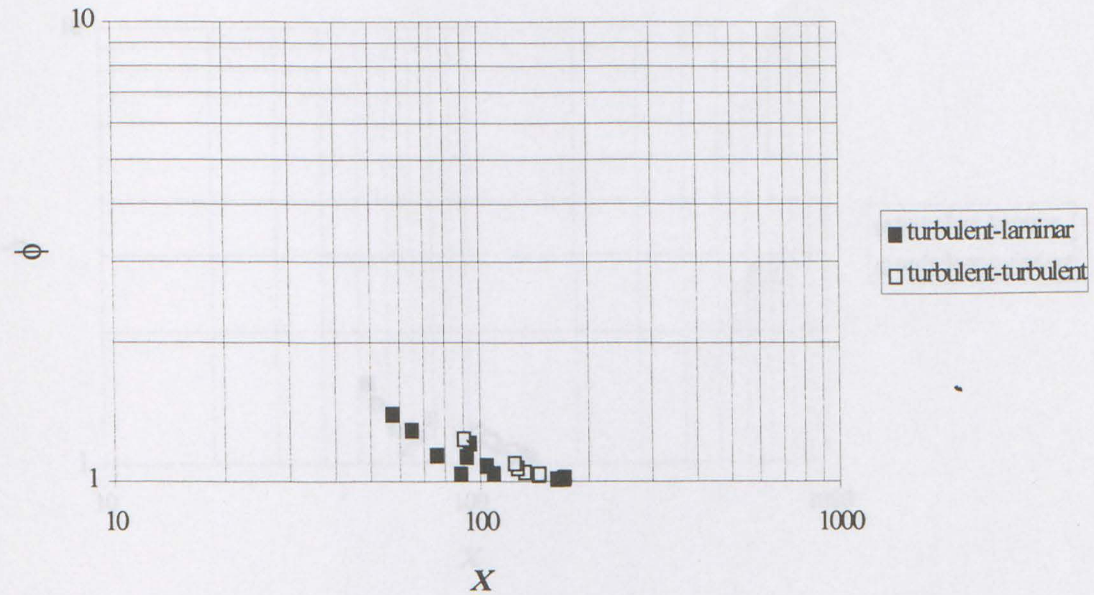

Figure 25: Lockhart-Martinelli transformation of data for pig slurry 2-3% TS-content

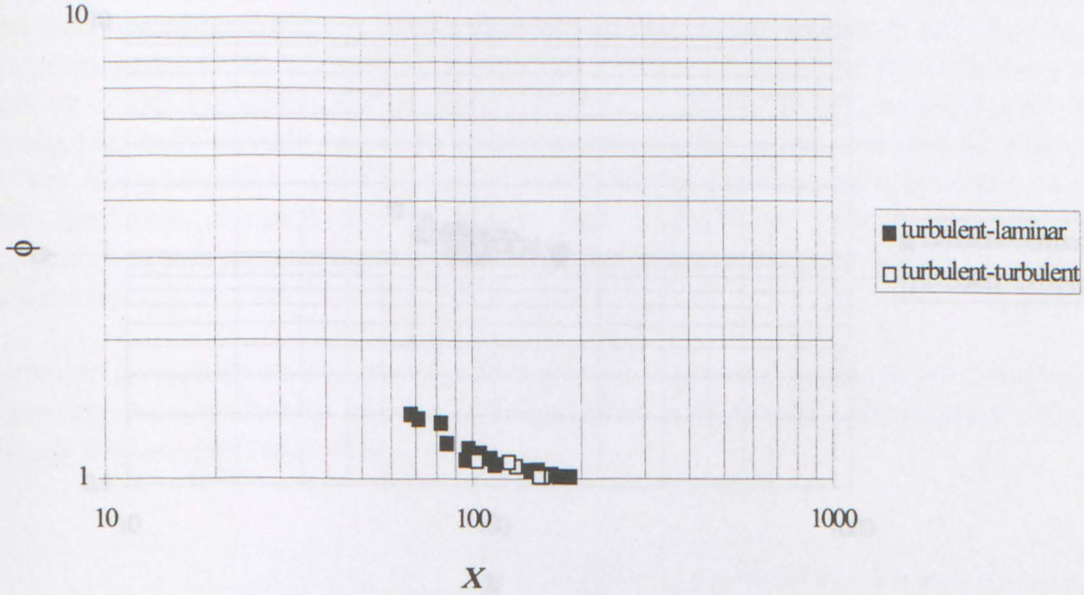

Figure 26: Lockhart-Martinelli transformation of data for pig slurry 3-4% TS-content

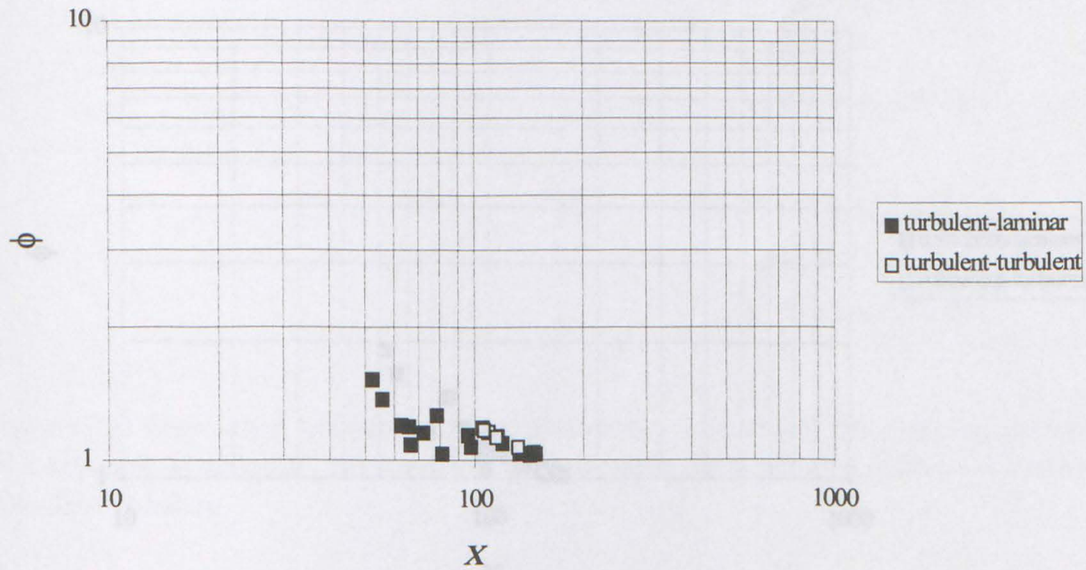

Figure 27: Lockhart-Martinelli transformation of data for cow slurry 1-2% TS-content

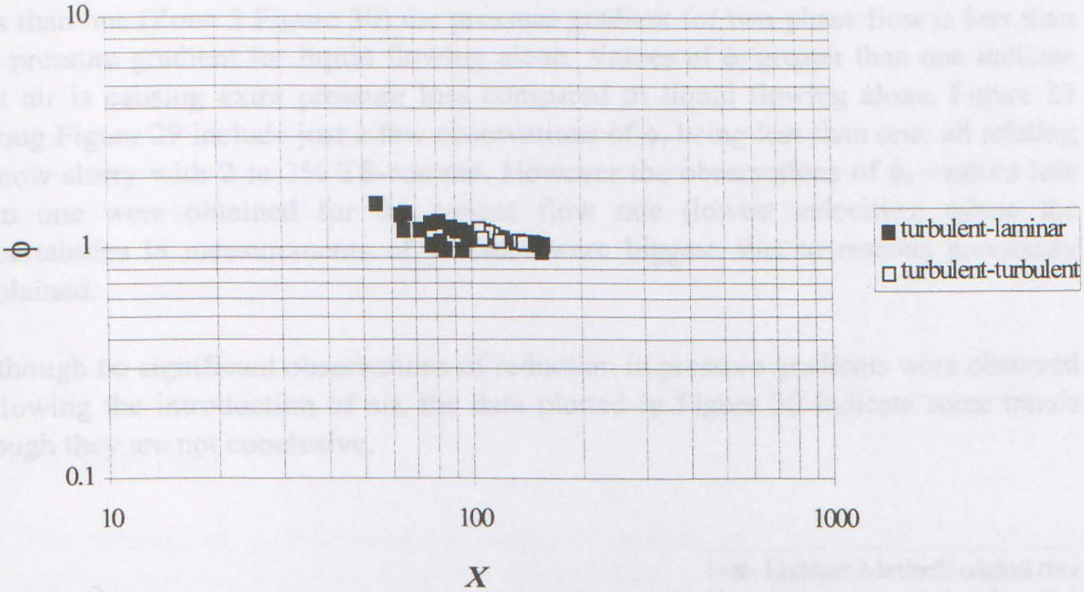

Figure 28: : Lockhart-Martinelli transformation of data for cow slurry 2-3% TS-content

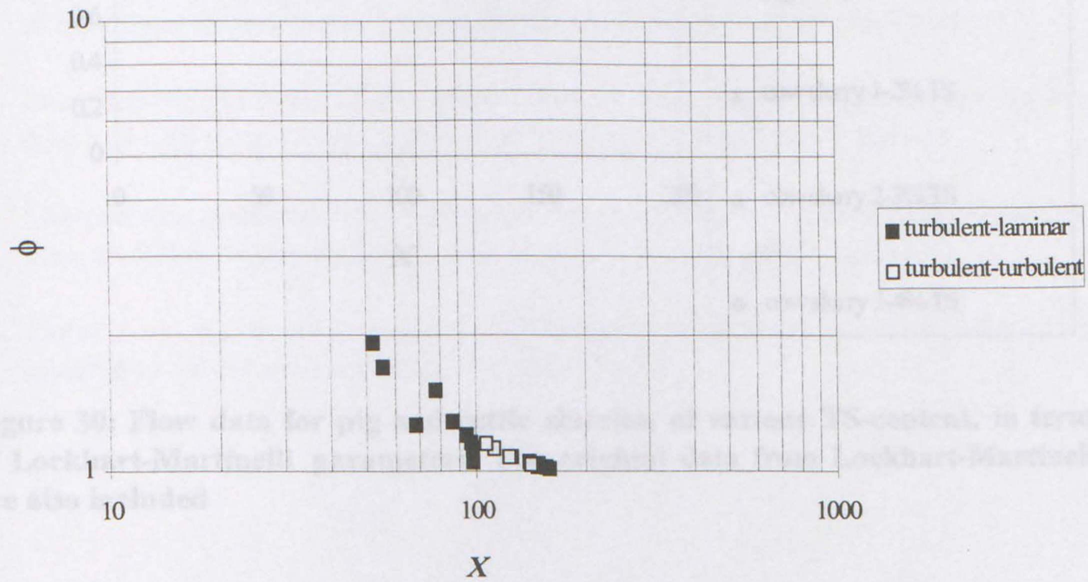

Figure 29: Lockhart-Martinelli transformation of data for cow slurry 3-4% TS-content

The ϕ_l –values from the Lockhart-Martinelli transformations provides the ratio of two-phase pressure gradient to the pressure gradient of single-phase flow of liquid. If ϕ_l is less than one (Zone 3 Figure 30) the pressure gradient for two-phase flow is less than the pressure gradient for liquid flowing alone. Values of ϕ_l greater than one indicate that air is causing extra pressure loss compared to liquid flowing alone. Figure 25 throug Figure 29 include just a few observations of ϕ_l being less than one: all relating to cow slurry with 2 to 3% TS-content. However the observations of ϕ_l –values less than one were obtained for the lowest flow rate (lowest velocities) where the uncertainties in measurements of pressure were biggest, due to reasons previously explained.

Although no significant observations of reduction in pressure gradients were observed following the introduction of air, the data plotted in Figure 30 indicate some trends though they are not conclusive.

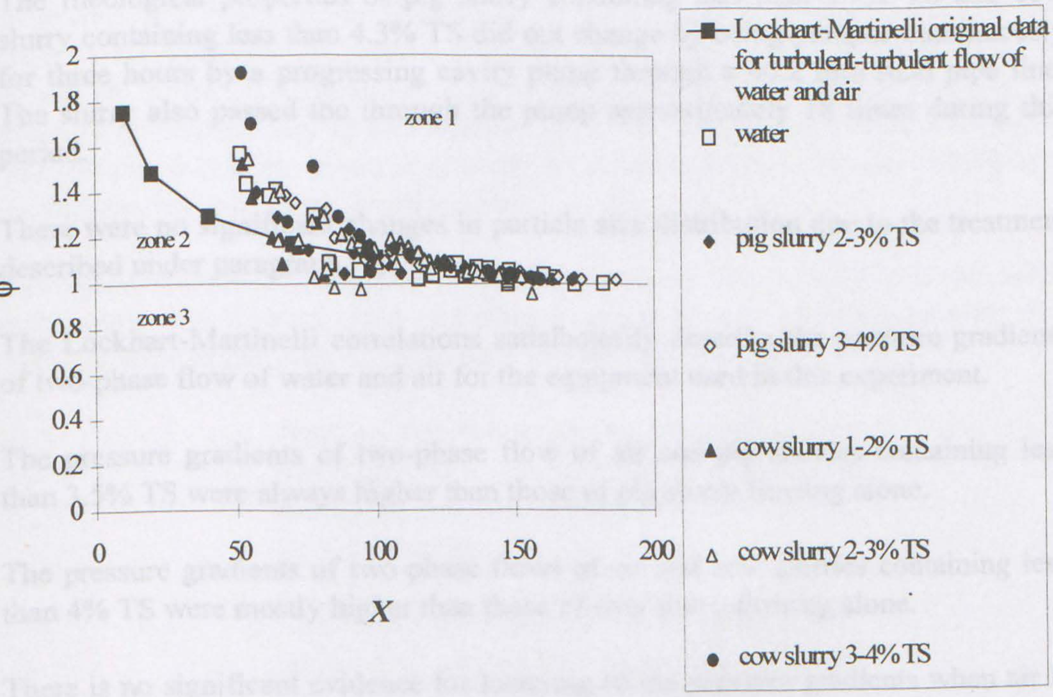

Figure 30: Flow data for pig and cattle slurries, of various TS-content, in terms of Lockhart-Martinelli parameters. The original data from Lockhart-Martinelli are also included

An overall comparison can be made with the three zones in Figure 30; Zone 1, data above the Lockhart-Martinelli line, for water and air and Zone 2, the area below the

Lockhart-Martinelli line and $\phi_l \geq 1$ (ie. values of ϕ_l lower than those predicted by Lockhart-Martinelli at a given value of X), Zone 3, $\phi_l < 1$. Data in Zone 2 indicate a general lowering of the two-phase pressure gradients. Although this does not mean that the total pressure gradients are less than for liquids flowing alone, results in this zone indicate that introduction of air has a shear-thinning effect.

For values of X between 60 and 120 (representing air injection up to approximately 4% v/v at injection point) there are several observations of ϕ_l, for slurries and air, less than Lockhart-Martinelli's predictions for water and air. Cow slurries showed a bigger reduction in ϕ_l- values (ie. pressure loss) than pig slurries, indicating that cow slurries were more shear-thinning than pig slurries.

3.6 Conclusions

1. The rheological properties of pig slurry containing less than 3.5% TS and cow slurry containing less than 4.3% TS did not change by being pumped continuously for three hours by a progressing cavity pump through a 40.2 mm steel pipe line. The slurry also passed the through the pump approximately 18 times during this period.

2. There were no significant changes in particle size distribution due to the treatment described under paragraph (1).

3. The Lockhart-Martinelli correlations satisfactorily describe the pressure gradients of two-phase flow of water and air for the equipment used in this experiment.

4. The pressure gradients of two-phase flow of air and pig slurries containing less than 3.5% TS were always higher than those of pig slurry flowing alone.

5. The pressure gradients of two-phase flows of air and cow slurries containing less than 4% TS were mostly higher than those of cow slurry flowing alone.

6. There is no significant evidence for lowering of the pressure gradients when air is injected to cow slurry containing less than 4% TS.

4. Measurements of pressure loss in a large-scale pipeline viscometer

4.1 Introduction

The previous chapter has shown that the rheological properties of animal waste slurries easily can be investigated measuring the pressure drop in a pipeline section when the slurry flows through it. The results of the investigations done in the TLA apparatus supported the previously established knowledge, that animal waste slurries exhibit non-Newtonian flow characteristic. Anyway, the TLA had only the option of one pipe diameter and that pipe was only 40.2 mm (ID). This made it impossible to investigate slurries containing more than 4% TS or unseparated slurries containing long fibrous material. There are also problems involved in scaling-up the results obtained for one pipe diameter, to make useful predictions for larger pipes.

There were a few observations of pressure gradients with cow slurries reduced by injection of air. However, the results from the investigations of combined flows of liquid and air in the TLA apparatus showed no significant evidence for lowering of the pressure gradients when air was injected into cow slurry containing less than 4% TS. For the pig slurry, the pressure gradient for combined flow with air was always higher than those of pig slurry flowing alone.

It was of great interest to find out how slurries with more than 4 % TS behaved, both when the slurry was flowing alone and when it was flowing in combination with air. The primary aims of the work reported here was therefore to:

1. Develop and test a pipeline viscometer that could provide a reliable mean of determining the flow properties of slurries with relatively high TS-content.

2. Investigate the flow properties of pig slurry containing up to 5% TS and cow slurry containing up to 6% TS.

3. Gain further knowledge of flow mechanisms and flow behaviour for combined flow of liquid and air.

4.2 Experimental apparatus and methods

To investigate the rheological properties of livestock waste slurries, a large-scale pipeline (capillary) viscometer was developed. The viscometer was a natural follow-up of the results obtained from the experiments done in the TLA previously described in this report.

The viscometer was designed to measure pressure gradients of fluids with a relatively high concentration of suspended solids at various flow rates, in pipes of different diameters. It was decided to use pipe diameters that one could normally find in plants handling livestock waste, to produce accurate and reliable data. A storage tank with a mixing unit was used to produce and maintain a homogeneous mixture.

4.2.1 General description of the apparatus

The pipeline viscometer is shown diagrammatically in Figure 31. Tank (MT) was used to prepare the fluids tested, it also acted as a storage reservoir to which the fluid was returned after passing through the viscometer. The storage capacity of the cylindrical tank (MT) was 34 m^3. To produce and maintain a homogeneous mixture a slow-speed impeller mixer was utilised. In a circular storage tank this mixer type satisfies the most important criteria of avoiding separation and sedimentation. The storage and mixing tank (MT) was connected by a valve (V_1) to the inlet of a 11.2 kW centrifugal pump (B). Another valve (V_2) was also connected to the pump's suction line making it possible to withdraw fluids from other tanks. The pump delivered into a horizontal pipe of 76.2 mm internal diameter and the flow to the viscometer was controlled by valve (V_4). A valve (V_3) was also connected to the pump outlet to allow the pipe system to be drained, or to divert the flow into one of the external storage tanks (T_x). A pressure relief valve (V_5) was fitted to protect the system against damage. In the delivery pipe from the pump a Doppler-effect ultrasonic flowmeter (F) was clamped on to the pipe line to measure the flow rate that the pump delivered. The valves (V_7, V_8, V_9, V_{10}, V_{11} and V_{12}) were arranged so that it was made possible to either measure flow through single pipes in the viscometer or to connect any three of the viscometric capillaries in series.

The viscometric capillaries (C_1, C_2, C_3 and C_4) had the following internal diameters: C_1 = 38.1 mm, C_2 = 50.8 mm , C_3 = 76.2 mm and C_4 = 101.6 mm. Pressure transducers (P_1, P_2, P_3, P_4, P_5, P_6, P_7 and P_8) were fitted in each end of these capillaries. The transducer housings were specially made in the same material as the rest of the pipe work (PVC, Polyvinylchloride) having the same internal diameter as the pipe they were fitted in to. Thermistors for measurement of fluid temperature were located in the same housings as the pressure transducers (P_1, P_3, P_5 and P_7). In both ends of all capillaries, flow stabilisation pipes (S_1, S_2, S_3, S_4, S_5, S_6, S_7 and S_8) were connected. All stabilisation pipes were 6 m long.

From the viscometer the fluid returned to the storage tank in a 76.2 mm pipe. Since the pump operated at constant speed, the only way of getting various flow rates was to restrict the flow. A manually operated diaphragm-valve (V_{13}) was therefore incorporated in the return line.

Air was injected into the liquid flow through a 2 mm nozzle (A). Air was supplied from a compressor (M). The air flow was controlled by the remotely actuated proportional valve (AA). The air flow was measured with a venturi flowmeter (N) and the air pressure with a pressure transducer (Q). The air temperature was measured with a thermistor (R). To prevent liquid from penetrating into the air supply system, a non-return valve (L) was fitted in the air supply line immediately upstream of the nozzle (A).

Fluid samples for analysis of total solid content (TS) or any other parameters could be withdrawn from the viscometer trough the valves (V_6 and V_{14}). If it was desirable to drain only the viscometer section of the apparatus that cold also be done through valve (V14).

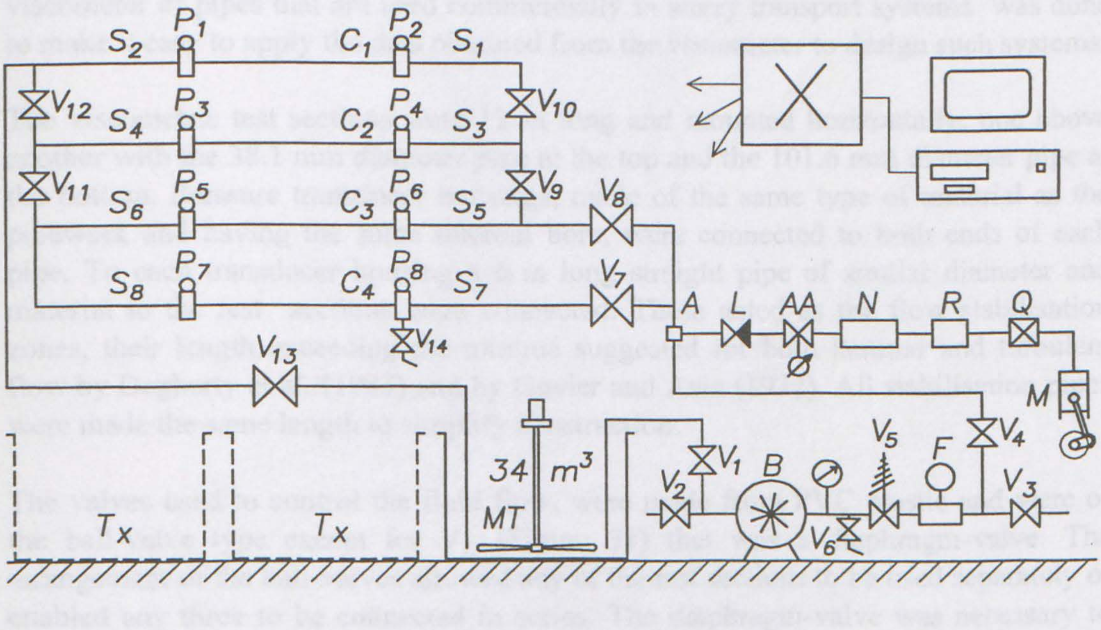

Figure 31: Hydraulic circuit of the pipeline viscometer

4.2.2 Description of individual components

4.2.2.1 The pump

The fluids were conveyed by a mixed flow centrifugal pump (4F Balco Torque flow pump) in which a vortex of whirling fluid mass was created as suspended solids or particles were rotated rapidly round the axis. This centrifugal force discharged most solids through the pump in less than one revolution. The creation of a whirling fluid mass of suspended solids reduced particle damages by impeller shatter and the pump was capable of handling slurries with high solids concentrations. The pump was side mounted to a 380/440 Volt three phase AC motor of 11.2 kW working at a speed of 2900 rpm. The power was transferred from the motor to the pump by three SPZ Fenner belts. To achieve optimum pumping conditions for slurry the motor/pump speed ratio was 2.5:1. The maximum volumetric output at this speed was 720 l/min.

4.2.2.2 The pipework

The viscometric test sections (capillaries) and other parts of the pipeline were constructed from PVC (Polyvinylchloride) plastic pipes. The material and sizes used were considered typical of those found in many commercial slurry transport systems both for internal transport in farm buildings and for long distance transport. These types of pipes are also frequently found in irrigation systems. Constructing the viscometer of pipes that are used commercially in slurry transport systems was done to make it easy to apply the data obtained from the viscometer to design such systems.

The viscometric test sections were 12 m long and mounted horizontally, one above another with the 38.1 mm diameter pipe at the top and the 101.6 mm diameter pipe at the bottom. Pressure transducer housings, made of the same type of material as the pipework and having the same internal bore, were connected to both ends of each pipe. To each transducer housing a 6 m long straight pipe of similar diameter and material to the test sections were connected. These acted as the flow stabilisation zones, their length exceeding the minima suggested for both laminar and turbulent flow by Dagherty et al. (1985) and by Govier and Aziz (1972). All stabilisation pipes were made the same length to simplify construction.

The valves used to control the fluid flow, were made from PVC plastic and were of the ball-valve type except for V_{13} (Figure 31) that was a diaphragm-valve. The arrangement of the ball-valves allowed any of the test sections to be used separately or enabled any three to be connected in series. The diaphragm-valve was necessary to achieve various flow rates since the pump was running at constant speed. It was placed in the return line which was considered the best place to restrict the flow.

4.2.2.3 The pressure transducers

Strain-gauged diaphragm pressure transducers (Tyco model AB), were used in the eight housings, each being mounted flush with the pipe wall to minimise the disturbances to the flow (Figure 32 and Figure 33)

Each pressure transducer gave an electrical output proportional to the pressure on the diaphragm, and each transducer was connected to a matched conditioning circuit which allowed the atmospheric pressure to be "zeroed out". Electrical output signals were passed to an analogue to digital (A/D) converter, from which data were recorded on a personal computer (PC).

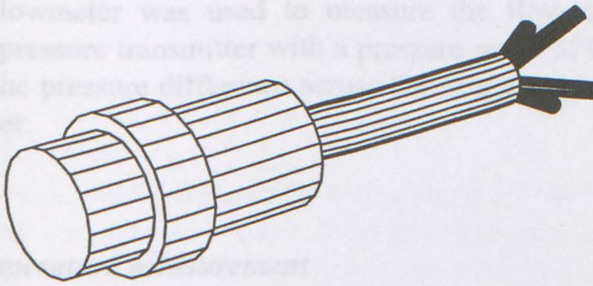

Figure 32: Pressure transducer

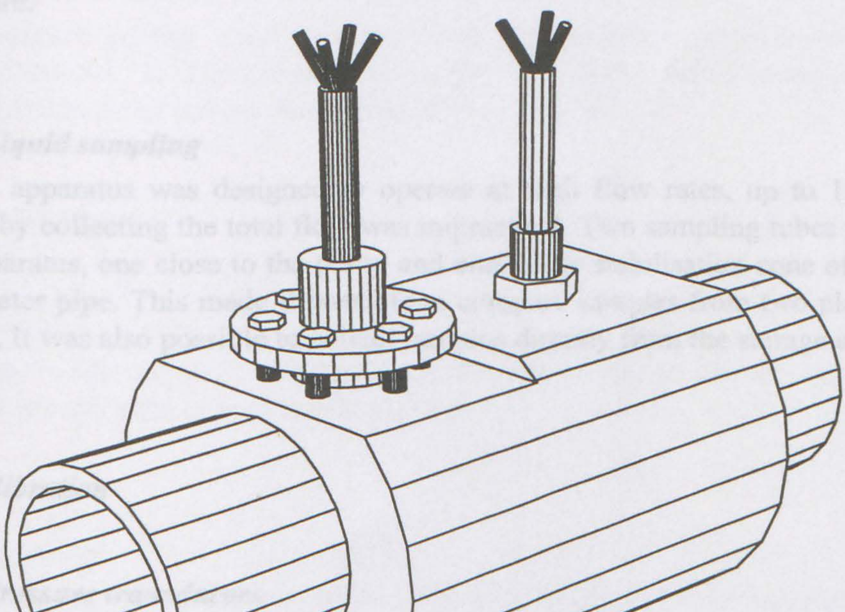

Figure 33: Pressure transducer fitted to housing

4.2.2.4 The liquid flowmeter

To reduce the risk of blockage inherent in many flowmeters, it was decided to use a Doppler-effect ultrasonic flowmeter (Bestobell). This flowmeter used beams of ultrasound to measure the flow velocity and hence the volumetric flow rate, knowing the cross-sectional area of the pipe. The flowmeter had a transmitter and a receiver mounted in a housing that was clamped onto the outside of the pipe. This flowmeter did not obstruct the flow and thus caused no loss of pressure and did not have mechanical parts that wear.

4.2.2.5 The air flowmeter

A venturi flowmeter was used to measure the flow of air. A Furness FCO 53 Differential pressure transmitter with a pressure range of 0 - 10 mm of water was use to measure the pressure difference across the venturi and to transmit the signal to the A/D converter.

4.2.2.6 Temperature measurement

One thermocouple probe was fitted at the beginning of each test section in the same housing as the pressure transducer. It was assumed that the temperatures of fluids in the apparatus would be unlikely to change rapidly and therefore only one temperature probe was fitted in each pipe. One similar probe was also used to measure the ambient temperature.

4.2.2.7 Liquid sampling

Since the apparatus was designed to operate at high flow rates, up to 1500 l/min, sampling by collecting the total flow was impractical. Two sampling tubes were fitted to the apparatus, one close to the pump and one in the stabilisation zone of the 101.6 mm diameter pipe. This made it possible to compare samples from two places in the apparatus. It was also possible to collect samples directly from the storage and mixing tank.

4.2.3 Calibration

4.2.3.1 Pressure transducers

The pressure transducers and the conditioning circuits were calibrated before installation using a dead-weight pressure gauge testing rig. The largest error was -0.010 bar; the rest were all within ±0.008 bar of the calibration pressures. In percentage terms, they were all calibrated to within 0.5% of true pressures.

4.2.3.2 *Liquid flowmeter*

The liquid flowmeter was calibrated by pumping water between two identical tanks with a storage volume of 10 m^3. The level of liquid was observed and times were taken with a stop-watch at 0.5 m intervals. The output from the flowmeter was recorded at the same time. Eighteen calibration runs were carried out and the flow rate was calculated and compared with the flowmeter readings. Once the flowmeter was calibrated with water, the flow of other fluids with different densities could be accurately measured using the same results because the flowmeter sensed fluid velocity and so was unaffected by changes in fluid densities. Therefore, volumetric calibrations with liquids other than water were unnecessary.

The accuracy of the liquid flowmeter was found to be within ±2% of the measured flow.

4.2.3.3 *Air flowmeter*

The air flow meter was calibrated by letting the flow from the air supply line, flow to the atmosphere through a rotameter (floating cone gas flowmeter) instead of into the pipework. The accuracy of the air flowmeter was found to be within ±1% of the measured flow.

4.2.3.4 *Temperature probes*

The temperature probes were calibrate with an electronic thermometer with an accuracy of ±0.001 °C. The temperature probes were calibrated to be within ±0.1 °C in the actual interval of measurement from +10 to +25 °C.

4.2.4 *Liquids tested*

4.2.4.1 *Water*

Ordinary tap water was used as a fluid of known behaviour to test the apparatus and for comparison with the animal waste slurries.

4.2.4.2 *Pig slurry*

Raw pig slurry was collected from a nearby piggery (fattening pigs fed on concentrates). The slurry collected from the farm had a TS-content of 4.8% (w/w). Experiments were done with raw slurry without any kind of treatment. The slurry was then diluted twice with water, first to about 3.5% TS-content (w/w) and then to about 2.5% TS-content (w/w).

4.2.4.3 Cow slurry

Untreated cow slurry was collected from a nearby dairy farm (dairy cows on a diet of freshly harvested grass and concentrates). The slurry contained long fibrous bedding material and it was necessary to remove that to carry out the experiments in the viscometer. This, to reduce the risk of blockage and to avoid the reduction in pump capacity caused by long fibres. The long fibres were removed from the slurry by raking the floating layer of fibres from the top of the slurry after letting it rest in the storage tank for one week. Though cumbersome, this was a very effective way of doing it. The TS-content of the raw slurry was 10.4% (w/w). After removal of the long fibres the TS-content was reduced to 5.9% (w/w).

4.2.5 Experimental procedure

The following is a description of how the experiments with the various fluids were carried out in the viscometer. Instrument electronic signals were sampled and stored simultaneously then sequentially scanned end recorded by a data acquisition system.

The description comprises of experiments in all four viscometric capillaries. Due to malfunction of the pressure transducers in the 101.6 mm diameter pipe, discovered after the experiments were finished, the results from this pipe were later rejected.

4.2.5.1 Experiments with water

Pressure gradients were measured in the four viscometric capillaries using clean water at various flowrates from 120 l/min to 700 l/min. First the tests with water only were carried out for comparison of results with manufacturer's data. Then the tests were repeated but now air was injected into the water at rates from 1% to 6% (v/v), calculated at the injection point.

The tests with different air injection rates were carried out successively for each liquid flow rate. The time required to pump the water once through the system was allowed to elapse at the start of every test with a different air flow rate. Following that, the liquid flow was allowed to stabilise for at least two minutes before any pressure readings were recorded. The data were logged every ten seconds for ninety seconds before changing the setting of the apparatus.

4.2.5.2 Experiments with pig slurry

The initial volume of pig slurry was 10 m^3 with an initial TS-content of 4.8%. To investigate the effects of TS-concentration upon pressure gradient, the slurry was successively diluted and the experiments repeated for all dilutions. As previously explained, slurry with lower TS-content than the initial 4.8%, was obtained by successive dilution. This was done by pumping the necessary volume of water into the storage tank and the let the mixer work for at least six hours before any new experiments were carried out. The effects of long duration pumping upon the rheological properties of the slurry were found insignificant when previously tested in the TLA apparatus. The torque flow pump used in the viscometer was more gentle to the fluid than the positive displacement pump in the TLA and therefore long duration pumping was considered to have no effects in the viscometer either.

Pig slurry was pumped through the viscometer at various flow rates from 195 l/min to 700 l/min. Air was injected into the slurry at rates of approximately 1%, 2%, 4%, and 6% (v/v) calculated at the point of injection. The experiments with slurry only and with slurry and air were done successively. For every flow rate, the tests with slurry only were first carried out. Then the tests with different air injection rates were completed from the lowest through to the highest air injection rate. Every time the air injection rate was changed the flow was allowed to stabilise for at least two minutes after the new air flow rate had become stable before any data were recorded. As for water, the data were logged every ten seconds for ninety seconds before the air flow rate was changed. The exit flow from the viscometer returned to the storage tank and was allowed to degas for four hours between every change of liquid flow rate.

Experiments were carried out in all four pipe diameters. Some experiments were done with single pipes to achieve maximum flow rates and some were done with the pipes connected in series. When three pipes were connected in series the fluid entered the largest diameter pipe first, then passed through the medium diameter pipe and left through the smallest diameter pipe.

Samples for TS-analysis were collected at the beginning of every run. The results from the TS-analysis shows that the TS-content was stable throughout the whole test program for every TS-group. The data from the experiments with pig slurry are presented in three groups, 2.5%, 3.5% and 4.4% TS-content, with standard deviations of 0.01%, 0.02% and 0.09% respectively. Thus indicating that the mixer was working satisfactory.

4.2.5.3 Experiments with cow slurry

To investigate the effects of TS-concentration upon pressure gradient, the cow slurry, as with the pig slurry, was successively diluted and the experiments repeated for all dilutions. The dilution of the initially concentrated cow slurry was done in the same way as it was done for pig slurry. The effects of long duration pumping upon the rheological properties of the cow slurry were found insignificant when tested in the TLA apparatus.

Cow slurry was pumped through the viscometer at various flow rates from 135 l/min to 650 l/min. Air was injected into the slurry at rates of approximately 1%, 2%, 4%, and 6% (v/v) calculated at the point of injection. The experimental procedure was the same for cow slurry as for pig slurry. The data from the experiments with cow slurry are presented in four groups, 3.5%, 4.0%, 5.2% and 5.5% TS-content, with standard deviations of 0,02%, 0,04%, 0,04% and 0,05% respectively.

Experiments were carried out in the three pipes with largest diameters. The 38.1 mm diameter pipe was considered being too small for conveying raw cow slurry. Unfortunately, the results from the experiments in the 101.6 mm diameter pipe were later rejected due to reasons previously explained. Some experiments were done with single pipes to achieve maximum flow rates and some were done with the pipes connected in series. When three pipes were connected in series the fluid entered the largest diameter pipe first, then passed through the medium diameter pipe and left through the smallest diameter pipe.

4.2.5.4 Experiments with air

For all liquid flow rates, air was injected into the slurry at flowrates from a minimum of 1.5 l/min to a maximum of 112 l/min of free air. For calculation of the Lockhart-Martinelli parameters for flow of liquid and air, it was necessary to know the pressure drop for air only flow. The pressure transducers used were not sensitive enough to measure the small pressure drops that those low flow rates of air created in the relatively large pipe diameters.

The tests of the apparatus with water shows that there is a good agreement for the results obtained and those published by the manufacturer (Durapipe, 1992). The calculations of the Lockhart-Martinelli parameters were therefore based on the calculations of pressure drop for air only instead of measurements.

4.3 Results and discussion

Due to reasons previously explained, the data obtained in the 101.6 mm diameter pipe had to be rejected. The results presented in this section therefore comprise the results from the 38.1 mm, 50.2 mm and the 76.2 mm diameter pipes.

All pressure drop observations are included in the figures and in the calculations. Many of the data points coincide and one point in the figure might therefore represent many observations. There were always ten or more observations of pressure loss for every liquid flow rate. For every flow curve calculated there were between 40 and 100 observations of pressure loss for various flow rates.

4.3.1 Comparison of theoretical and viscometric results for water

To investigate the hydrodynamic characteristics of the viscometer, and get data from a fluid with known behaviour for comparison to the results of slurries, ordinary tap water was used. The results obtained were found to be in reasonable agreement with those published by the manufacturers (Durapipe, 1992), thus indicating that the pipes used to construct the viscometer were likely to be typical of those normally produced in terms of surface roughness and actual internal diameter (Figure 34).

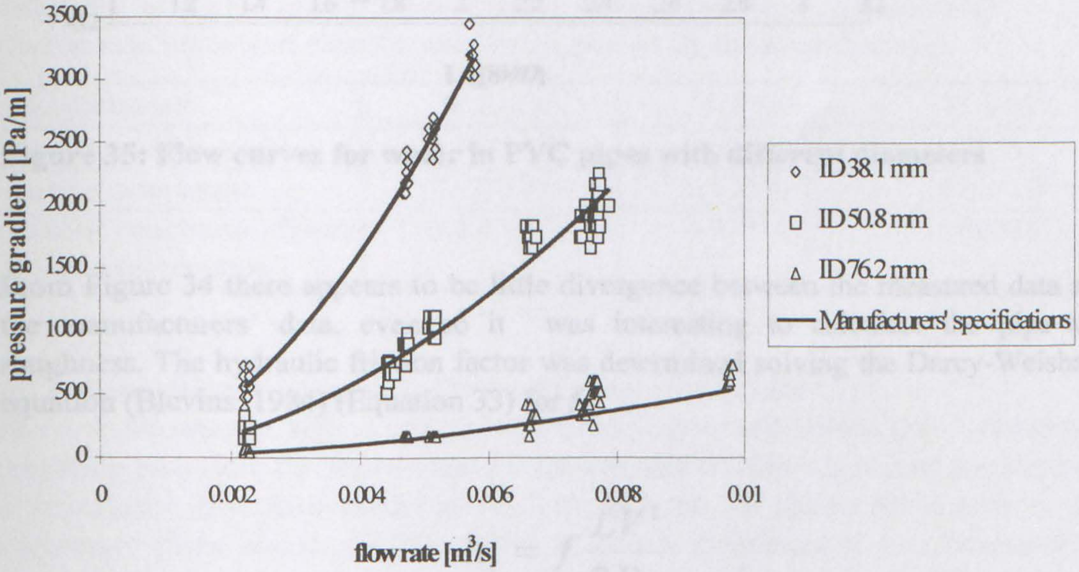

Figure 34: Comparison between pipe manufacturers' specifications and results obtained from the capillary viscometer for water

The paired measurements of differential pressure, (Δp), and flow rate, (Q) were converted to corresponding values of wall shear stress, ($\tau_w = D\Delta p/4L$) and apparent shear rate ($\gamma = 8V/D$) (Metzner and Reed, 1955). As expected, a plot of logarithmic values of τ_w and γ in a linear axis system, showed a linear relationship between these two parameters. This supported the previously established theory that the relationship follows a power-law form ($\tau_w = K\gamma^n$). Figure 35 shows the flow curves (also called stress-flow diagram) calculated for the three viscometric pipes. The calculations were based on least-square linear regression. The slopes of the lines are 1.837, 1.827 and 1.794 for the 38.1, 50.8 and 76.2 mm diameter pipes respectively.

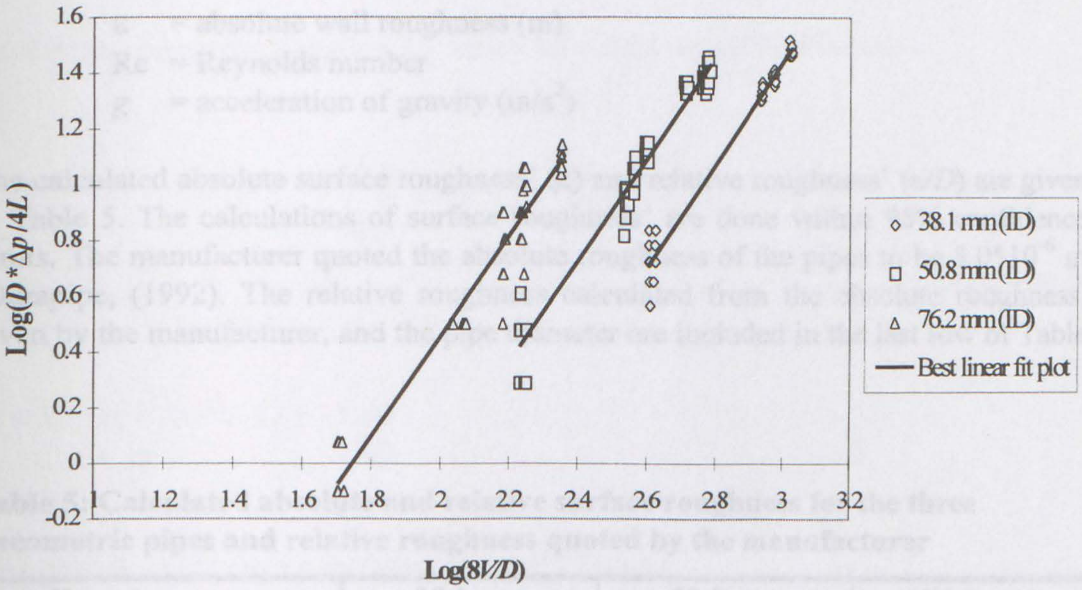

Figure 35: Flow curves for water in PVC pipes with different diameters

From Figure 34 there appears to be little divergence between the measured data and the manufacturers' data, even so it was interesting to calculate the pipe-wall roughness. The hydraulic friction factor was determined solving the Darcy-Weisbach equation (Blevins, 1984) (Equation 33) for *f*.

$$h_f = f\,\frac{LV^2}{2Dg}$$

Equation 33

The calculated friction factor (*f*) was then inserted in the Colebrook-White correlation (Equation 34) (Blevins, 1984) to calculate the surface roughness for each individual pipe.

$$\frac{1}{\sqrt{f}} = 1.74 - 2\log_{10}\left(\frac{2\varepsilon}{D} + \frac{18.7}{\sqrt{f}\,\mathrm{Re}}\right)$$

Equation 34

where: h_f = head loss (meter of water, a function of Δp)
f = friction factor (dimension less)
L = pipe length (m)
D = pipe diameter (m)
V = fluid velocity (m/s)
ε = absolute wall roughness (m)
Re = Reynolds number
g = acceleration of gravity (m/s^2)

The calculated absolute surface roughness' (ε) and relative roughness' (ε/D) are given in Table 5. The calculations of surface roughness' are done within 95% confidence limits. The manufacturer quoted the absolute roughness of the pipes to be $3.0*10^{-6}$ m (Durapipe, (1992). The relative roughness calculated from the absolute roughness, given by the manufacturer, and the pipe diameter are included in the last row of Table 5.

Table 5: Calculated absolute and relative surface roughness for the three viscometric pipes and relative roughness quoted by the manufacturer

Pipe diameter	38.1 mm	50.8 mm	76.2 mm
absolute roughness (m)	$1.91*10^{-6}$	$3.62*10^{-6}$	$3.93*10^{-5}$
relative roughness	$5.03*10^{-5}$	$7.13*10^{-5}$	$5.16*10^{-4}$
relative roughness, from manufacturers data	$7.87*10^{-5}$	$5.91*10^{-5}$	$3.94*10^{-5}$

4.3.2 Some theoretical aspects of pressure drop calculations

Based on the ideas of Melton and Malone, Lord, Hulsey and Melton (1967) developed a scale-up procedure for results obtained for one pipe diameter. It was of great interest to investigate how their model could later be used for slurry. Since each of the viscometer pipes had a slightly different surface roughness it was necessary to calculate theoretical pressure losses in similar pipes, using the Darcy-Weisbach and the Colebrook-White equations (Blevins, 1984). The results from these calculations were then used to investigate what effects they had on the different constants in the model of Lord et al. (1967), which was based on Equation 35.

$$\frac{D\Delta p}{4*L} = A*D^e(\frac{8*V}{D})^s$$

Equation 35

where, $D\Delta p/4L$ = wall shear stress
$8V/D$ = flow function, apparent shear rate
A = constant containing fluid density and viscosity
e, s = constants, dimensionless

Lord et al. rearranged Equation 35, which for a Newtonian fluid becomes

$$\frac{\Delta p}{4L} = A*D^m(8V)^s$$

Equation 36

where, $m = (e - s - 1) = -1.20$
$s = 1.80$

The procedure for these calculations was as follows:

1. A range of 20 values of ε from $1*10^{-7}$ m to $6*10^{-3}$ m, 19 superficial liquid velocities, V, from 0.1 m/s to 8 m/s and a range of 8 pipe diameters, D, from 0.04 m to 0.11m were selected. These represented Reynolds numbers (Re) from 5,000 to 800,000 ($Re = V*D/\nu$, where ν = kinematic viscosity, V and D as above).
2. For each combination of selected ε, V and D, f was calculated from Equation 34.
3. Then h_f was calculated from Equation 33 and converted to $\Delta p/4L$.
4. A, m and s in Equation 36 were evaluated for each value of ε using the paired data for h_f and V and the whole range of eight different pipe diameters. Equation 36 was linearized using logarithmic linearization and then the analysis was carried out using multiple-regression or least square techniques.

In the calculations, the kinematic viscosity (ν) of water was assumed constant and equal to $1.00*10^{-6}$ and all calculations were made for a unity length of pipe (L = 1 m). The results of these calculations are shown in Figure 36 and Figure 37.

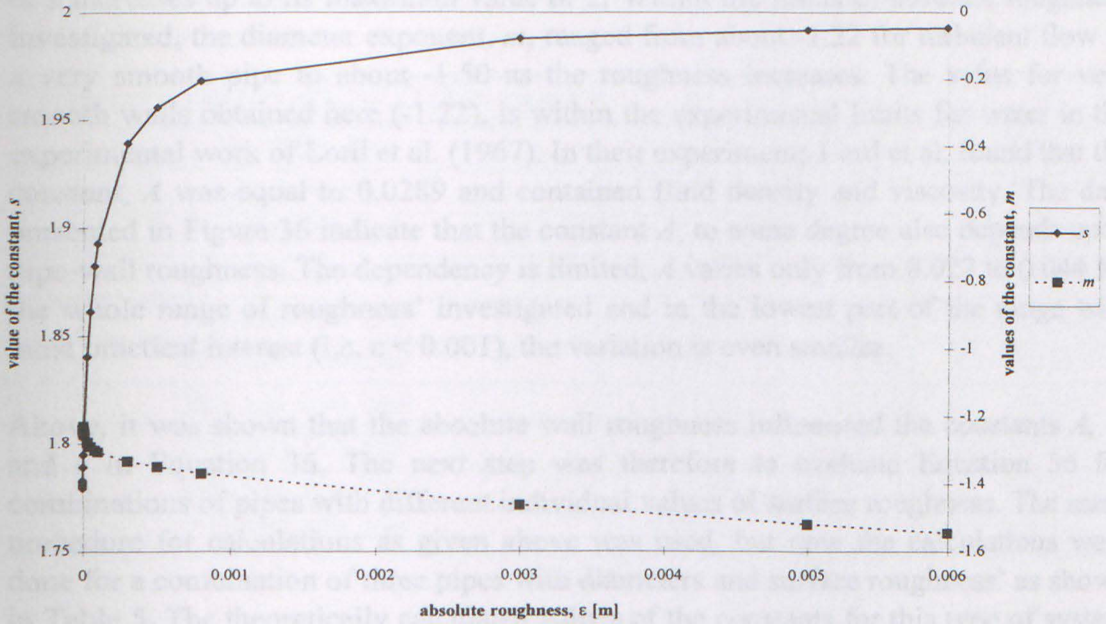

Figure 36: The development of the constants *m* and *s* in the equation of Lord et al as a function of surface roughness

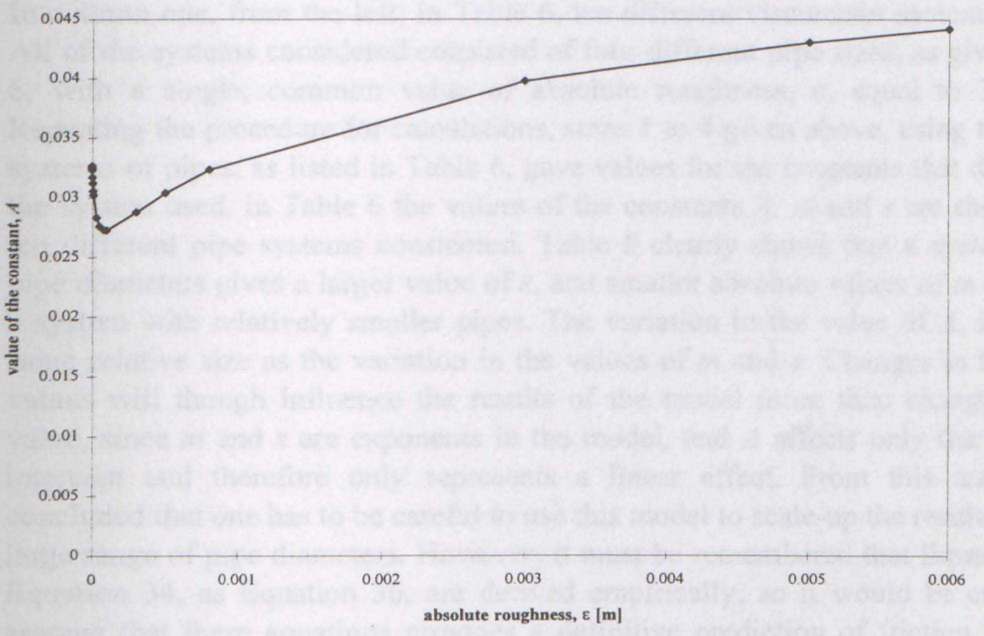

Figure 37: The development of the constant *A* in the equation of Lord et al as a function of surface roughness

As expected, *s* ranged from about 1.75 to 2. The lower value of 1.75 for turbulent flow is found for pipes with very smooth walls; as the wall roughness increases, the value of s increases up to its maximum value of 2. Within the limits of absolute roughness investigated, the diameter exponent, m, ranged from about -1.22 for turbulent flow in a very smooth pipe to about -1.50 as the roughness increases. The value for very smooth walls obtained here (-1.22), is within the experimental limits for water in the experimental work of Lord et al. (1967). In their experiments Lord et al. found that the constant, A was equal to 0.0289 and contained fluid density and viscosity. The data presented in Figure 36 indicate that the constant A, to some degree also depends upon pipe-wall roughness. The dependency is limited, A varies only from 0.027 to 0.044 for the whole range of roughness' investigated and in the lowest part of the range with most practical interest (i.e. $\varepsilon < 0.001$), the variation is even smaller.

Above, it was shown that the absolute wall roughness influenced the constants A, m and s in Equation 36. The next step was therefore to evaluate Equation 36 for combinations of pipes with different individual values of surface roughness. The same procedure for calculations as given above was used, but now the calculations were done for a combination of three pipes with diameters and surface roughness' as shown in Table 5. The theoretically calculated values of the constants for this type of system were as follows: $A = 0.05958$, $m = -1.0058$ and $s = 1.8193$. The constants were estimated using least-squares techniques.

The last issue to deal with in this section was to investigate how the viscometer system, i.e. the combination of different pipe sizes, affected the values of A, m and s. In column one, from the left, in Table 6, ten different viscometer systems are listed. All of the systems considered consisted of four different pipe sizes, as given in Table 6, with a single, common value of absolute roughness, ε, equal to $3.0*10^{-6}$ m. Repeating the procedure for calculations, steps 1 to 4 given above, using the different systems of pipes, as listed in Table 6, gave values for the constants that depended on the system used. In Table 6 the values of the constants A, m and s are shown for the ten different pipe systems considered. Table 6 clearly shows that a system of large pipe diameters gives a larger value of s, and smaller absolute values of m and A, than a system with relatively smaller pipes. The variation in the value of A, is about the same relative size as the variation in the values of m and s. Changes in the m and s values will though influence the results of the model more than changes in the A value, since m and s are exponents in the model, and A affects only the value of y-intercept and therefore only represents a linear effect. From this analysis it is concluded that one has to be careful to use this model to scale-up the results over a too large range of pipe diameters. However, it must be remembered that Equation 33 and Equation 34, as Equation 36, are derived empirically, so it would be erroneous to assume that these equations provides a definitive prediction of friction factors and pressure losses. Therefore it should be emphasised that a comparison of the Lord et al. method against measured data provides the best evaluation of its accuracy.

Table 6: Values of the exponents *s, m, A* in the equation of Lord et al (1967) for different pipe systems

diameter combinations (ID in mm)	*s*	*m*	*A*
10-20-30-40	1.7637	-1.2363	0.0346
50-60-70-80	1.7919	-1.2065	0.0349
90-100-110-120	1.8024	-1.1962	0.0347
130-140-150-160	1.8087	-1.1899	0.0345
170-180-190-200	1.8132	-1.1855	0.0343
210-220-230-240	1.8167	-1.1821	0.0341
250-260-270-280	1.8195	-1.1794	0.0339
290-300-310-320	1.8218	-1.1770	0.0338
330-340-350-360	1.8238	-1.1751	0.0337
370-380-390-400	1.8255	-1.1734	0.0335

4.3.3 Pressure gradients for liquid flow only

4.3.3.1 Pressure gradients for all liquids

Pressure gradients in the three viscometric pipes for all the liquids used in the experiments are shown in Figure 38 through Figure 40. As expected, the pressure gradients increased with increasing flow rates. The pressure gradients also became grater for increasing TS-content, this was also expected and in accordance with the results obtained from the experiments in the TLA, part two of this report.

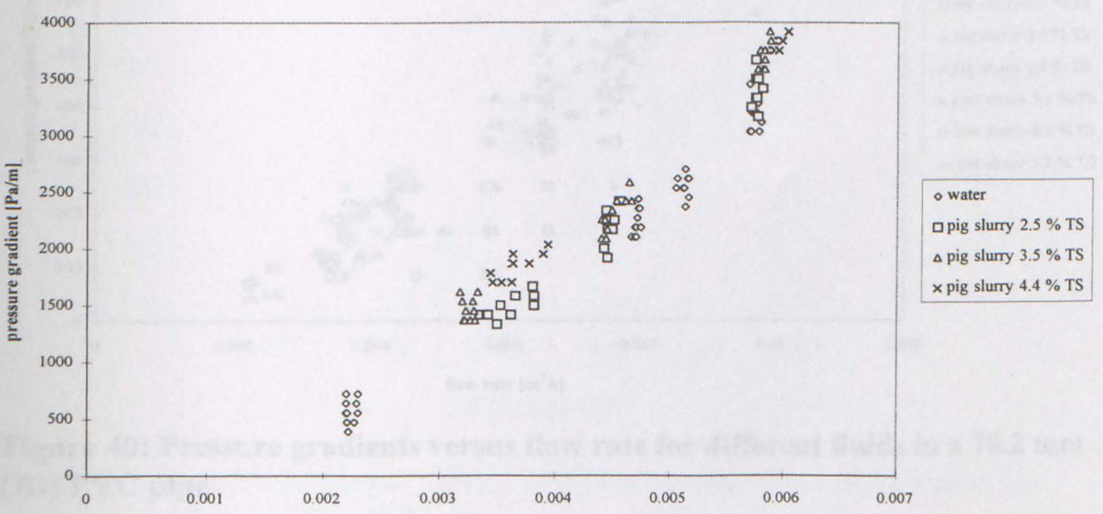

Figure 38: Pressure gradients versus flow rate for different fluids in a 38.1 mm (ID) PVC pipe

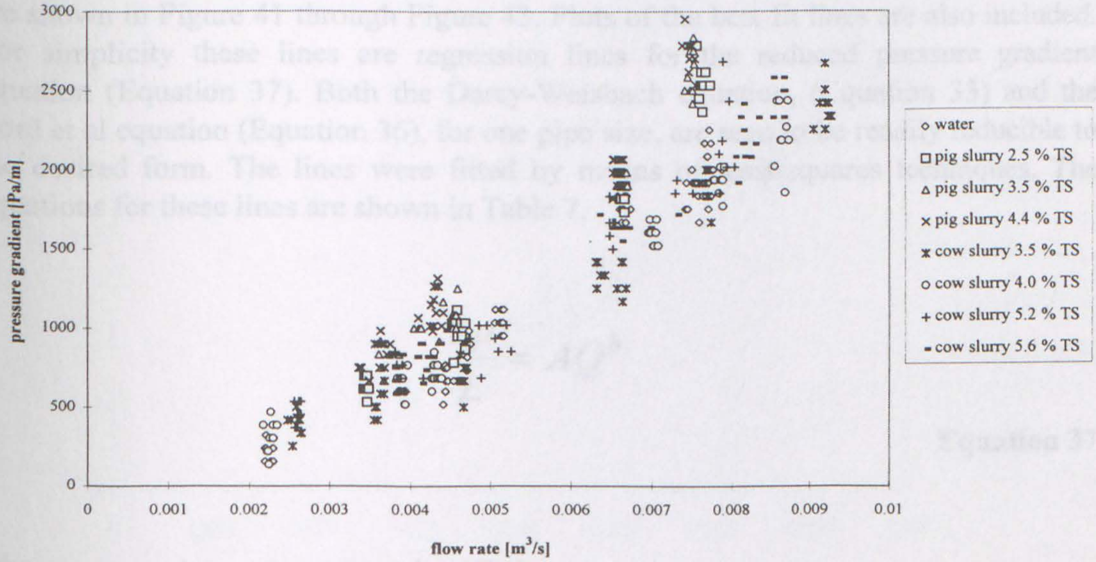

Figure 39: Pressure gradients versus flow rate for different fluids in a 50.8 mm (ID) PVC pipe

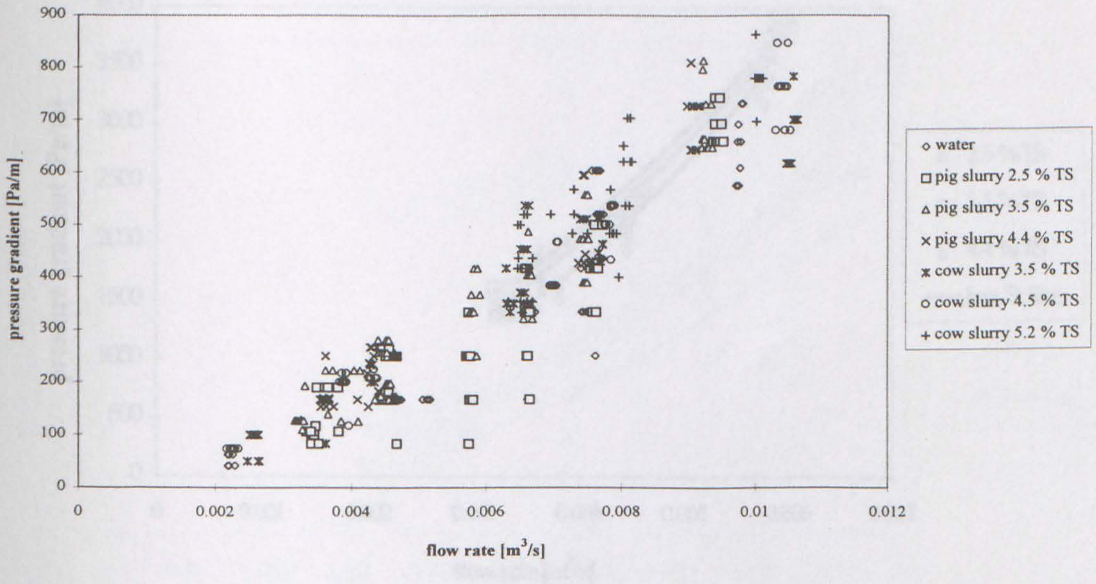

Figure 40: Pressure gradients versus flow rate for different fluids in a 76.2 mm (ID) PVC pipe

4.3.3.2 Pressure gradients for pig slurries

Pressure gradients in the three viscometric pipes for pig slurry of various TS-content are shown in Figure 41 through Figure 43. Plots of the best fit lines are also included. For simplicity these lines are regression lines for the reduced pressure gradient equation (Equation 37). Both the Darcy-Weisbach equation, (Equation 33) and the Lord et al equation (Equation 36), for one pipe size, are seen to be readily reducible to the desired form. The lines were fitted by means of least-squares techniques. The equations for these lines are shown in Table 7.

$$\frac{\Delta p}{L} = AQ^b$$

Equation 37

where: Δp = pressure loss (Pa)
L = length of pipe (m)
Q = liquid flow (m^3/s)
A, b = constants

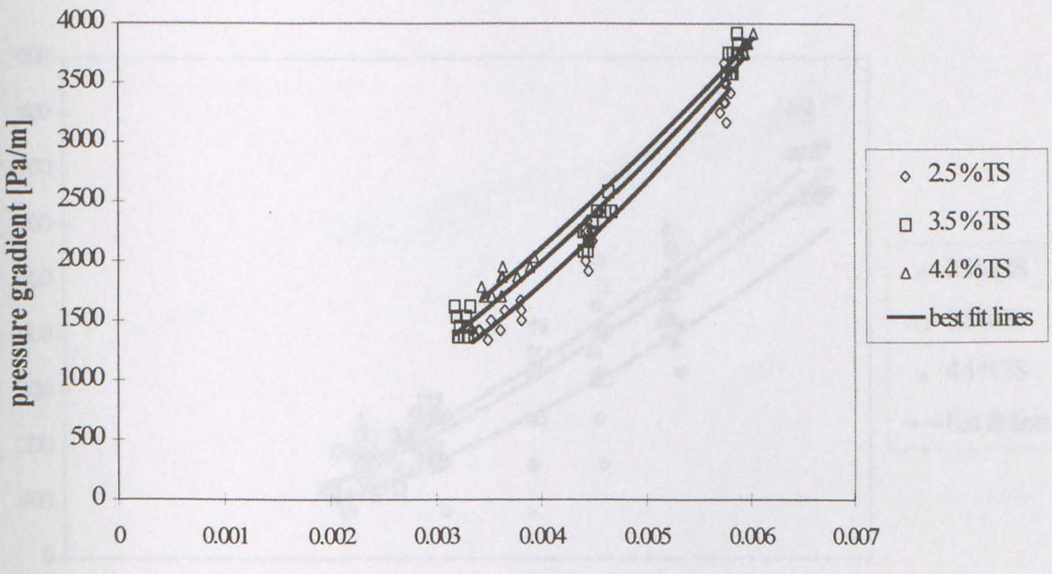

Figure 41: Pressure gradients versus flow rate for pig slurry of different TS-content in a 38.1 mm (ID) PVC pipe

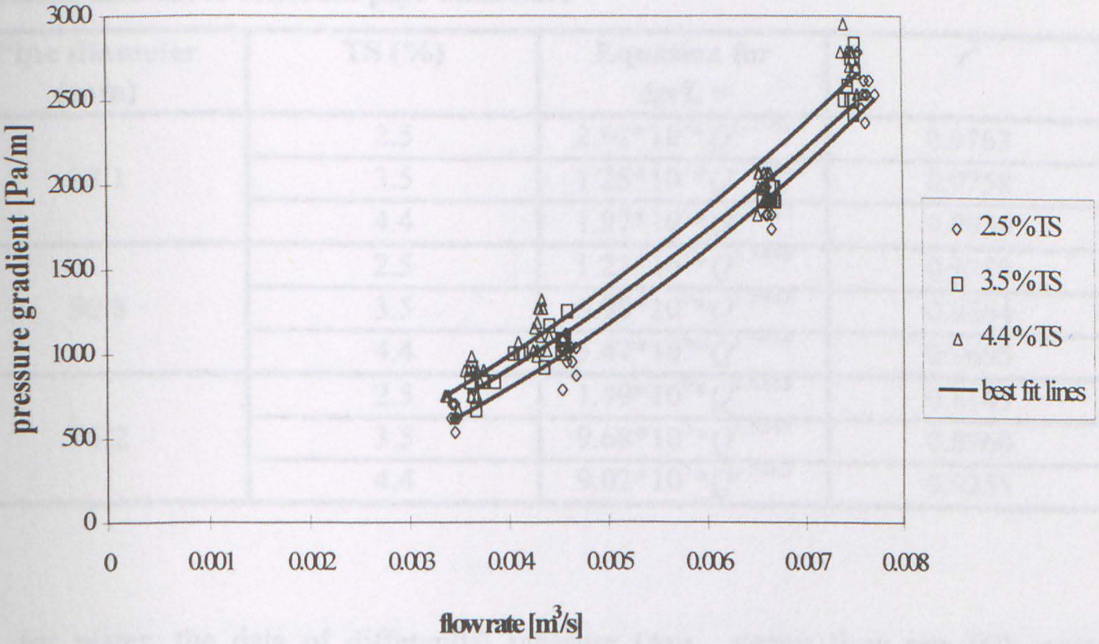

Figure 42: Pressure gradients versus flow rate for pig slurry of different TS-content in a 50.8 mm (ID) PVC pipe

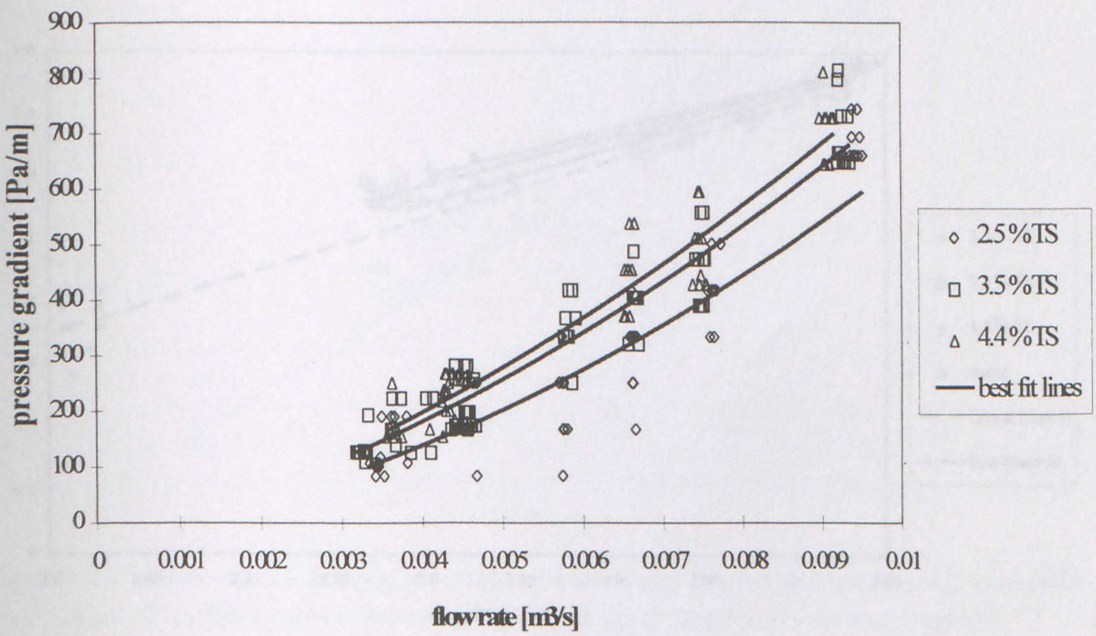

Figure 43: Pressure gradients versus flow rate for pig slurry of different TS-content in a 76.2 mm (ID) PVC pipe

Table 7: Equations of the type, $\Delta p/L = A*Q^b$, for pig slurry of three different TS-contents and three different pipe diameters

Pipe diameter (mm)	TS (%)	Equation for $\Delta p/L$ =	r^2
38.1	2.5	$2.92*10^7*Q^{1.7562}$	0.9763
	3.5	$1.25*10^7*Q^{1.5838}$	0.9758
	4.4	$1.97*10^6*Q^{1.4922}$	0.9934
50.8	2.5	$1.21*10^7*Q^{1.7448}$	0.9758
	3.5	$5.98*10^6*Q^{1.5929}$	0.9664
	4.4	$5.47*10^6*Q^{1.5614}$	0.9695
76.2	2.5	$1.49*10^6*Q^{1.6813}$	0.8143
	3.5	$9.68*10^5*Q^{1.5547}$	0.8960
	4.4	$9.02*10^5*Q^{1.5262}$	0.9255

As for water, the data of differential pressure (Δp), versus flow rate (Q), were converted to corresponding values of wall shear stress, ($\tau_w = D\Delta p/4L$) and apparent shear rate ($\gamma = 8V/D$). The converted data are shown in Figure 44 through Figure 46, the flow curves for water are also included for comparison.

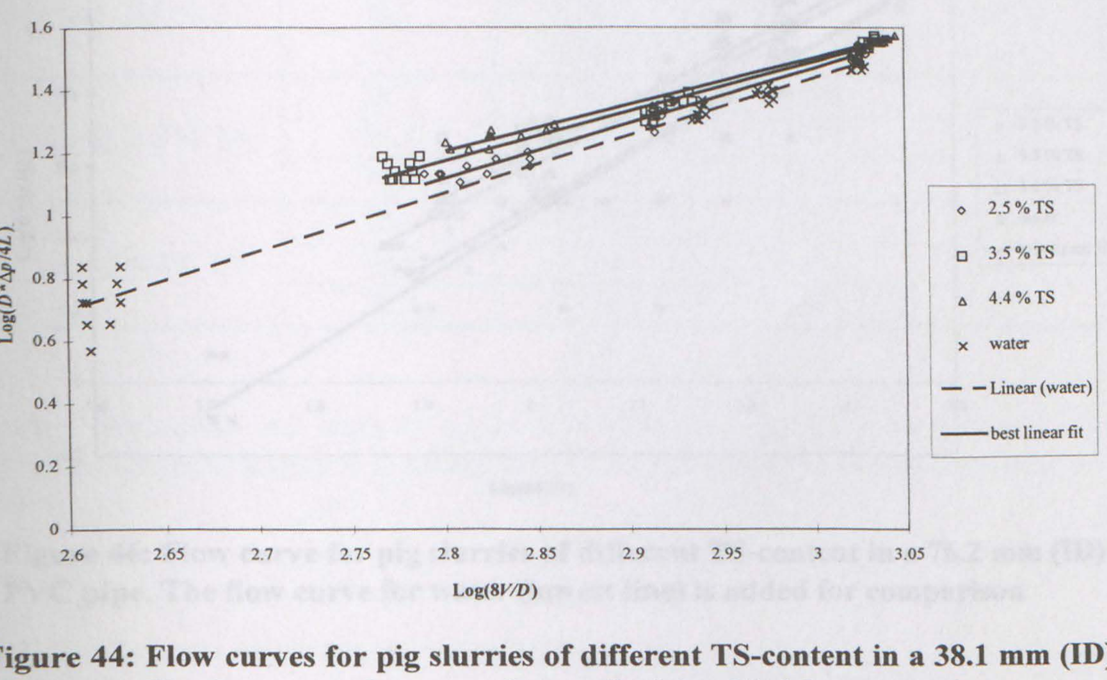

Figure 44: Flow curves for pig slurries of different TS-content in a 38.1 mm (ID) PVC pipe. The flow curve for water (lowest line) is added for comparison

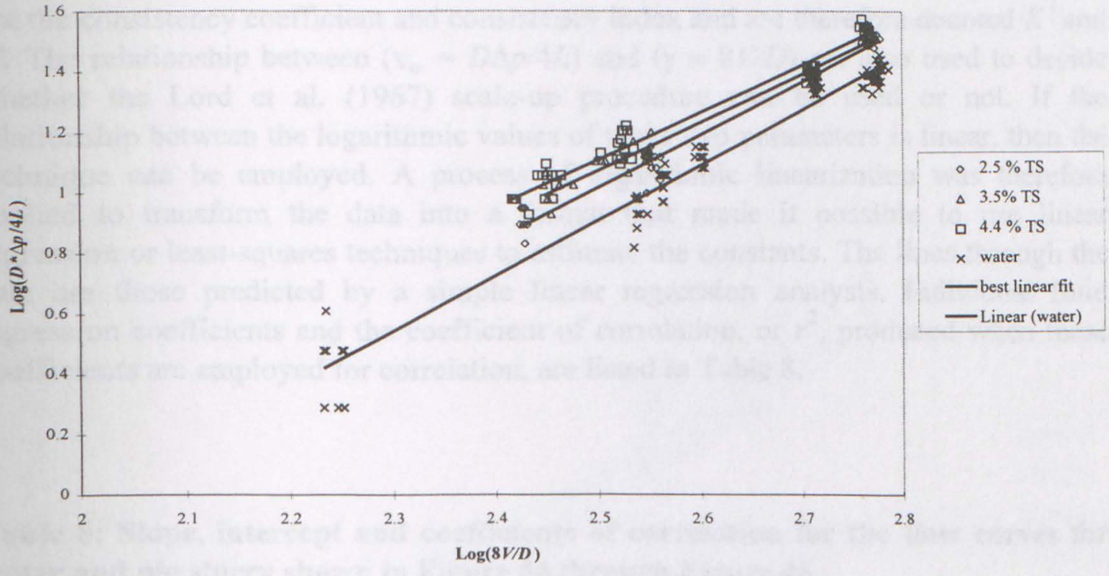

Figure 45: Flow curves for pig slurries of different TS-content in a 50.8 mm (ID) PVC pipe. The flow curve for water (lowest line) is added for comparison

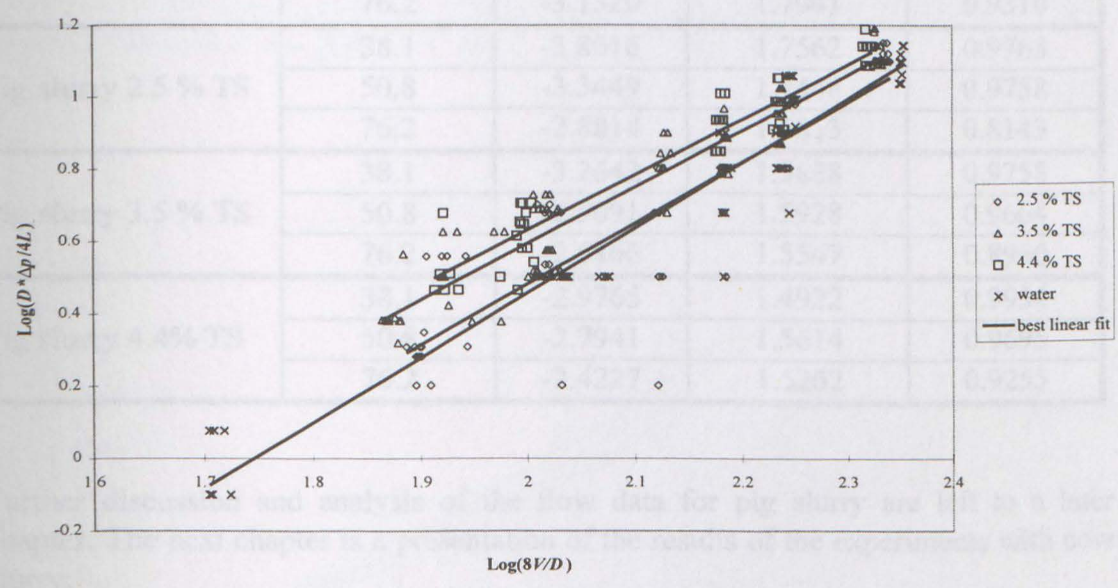

Figure 46: Flow curve for pig slurries of different TS-content in a 76.2 mm (ID) PVC pipe. The flow curve for water (lowest line) is added for comparison

The power-law ($\tau_w = K\gamma^n$), previously described, produces a non-linear equation provided that $n \neq 0$ and $n \neq 1$, and K and n need to be evaluated under laminar flow conditions. Dodge and Metzner (1959) found that the equation also described the turbulent flow in smooth pipes of many non-Newtonian fluids, but then *K* and *n* are not the consistency coefficient and consistency index and are therefore denoted *K'* and *n'*. The relationship between ($\tau_w = D\Delta p/4L$) and ($\gamma = 8V/D$) are also used to decide whether the Lord et al. (1967) scale-up procedure can be used or not. If the relationship between the logarithmic values of these two parameters is linear, then the technique can be employed. A process of logarithmic linearization was therefore applied to transform the data into a format that made it possible to use linear regression or least-squares techniques to estimate the constants. The lines through the data are those predicted by a simple linear regression analysis. Individual fluid regression coefficients and the coefficient of correlation, or r^2, produced when these coefficients are employed for correlation, are listed in Table 8.

Table 8: Slope, intercept and coefficients of correlation for the flow curves for water and pig slurry shown in Figure 44 through Figure 46

Fluid	Diameter (mm)	Intercept	slope	r^2
Water	38.1	-4.0770	1.8375	0.9787
	50.8	-3.6602	1.8272	0.9670
	76.2	-3.1320	1.7941	0.9310
Pig slurry 2.5 % TS	38.1	-3.8016	1.7562	0.9763
	50.8	-3.3449	1.7448	0.9758
	76.2	-2.8814	1.6813	0.8143
Pig slurry 3.5 % TS	38.1	-3.2642	1.5838	0.9758
	50.8	-2.9091	1.5928	0.9664
	76.2	-2.5160	1.5547	0.8960
Pig slurry 4.4% TS	38.1	-2.9765	1.4922	0.9934
	50.8	-2.7941	1.5614	0.9695
	76.2	-2.4227	1.5262	0.9255

Further discussion and analysis of the flow data for pig slurry are left to a later chapter. The next chapter is a presentation of the results of the experiments with cow slurry.

4.3.3.3 Pressure gradients for cow slurries

Due to reasons previously explained, the results of the experiments with cow slurry comprise of results from experiments in the 50.8 mm and 76.2 mm diameters pipes only. Pressure gradients in the two viscometric pipes for cow slurry of various TS-content are shown in the Figure 47 and Figure 48. A plot of the best fit lines, of the same type as described above for pig slurry, is also included. As for pig slurry, curves of the type described by Equation 37 were fitted to the data. The equations are shown in Table 9.

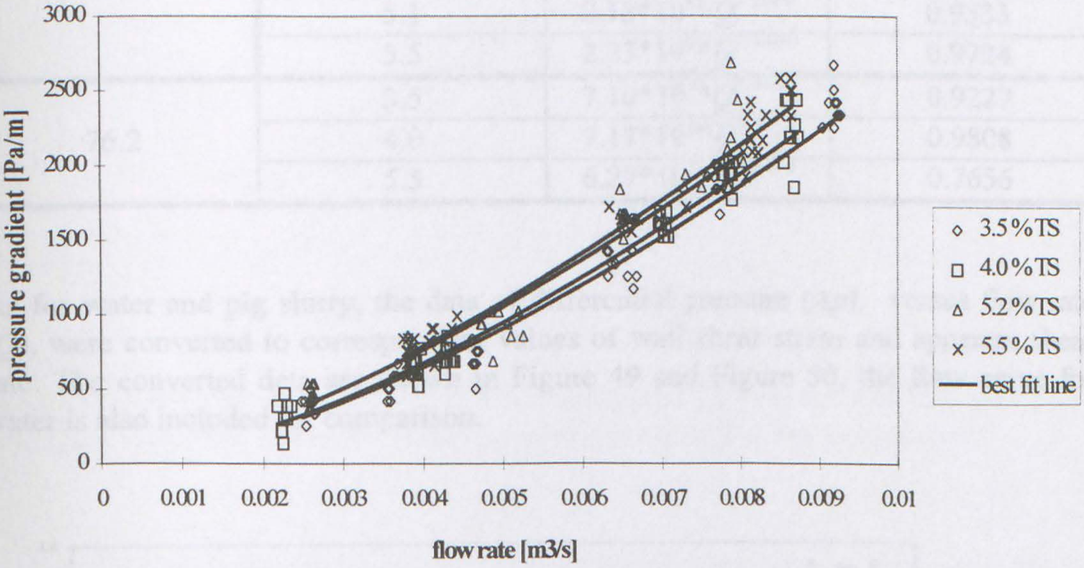

Figure 47: Pressure gradients versus flow rate for cow slurry of different TS-content in a 50.8 mm (ID) PVC pipe

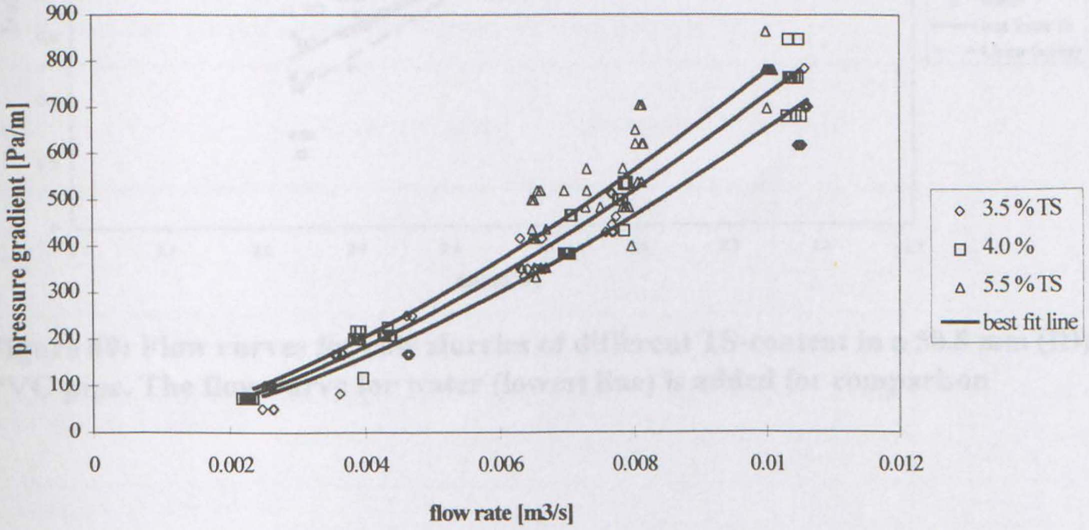

Figure 48: Pressure gradients versus flow rate for cow slurry of different TS-content in a 76.2 mm (ID) PVC pipe

Table 9: Equations of the type, $\Delta p/L = A*Q^b$, for cow slurry of four different TS-contents and two different pipe diameters

Pipe diameter (mm)	TS (%)	Equation for $\Delta p/L =$	r^2
50.8	3.5	$3.10*10^6*Q^{1.5304}$	0.9479
	4.0	$3.14*10^6*Q^{1.5306}$	0.9510
	5.1	$2.13*10^6*Q^{1.4369}$	0.9333
	5.5	$2.23*10^6*Q^{1.4404}$	0.9724
76.2	3.5	$7.10*10^5*Q^{1.5184}$	0.9227
	4.0	$7.17*10^5*Q^{1.4978}$	0.9808
	5.5	$6.27*10^5*Q^{1.4535}$	0.7656

As for water and pig slurry, the data of differential pressure (Δp), versus flow rate (Q), were converted to corresponding values of wall shear stress and apparent shear rate. The converted data are shown in Figure 49 and Figure 50, the flow curve for water is also included for comparison.

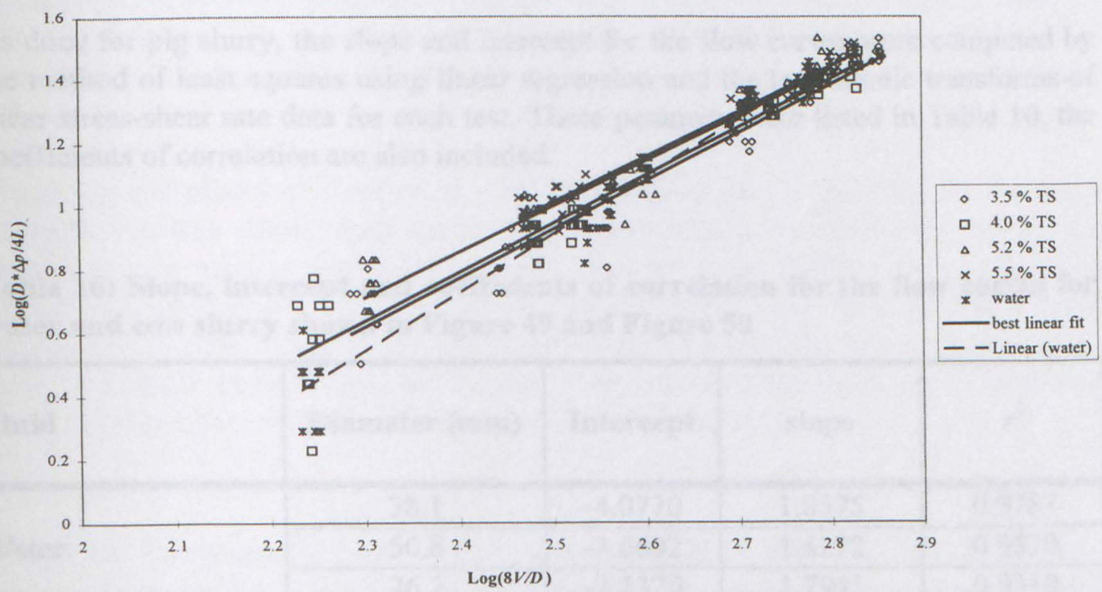

Figure 49: Flow curves for cow slurries of different TS-content in a 50.8 mm (ID) PVC pipe. The flow curve for water (lowest line) is added for comparison

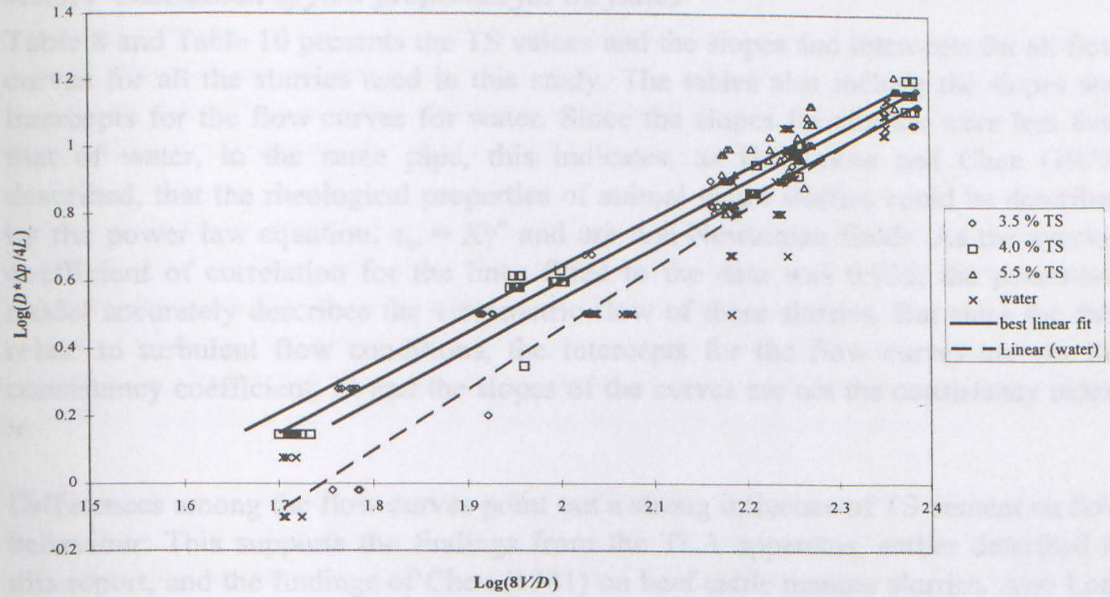

Figure 50: Flow curves for cow slurries of different TS-content in a 76.2 mm (ID) PVC pipe. The flow curve for water (lowest line) is added for comparison

As done for pig slurry, the slope and intercept for the flow curves were computed by the method of least squares using linear regression and the logarithmic transforms of shear stress-shear rate data for each test. These parameters are listed in Table 10, the coefficients of correlation are also included.

Table 10: Slope, intercept and coefficients of correlation for the flow curves for water and cow slurry shown in Figure 49 and Figure 50

Fluid	Diameter (mm)	Intercept	slope	r^2
Water	38.1	-4.0770	1.8375	0.9787
	50.8	-3.6602	1.8272	0.9670
	76.2	-3.1320	1.7941	0.9310
Cow slurry 3.5% TS	50.8	-2.9028	1.5307	0.9479
	76.2	-2.4921	1.5884	0.9227
Cow slurry 4.0% TS	50.8	-2.8841	1.5306	0.9510
	76.2	-2.3981	1.4978	0.9808
Cow slurry 5.2% TS	50.8	-2.5951	1.4369	0.9332
	76.2	--	--	--
Cow slurry 5.5% TS	50.8	-2.5910	1.4404	0.9724
	76.2	-2.2633	1.4535	0.7656

4.3.3.4 Discussion of flow properties for all fluids

Table 8 and Table 10 presents the TS values and the slopes and intercepts for all flow curves for all the slurries used in this study. The tables also include the slopes and intercepts for the flow curves for water. Since the slopes for slurries were less than that of water, in the same pipe, this indicates, as Hashimoto and Chen (1975) described, that the rheological properties of animal waste slurries could be described by the power law equation, $\tau_w = K\gamma^n$ and are non-Newtonian fluids. As the average coefficient of correlation for the lines fitted to the data was 0.935, the power-law model accurately describes the viscometric flow of these slurries. But since the data relate to turbulent flow conditions, the intercepts for the flow curves are not the consistency coefficient, K, and the slopes of the curves are not the consistency index, n.

Differences among the flow curves point out a strong influence of TS-content on flow behaviour. This supports the findings from the TLA apparatus, earlier described in this report, and the findings of Chen (1981) on beef cattle manure slurries. Also Lord et al. (1967) whose work was done on bentonite, $CaCO_3$, CMC and guar gum slurries, observed a relationship between TS-content and flow behaviour. The tables show that, in general, the slopes of the flow curves decreased as TS-content increased. The more gently sloped curves at higher TS-content indicate that these slurries deviate from Newtonian properties more than slurries with lower TS-content. This is only an indication, it cannot be concluded from these observations that these slurries really are non-Newtonian fluids described by the power law, since the data relate to turbulent flow.

Applying the model of Lord et al. (1967), Equation 36, to the data for the fluids described in this report, does not at first, give a conclusive answer to whether the model can be used to determine pressure drop for these fluids. Lord et al. (1967) found that their model was applicable to an extremely wide range of fluids which produce a diameter family of straight parallel lines on a $\log(D\Delta p/4L)$ versus $\log(8V/D)$ plot or a shear stress-shear rate diagram. The constants for Equation 36 evaluated from the data of the fluids in this report are listed in Table 11.

Table 11: Constants for Lord et al. equation, $(\Delta p/4L) = AD^m(8v)^s$, (Equation 36)

Fluid	*A*	*m*	*s*	r^2
water	0.7953	-0.0583	1.8297	0.9766
pig slurry 2.5% TS	0.4479	-0.3720	1.7471	0.9598
pig slurry 3.5% TS	0.7801	-0.3583	1.6162	0.9753
pig slurry 4.4% TS	0.6601	-0.5522	1.5120	0.9730
cow slurry 3.5% TS	0.8277	-0.3578	1.5241	0.9650
cow slurry 4.0% TS	0.6869	-0.1938	1.5129	0.9801
cow slurry 5.5% TS	0.9209	-0.4081	1.4428	0.9702

The fluids studied here produces a diameter family of curves, as mentioned above, and the slope for water does not differ significantly from what Lord et al. got in their investigation considered the differences in surface roughness. The slopes, *s*, for the slurries are following the same pattern as Lord et al. observed, that an increase in TS-content lead to a decrease of *s*; also a more gently sloped curve.

The net diameter exponent, *m*, for the non-Newtonian fluids was found by Lord et al. (1967) to be -1.206 ±0.025 for 95% confidence limits. Their mathematical model indicated the diameter exponent to be -1.20 for Newtonian fluids. This exponent value was also obtained for water in their experiments within experimental limits. They therefore concluded that the diameter exponent was more or less independent of fluid properties, and that a value of -1.20 would produce an adequate correlation.

The value of -1.20 for the exponent was not obtained for water in this study as shown in Table 11. The arithmetic mean diameter exponent (*m*) for the non-Newtonian fluid sample set in this study is -0.3737 ±0.0919 for 95% confidence limits. The theoretical analysis in Chapter 4.3.2 indicated that a combination of three pipes with different values of surface roughness will give a value of *m* equal to -1.0058 and a value of *A* equal to 0.05958. Lord et al. (1967) obtained their values of the constants from analysis of data from their experiments in pipes ranging from 1/8 to 1 inch in diameter. Table 6 showed that one would expect a lower value for both *m* and *A* for combination of pipes with larger diameters. Part of the deviation can therefore be explained by the differences in surface roughness and differences in pipe diameters, but the rest of the difference must have another explanation. The reason may lie in the statistical methods used to evaluate *A* and *m*, mainly because two parameters are estimated from three values (i.e. three pipe diameters), leaving only one degree of freedom. The following is an investigation and analysis of that possibility.

An inherent characteristic of Equation 36 is that of autocorrelation between *A* and *m*, particularly where the number of pipe diameters is small. In other words, if experimental data relate to just a few pipe diameters, falling within a small range of sizes, the combined term ($A*D^m$) may be fitted to the data using any value of *A* (from within a limited range), because the resulting value of *m* can compensate for the variation in *A*. Likewise, if m is fitted first, the value of *A* will follow. Lord et al. used this principle by assigning the value of -1.2 to m (based on Newtonian liquids), and then showing that it could be applied to other liquids.

The following analysis shows variation of *m* with *A*. This analysis will show how *A* and *m* can be mutually dependent such that a given constant of pressure gradient is maintained in a pipe of given diameter at a given liquid velocity. The initial prediction of pressure gradient is based on Equation 36 with the constants *A, m* and *s* assigned the values determined for water by Lord et al. (1967) 0.0289, -1.200, 1.780 respectively. In the analysis, the velocity is assigned a value of 1.000 m/s and the pipe diameter is chosen to be 0.0508 m. When the pressure gradient was calculated, a range of *A* values from 0.010 to 1.000 was selected and *m* as a function of *A* was calculated using Equation 38. For comparison, similar calculations were carried out using *A* =

0.05958, m = -1.0058 and s = 1.8193 which were the values for the constants in Equation 36, calculated for pipes with different surface roughness in Chapter 4.3.2. The results of these calculations are shown in Figure 51.

$$m(A) = \frac{\ln\left(\frac{\psi}{A*(8*V)^s}\right)}{\ln(D)}$$

Equation 38

where, ψ = pressure gradient calculated using Equation 36
A, m, s = constants in Equation 36
D = pipe diameter

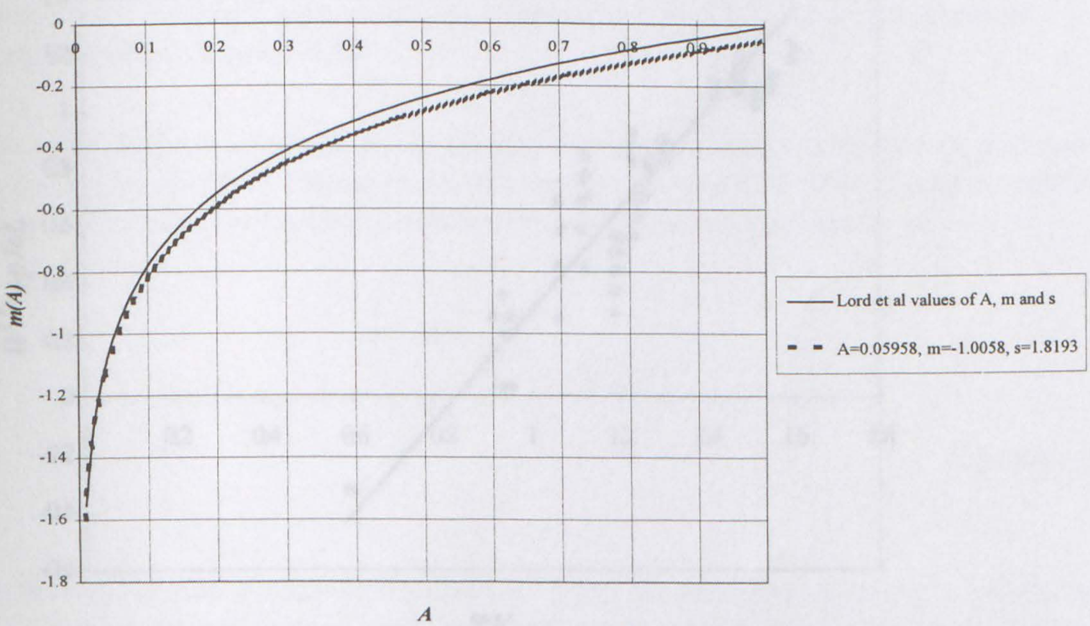

Figure 51: The graph of Equation 38, showing how different combinations of *m* and *A*, on the curves, can maintain a constant value of pressure gradient in a pipe with given diameter and given liquid velocity for two sets of constants used in Equation 36

From Equation 38 and Figure 51 it is concluded that the argument of m will increase as the argument of A increases, if $D < 1$. Where $D > 1$, the argument of m will decrease as the argument of A increases. Since $D < 1$ for all pipes studied, this analysis explains the high values of A combined with the low values of m in Table 11.

The results from the analysis above indicates that the principle used by Lord et al. (1967), by assigning *m*, a constant value, should be tried here. By assigning *A* and *m* the values found for water by Lord et al. (1967) (A = 0.0345 for multiple pipe equation, m = -1.2. It should be observed that the *A* value for water, determined by Lord et al. (1967), for the multiple pipe equation is different from the *A* value obtained when *m* was not assigned a constant value of - 1.2.), *s* was estimated from this data set using techniques described earlier. This analysis gave s = 1.7561, with a coefficient of correlation r^2 = 0.8640, which was close to the value for *s* of 1.780 estimated by Lord et al. (1967). In Chapter 4.3.2 it was found that a system of pipes with different surface roughness' would give values of *A*, *m* and *s* equal to 0.05958, -1.0058 and 1.8193 respectively. Using these values for *A* and *m*, *s* was estimated from the data to be 1.7645 with r^2 = 0.9024. As expected from the analysis in Chapter 4.3.2, a curve with these values for *A* and *m* fitted the data better (a higher r^2) than the values of Lord et al. (1967). The results of these analyses are shown in Figure 52 and Figure 53.

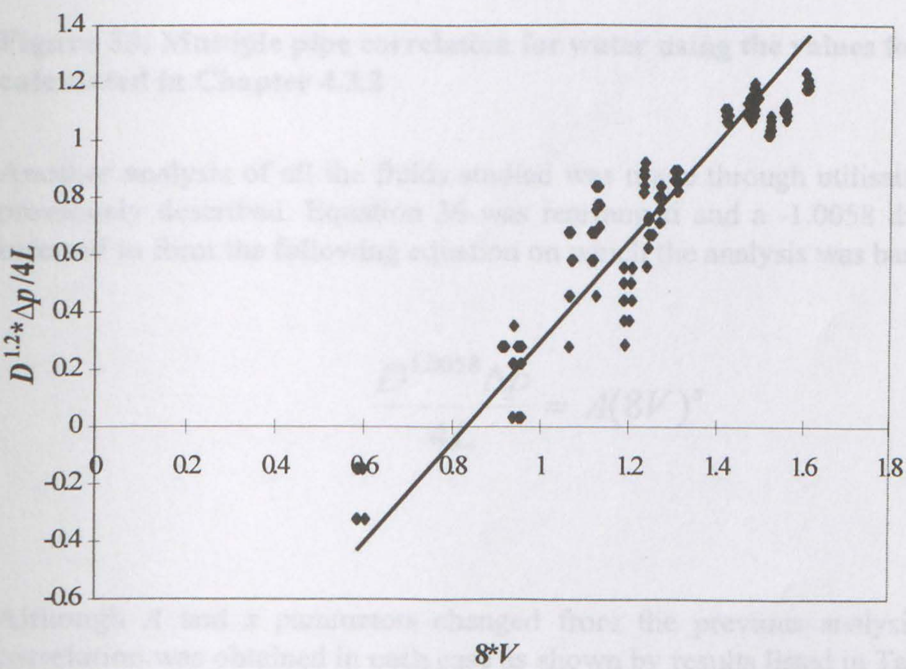

Figure 52: Multiple pipe correlation for water using the values for *A* and *m* found by Lord et al. (1967)

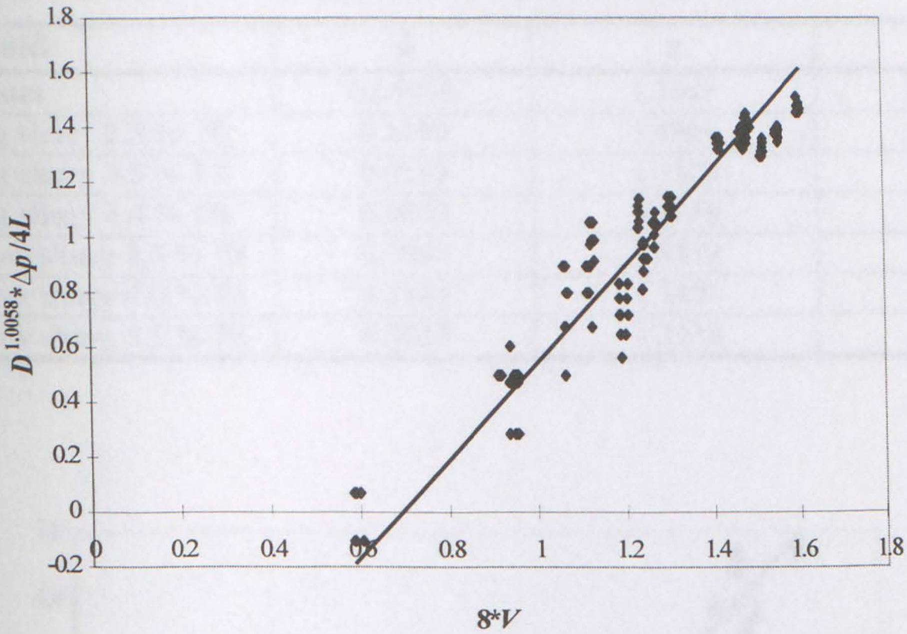

Figure 53: Multiple pipe correlation for water using the values for *A* and *m* calculated in Chapter 4.3.2

Another analysis of all the fluids studied was made through utilisation of techniques previously described. Equation 36 was rearranged and a -1.0058 diameter exponent inserted to form the following equation on which the analysis was based.

$$\frac{D^{1.0058}\Delta p}{4L} = A(8V)^s$$

Equation 39

Although *A* and *s* parameters changed from the previous analysis, a satisfactory correlation was obtained in each case as shown by results listed in Table 12. With this model, data from all pipe diameters form a single line on a Log($D^{1.0058}\Delta p/4L$) versus Log(8*V*) plot for each fluid. One plot for pig slurry and one plot for cow slurry are shown in Figure 54 and Figure 55 as examples. The plot for water is shown in Figure 53. This is indicating that the model of Lord et al. (1967) with diameter exponent, *m* = -1.20, can be used to design slurry pipelines.

Table 12: Constants for Equation 39 for all fluids studied

Fluid	*A*	*s*	r^2
Water	0.05958	1.7645	0.9024
Pig slurry 2.5 % TS	0.1499	1.4905	0.9268
Pig slurry 3.5 % TS	0.2559	1.3523	0.9458
Pig slurry 4.4 % TS	0.3019	1.3279	0.9453
Cow slurry 3.5 % TS	0.1990	1.3819	0.9405
Cow slurry 4.0 % TS	0.2345	1.3491	0.9593
Cow slurry 5.5 % TS	0.4017	1.2118	0.9198

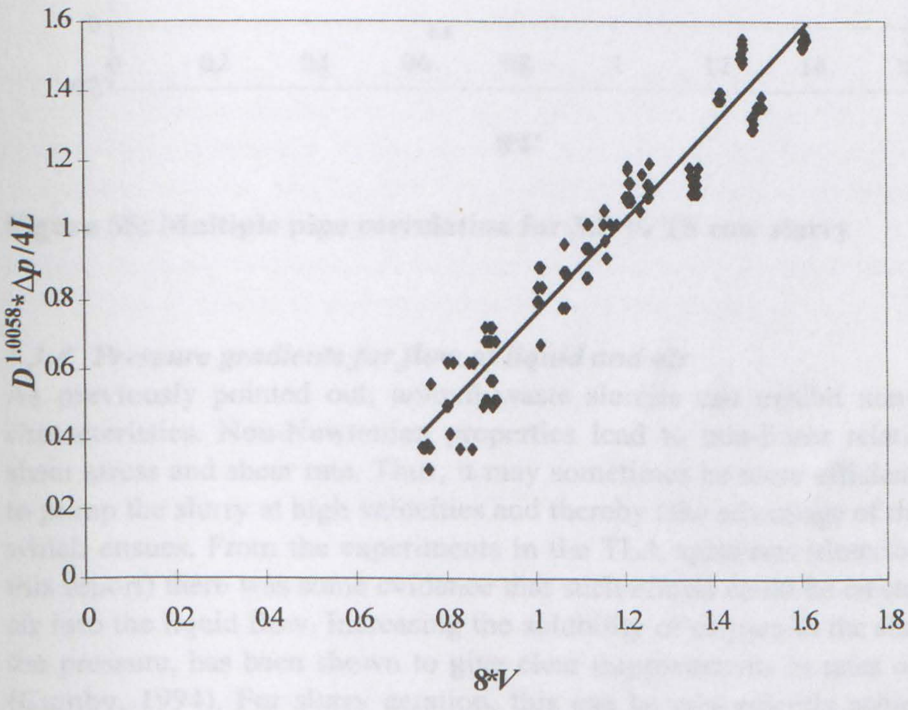

Figure 54: Multiple pipe correlation for 3.5 % TS pig slurry

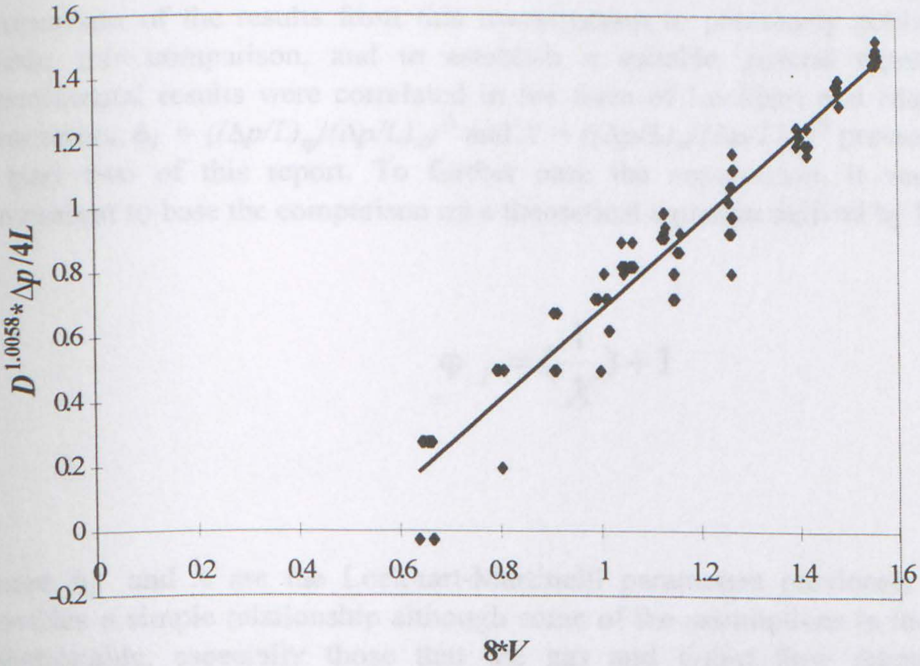

Figure 55: Multiple pipe correlation for 3.5 % TS cow slurry

4.3.4 Pressure gradients for flow of liquid and air

As previously pointed out, animal waste slurries can exhibit non-Newtonian flow characteristics. Non-Newtonian properties lead to non-linear relationships between shear stress and shear rate. Thus, it may sometimes be more efficient in energy terms to pump the slurry at high velocities and thereby take advantage of the lower viscosity which ensues. From the experiments in the TLA apparatus (described in part two of this report) there was some evidence that such effects could be created by introducing air into the liquid flow. Increasing the solubility of oxygen in the slurry by increasing the pressure, has been shown to give clear improvements in rates of oxygen transfer (Cumby, 1994). For slurry aeration, this can be conveniently achieved by pumping slurries through horizontal pipelines. It is therefore a possibility to gain both a more effective treatment by a more effective oxygen transfer, and a more energy efficient pipeline transportation of the slurries. In this work, air was injected into the liquid in the pipeline to investigate the effect that had on the rheological properties of the fluid.

As expected, the pressure gradients became greater with increasing flows of both air and water. This is mostly the case for the slurries too, but there were some observations of pressure drop being less for two-phase flow than for liquid flow only but these were not statistically significant. These observations all occurred for cow slurry with 5.5% TS-content and low voidage, less than 1.6% (vol./vol.) calculated at the point of injection. A high density of data points obtained with each fluid made it impractical for all to be plotted as pressure gradient versus liquid flow for different voidage. This type of data presentation did not represent a useful method to readily compare different fluid types, different TS-content and different air injection rates or comparison of the results from this investigation to previously published data. To enable this comparison, and to establish a suitable general representation, the experimental results were correlated in the form of Lockhart and Martinelli (1949) parameters, $\phi_l = ((\Delta p/L)_{tp}/(\Delta p/L)_{sl})^{1/2}$ and $X = ((\Delta p/L)_{sl}/(\Delta p/L)_{sg})^{1/2}$ previously described in part two of this report. To further ease the comparison, it was found most convenient to base the comparison on a theoretical equation derived by Lin (1982):

$$\varphi_l = (\frac{1}{X}) + 1$$

Equation 40

where ϕ_l and X are the Lockhart-Martinelli parameters previously defined. This provides a simple relationship although some of the assumptions in its derivation are questionable, especially those that the gas and liquid flow separately with no momentum transfer, and the gas is incompressible. Equation 39 is the separated flow model correlation obtained under the above assumptions. It does not wholly correspond to the real case and it is proposed to modify it with an empirically derived corrective coefficient, θ, and an arithmetic corrective term, α:

$$(\varphi_l - 1) = \theta \frac{1}{X} + \alpha$$

Equation 41

To test how accurately Equation 40 describes the pressure losses for different fluids, the experimental results were first converted into Lockhart-Martinelli parameters and then correlated in the form suggested by Lin. The experimental data are presented as plots of (ϕ_l - 1) versus $1/X$. The results for water are shown in Figure 54. The same transformations were carried out for the data from the different slurries. The results from these calculations are shown in Figure 55 and Figure 56. The pipe diameter had no significant effect on the Lockhart-Martinelli parameters, the results presented here are therefore only related to the type of fluid. A linear regression was carried out to calculate the correction coefficients, θ, and the corrective term, α, shown in Table 13.

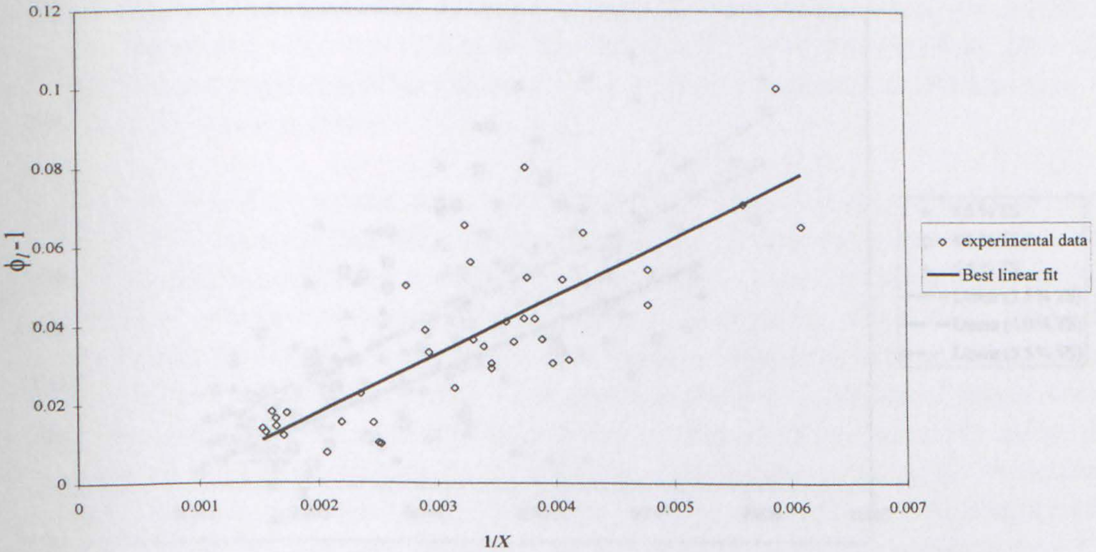

Figure 56: Theoretical curves of the form suggested by Lin fitted to experimental data for water

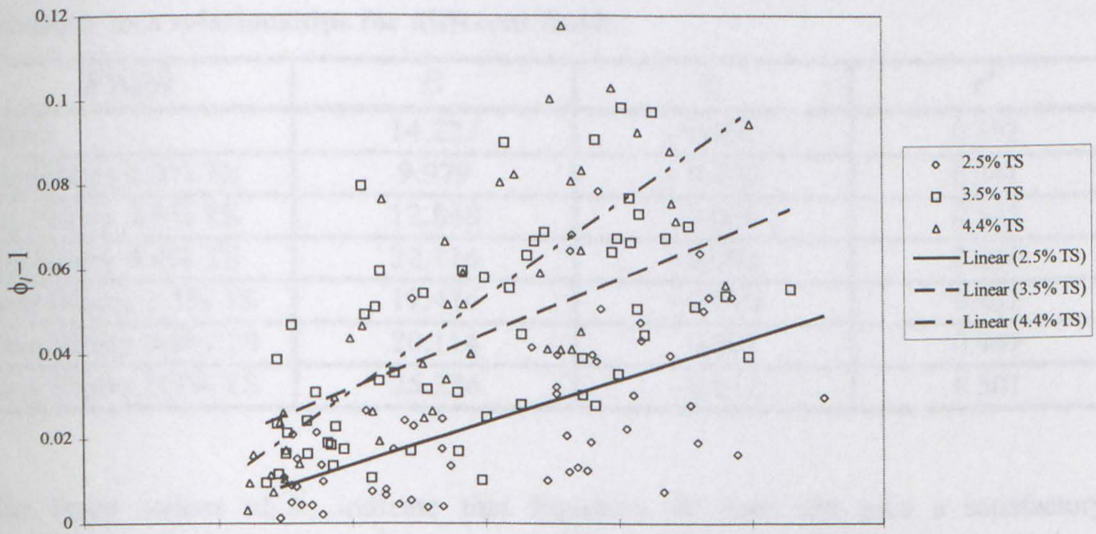

Figure 57: Theoretical curves of the form suggested by Lin fitted to experimental data for pig slurries of different TS-content

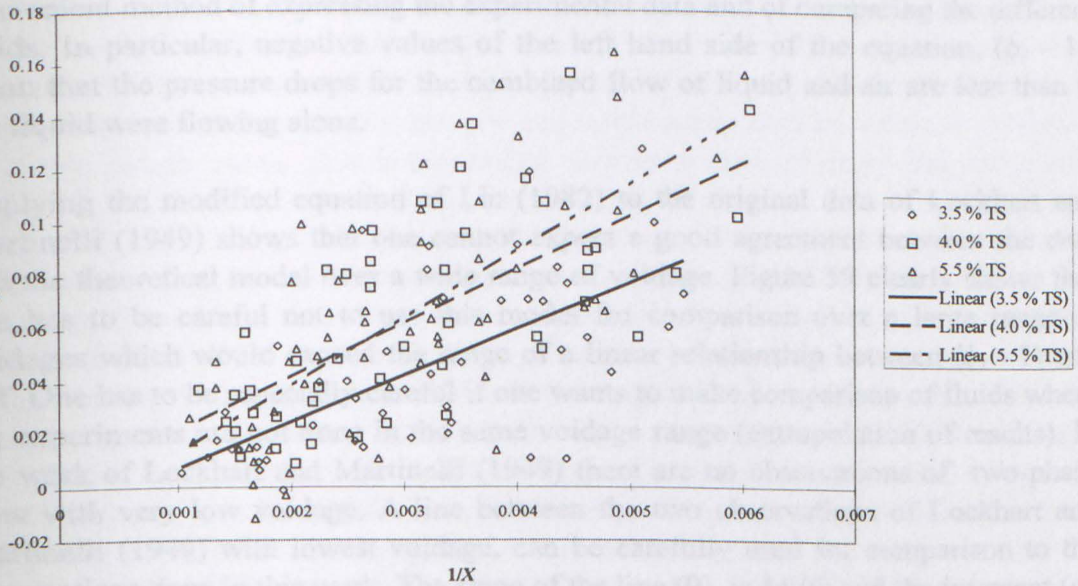

Figure 58: Theoretical curves of the form suggested by Lin fitted to experimental data for cow slurries of different TS-content.

Table 13: Correction coefficients and arithmetic correction terms for theoretical pressure loss relationships for different fluids.

Fluid	θ	α	r^2
Water	14.223	- 0.007	0.592
Pig Slurry 2.5% TS	9.979	- 0.006	0.341
Pig Slurry 3.5% TS	12.848	0.006	0.343
Pig Slurry 4.4% TS	22.116	- 0.001	0.618
Cow Slurry 3.5% TS	17.434	- 0.010	0.432
Cow Slurry 4.0% TS	20.114	0.001	0.449
Cow Slurry 5.5% TS	25.226	- 0.012	0.501

The large values of θ, indicate that Equation 40 does not give a satisfactory description of the pressure losses, especially compared to the θ values obtained experimentally by Lin (1982). The θ values found by Lin fell between 0.89 and 1.49, the highest value for lowest voidage. Cumby and Slater (1984) also experimentally determined higher values of θ than Lin did, their θ values fell between 3.40 and 7.40, in experiments with pressure drops across different insert in pipes. However, Lin's data were for combined flows of greater voidage through sharp-edged orifices, and he points to the poor agreement between his theory and experimental data at low voidages. Bearing this in mind when later comparing the original data of Lockhart and

Martinelli to the results of these experiments one would expect higher values of θ than Lin (1982) got in his experiments. Nevertheless, this relationship provides a convenient method of expressing the experimental data and of comparing the different fluids. In particular, negative values of the left hand side of the equation, (ϕ_l - 1), mean that the pressure drops for the combined flow of liquid and air are less than if the liquid were flowing alone.

Applying the modified equation of Lin (1982) to the original data of Lockhart and Martinelli (1949) shows that one cannot expect a good agreement between the data and the theoretical model over a wide range of voidage. Figure 59 clearly shows that one has to be careful not to use this model for comparison over a large range of voidages which would exceed the range of a linear relationship between (ϕ_l - 1) and $1/X$. One has to be especially careful if one wants to make comparison of fluids where the experiments are not done in the same voidage range (extrapolation of results). In the work of Lockhart and Martinelli (1949) there are no observations of two-phase flow with very low voidage. A line between the two observations of Lockhart and Martinelli (1949) with lowest voidage, can be carefully used for comparison to the observations done in this work. The slope of the line (θ) is 14.00 and the intercept (α) is -0.03. The best linear fit to the experimental data obtained for water in these experiments, gives a line with a slope of 14.223 and intercept -0.007, but the coefficient of correlation (r^2) is not better than 0.592. The slope here is close to the slope previously calculated for the original data of Lockhart and Martinelli (1949) supporting the conclusions of Chen and Spedding (1981) and of Cumby and Slater (1984) that the Lockhart-Martinelli correlation provides a satisfactory description of air-water two-phase flows. It also shows that the Lin (1982) equation is a useful development of the Lockhart Martinelli correlation.

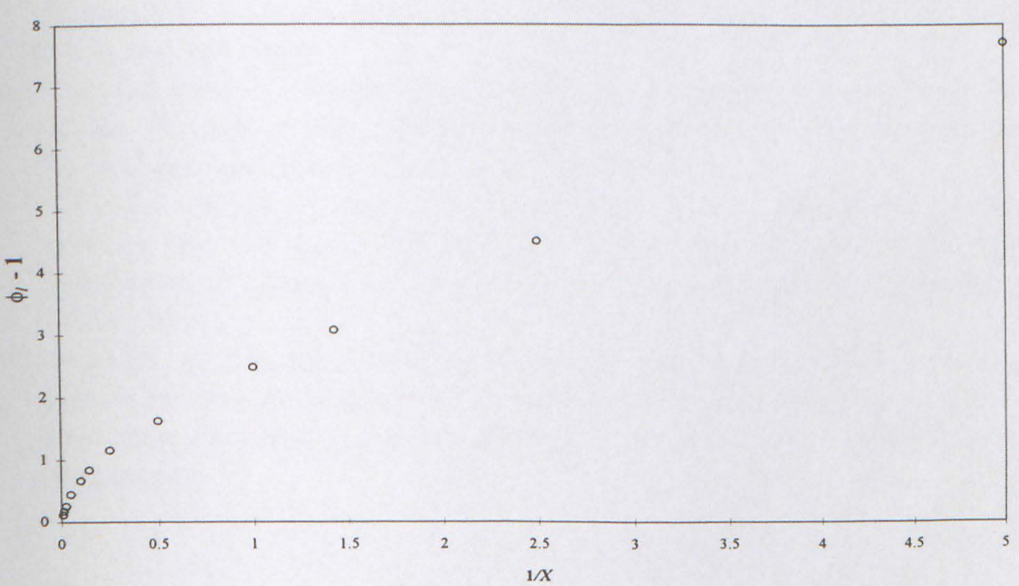

Figure 59: Original Lockhart-Martinelli values expressed on the form suggested by Lin

In Table 13 the θ – and α–values and coefficients of correlation for the regression lines fitted to the experimentally obtained data for all fluids in these experiments are listed. The θ value for water is 14.223 ±3.429 for 95% confidence limits (14.223 ±4.574 for 99% confidence limits). Ninety-five percent confidence limits mean that one is ninety-five percent confident the true population mean, which is based on all samples obtained at these conditions now and in the future, will be within the interval about this sample mean. This indicates that combined flow of slurry and air do not behave significantly differently from water and air, if the slurries contain less than 3.5% TS. There is a significant increase in θ values as the TS-content increases. From the θ values, there are no reasons to believe that there are differences between the behaviour of combined flow of pig slurry and air or cow slurry and air for TS-content lower than 5.5%. This means that the type of slurry is less important than the TS-content for the slurries investigated here. There are no reasons to reject a hypothesis of the α–values being equal for all liquids in these experiments on a 95% confidence level. This shows, despite the fact that the experimental data are somewhat scattered, low values of r^2, that the modified Lin (1981) relationship as it appears in Equation 41 is a useful method of expressing the experimental data and a convenient way of comparing different fluids in the same voidage range.

From the analysis of these experiments there are no significant observations of pressure reduction following the introduction of air into the liquid flow. The development of the θ value as the TS-content increase indicates that there might be some reductions in pressure loss for combined flows of air and cow slurries with higher TS-content than 5.5%. This will need further investigations to be answered.

4.4 Conclusions

1. The pipeline viscometer has proven to be a useful apparatus for investigation of fluid behaviour. It is capable of providing a large shear rate range and the flow mechanisms are close to what we find in ordinary pipelines. The results obtained are therefor easily converted into practical use in design of pipeline transportation systems.
2. A theoretical study of how surface roughness effects the different constants in the model of Lord et al. (1967) shows that the flow function exponent, *s*, increase from about 1.75 for smooth wall turbulent flow to about 2.0 for rough wall turbulent flow. The diameter exponent, *m*, decrease from about -1.2 for smooth wall turbulent flow to about -1.55 for rough wall turbulent flow.
3. Calculations of the constants in the equation of Lord et al (1967) for different systems of pipe diameters, shows that the constants *A* and *m* decrease as the pipe diameters get larger, while the constant s is increasing as the pipe diameters get larger. From this analysis it is clear that one has to be careful not to use this model to scale-up the results over an excessively large range of pipe diameters.
4. All slurries tested had more gently sloped flow curves than water. The flow curves for slurries got more gently sloped as the TS-content increased. This indicated that these slurries deviate from Newtonian properties more than slurries with lower TS-content. The results points out a strong influence of TS-content on flow behaviour.
5. The fluids studied here produced a diameter family of curves, being one of the criteria for using the model of Lord et al. (1967). The principles of the Lord et al. scale-up procedure were developed for the design of slurry pipelines.
6. A modified version of the model first suggested by Lin (1982) has been shown to be useful for comparison of pressure drops for combined flows of liquid and air. However, the assumptions behind the model are questionable.
7. Combined flow of air and slurries containing less than 3.5% TS did not differ significantly from combined flow of water and air. This was valid for both pig slurry and cow slurry.
8. From the analysis, using the modified Lin equation, pig slurry and cow slurry, with similar TS-content, did not behave differently when flowing together with air for the voidages investigated, up to 6% volume of air to slurry.
9. From the analysis of these experiments, there were no significant observations of pressure loss reduction following the introduction of air into the liquid flow. Introducing air always led to an increase in pressure gradient compared to liquid flowing alone.
10. From the development of the data, as the TS-content increases, there are some indications that pressure reductions might occur when injecting air into a flow of cow slurry containing more than 5.5% TS. This will need further investigations to be answered.

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