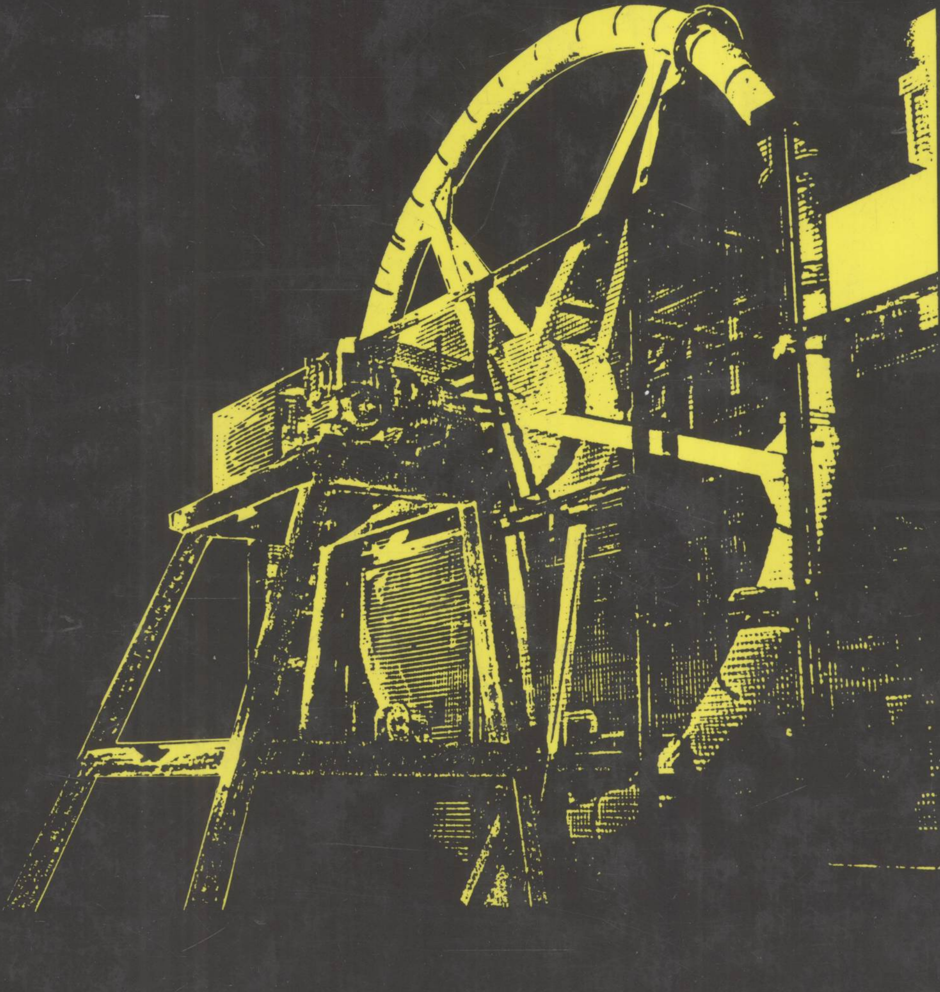
Design of Slurry Transport Systems

B.E.A. Jacobs



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PREFACE

Interest in practical hydraulic transport systems has ebbed and flowed over the years although study of the fundamentals has continued steadily. A review of the literature shows there was a flurry of interest in the 1940s. In the 1950s significant technical progress was made in several countries through a strong research effort. In the UK, experimental work was conducted particularly on the handling of coarse coal slurries. This work was mainly carried out by the British Hydromechanics Research Association in conjunction with the National Coal Board. In France, Durand and Condolios carried out a large amount of work on the hydraulic transport of aggregates. During the 1960s several countries became involved in developing hydraulic transport for mining and a number of coal mine haulage systems were installed. A new surge of interest became evident after the oil crisis in the mid 1970s.

At the present time there are many organisations throughout the world carrying out research and development in the field of slurry transport, although there are few long-distance pipelines either under construction or recently commissioned. It is understandable that the greatest interest is shown in these major lines because of their substantial engineering content. It must be noted, however, that there are many small pipelines being designed and built particularly in the mining, chemical and food processing industries, for which the details remain unpublished.

Important issues which have significant implications on the growth of slurry pipeline systems, particularly for coal and power generation, include the price of oil in relation to that of coal. The level of investment put into the energy industry by government and industrial organisations will influence growth. For example, the fall in oil prices from their peak has led to a decline in investment in other forms of energy.

Environmental pressures brought to bear by the general public will also be significant. Requirements are now placed on public utilities and mining companies to incorporate effective means of waste disposal into their future plans. Slurry systems are used in Flue Gas Desulphurisation and in waste material transport.

The use of hydraulic transport for feeding gasifiers and liquefaction plants is long term and apart from experimental facilities, the widespread commercial use of such equipment is still in the future.

The purpose of this book is to benefit users, manufacturers and engineers by drawing together an overall view of the technology. It attempts to give the reader an appreciation of the extent to which slurry transport is presently employed, the theoretical basis for pipeline design, the practicalities of design and new developments.

Each chapter is self-contained, thus the reader requiring information on a particular topic will find it principally in the appropriate section with only a minimum of cross-referencing. For this reason references are given at the end of each chapter.

The book is structured so that the reader is led through the sequence in which a slurry pipeline transport system could be designed. First, the type and size distribution of the materials to be transported and the flow rate and pipe diameter define the flow regime. The various types of flow regime are described and the methods used to predict the pressure gradients discussed. The information generated leads to the type of pump required and materials of construction. Slurry pumps are described along with the effect of wear on both pumps and pipelines.

At this stage, it would be possible to carry out a rough economic analysis to assess the likely cost advantages compared with other forms of transport. On the assumption that the economics are satisfactory, the designer would then consider the further engineering and cost implications of slurry preparation and dewatering. The necessary instrumentation and control functions are also considered. Further aspects such as start-up, shut-down and particle degradation are discussed, together with applications additional to that of simple bulk materials transport. A section dealing with carrier fluids, other than water, is included as well as some information on three-phase mixtures.

The book finishes with a chapter on existing applications including some cost information where available. Costs for proposed pipelines need to be generated for each application but a methodology to generate approximate costs is described.

The reader will discover, if he is not already aware, that there is no simple way to design a solids handling pipeline. For large schemes complex feasibility studies must be undertaken including practical development work. Research is also required for the new techniques being considered.

CONTENTS

1. PREDICTION OF FLOW PARAMETERS

1. INTRODUCTION

Theoretical aspects of slurry pipelining are reviewed, with the objective of identifying the current limits of knowledge. It has been said that there is nothing quite so practical as a good theory. Indeed, the ultimate test of any theory is its agreement with reliable experimental results. Nevertheless, such results cannot be known to be reliable without some prior theoretical understanding. For a practical subject like slurry pipelining, such abstractions may seem a little irrelevant, if the objective is seen simply in terms of getting the product from A to B. However, if we consider that A and B may be a long way apart and that a few per cent error in operating conditions may have critical cost implications, the need for good theory becomes apparent. In the practical hydrotransport context, a further requirement exists that the theory be accessible to and usable by the designers of slurry systems, not just the academic colleagues of the theoretician.

Literature in the field of hydraulic transport is continually being reviewed over the whole spectrum of subject area. Whenever a new theory is presented, a collection of prior experimental data is usually produced to support it. The publication of new test data is, conversely, often set against the background of existing theories. On another level, reviews have been written with the objective of producing a design guide, or simply to gather together existing work and make some sense of it. With this in mind, this section begins with a guide to the various sources of information from which the literature has been drawn. There follows a discussion of pipeline design in terms of the design process, which is frequently subject to constraints that prevent it from passing rigorously from hypothesis to conclusion. The designer is often saddled with insufficient information, and time or cost restrictions that preclude him from obtaining what he needs.

1.1 SOURCES OF INFORMATION

The 'Hydrotransport' series of conferences, organised by BHRA in conjunction with other interested organisations, have proven a productive source of information. Coupling these Proceedings with those of the Slurry Transport Association, now entitled the Coal and Slurry Technology Association, has helped towards a balance between theory and practice. Many other sources of information exist, however, ranging from the very academic to the very practical. Reviews tend to mix theory and application. Stern (1), for instance, considered slurry transport technology in the context of its possibilities for South Africa. He highlighted the basically different approaches needed for short and long distance slurry lines. He referred to existing systems in other countries, making the useful point that a material must not lose its value when crushed or wetted before it can be considered for slurry transport. In this context, iron ore is an ideal material as it makes excellent pellets from granulated fines, easing its passage through the steel mill. Referring to South Africa's shortage of water, Stern recommended looking to high solids concentrations. If this were to be combined with coarse material transport, the entire spectrum of slurry technology, from non-Newtonian to settling suspensions, would be invoked in the one system. Alternatively, as suggested by Parkes and Lindsay (2) for lifting coal from mines, the coarse material could be lifted mechanically and the fines hoisted hydraulically.

Rigby (3) took a wide historical view concerning slurry transport, referring to its early development in the American gold rush of the mid-nineteenth century. Since then, the Ohio Cadiz coal line, built in 1957 but later moth-balled (1963) for economic reasons, pioneered the large scale (147 km long × 254 mm diameter) transport of material at high throughputs (1.5 Mtpa). It was later overtaken by the Black Mesa, 439 km × 457 mm × 5 Mpta, supplying coal to the Mohave power station in southern Nevada. The first iron ore concentrate line (Savage River) was built in Tasmania (1967), with conservative slope specifications to cope with the solids specific gravity. It too has been overtaken in scale by the Brazilian Samarco line, carrying 7 Mtpa of iron ore concentrate over 400 km. Other materials have included limestone (UK), gold slime (Australia, South Africa), phosphate (Canada, South Africa), copper concentrate (Papua New Guinea), copper tailings (Chile), and zinc sulphites (Japan), to name but a few. In many cases, grinding for slurry transportation is consistent with other process requirements, such as ore concentration by flotation. Hydraulic transport of waste material, such as bauxite residue, coal mine tailings and sewage, is also a widely accepted and practised application.

In an overview of slurry transport technology, Lee (4) looked at various means of transporting coal, ranging from the very fine yet concentrated mixtures for direct combustion, to dilute transport of run-of-mine (ROM) coal. ROM coal usually reaches a maximum size of 50 mm (2 inches), and two opposite approaches to its transportation have arisen. One has been to pump it in low concentrations with devices such as jet pumps. The application for such systems include ship loading, where no shortage of water exists and the pumping distances are short. Where there is a shortage of water, high concentration coarse coal suspensions, stabilised both by the presence of fines and the high total solids, come into their own. The difficulty here is that of finding a high pressure pump capable of handling coarse solids. For this, the most promising candidate appears to be the Boyle rotary ram pump, capable of shearing lumps of coal obstructing the valve gear. Another kind of concentrated suspension, the 70 per cent coal-water-mixture (CWM) avoids the dewatering step by offering itself for directly fired combustion.

Other reviews have focused more particularly upon the theory. Shook (5), for example, considered hydrotransport in the context of general two-phase flow. He compared capsule and slurry transport, commenting that capsule transport was, at that time, further advanced technically despite being a later development. He mentioned the possibility of turbulence suppression in channel flow and some benefit to be gained from the use of drag-reducing additives. Some difficulties were highlighted concerning the prediction of critical velocity for settling slurries, and scale-up from model to prototype. Turbulence suppression in non-Newtonian and fibrous suspensions was noted, with the observation that most of the equations for the flow of such media were empirically based. In another comparison between capsule and suspended sediment transport, Lazarus (6) presented a break-even curve for the two systems. For a 300 m line, capsules were favoured at throughputs of sand-weight material above 300 kg^{-1}. Capsules had the advantage that they could be made neutrally buoyant by not filling them completely, whilst slurries were found to be favoured by their independence of a fabricated vehicle.

Thomas and Flint (7) reviewed pressure drop prediction in slurry lines, considering low and high concentrations of both settling and stable suspensions. They refer to the use of an effective turbulent viscosity for the Reynolds number determination of a turbulently flowing non-Newtonian slurry, and to the practice of splitting a slurry of mixed particle sizes into homogeneous and heterogeneous portions. Kazanskij (8) presented an especially comprehensive review, tabulating thirty-seven different correlations for pressure drop in heterogeneous flow alone, between the years of 1954 and 1976. They concluded that a scale-up criterion based purely on theory was disallowed by a lack of fundamental knowledge concerning the physics of suspension. To some degree, that situation has changed as explained in sections 3.1 and 3.2. The change is, however, recent and not yet complete. Duckworth (9), reviewing the field at the same time as Kazanskij (8), noted a large number of empirical expressions in more common use than any based on theory alone. One difficulty, of course, with the latest theoretical developments is their complexity, requiring them to be tied to a powerful computer, perhaps inaccessible to the pipeline system design team.

1.2 PIPELINE DESIGN

The designer is faced with a number of problems. We can assume that he starts with a material to be transported at a known rate. We can also take it that there is a well-specified destination, perhaps a port, for shipping the material abroad, perhaps a central depot for inland distribution, or a down stream reactor in a chemical production plant. He must now select a means of transport. Where applicable, road and rail offer a certain flexibility at high cost in running expenses, but little capital expenditure is required unless new roads or rail lines have to be laid. Should he choose a slurry line for its low running costs, he must ensure that it will pay for itself well within the life of the project. Short payback periods are the rule if finance is to be sought for the venture. Delays due to opposition by existing transport contractors, government planning requirements and unforeseen technical hitches can significantly affect the project completion date, and hence the payback period.

Figure 1, based on Pitts and Hill (10), shows the basic elements required of a typical pipeline system. From the mine, assumed for present purposes to be iron ore, the product is

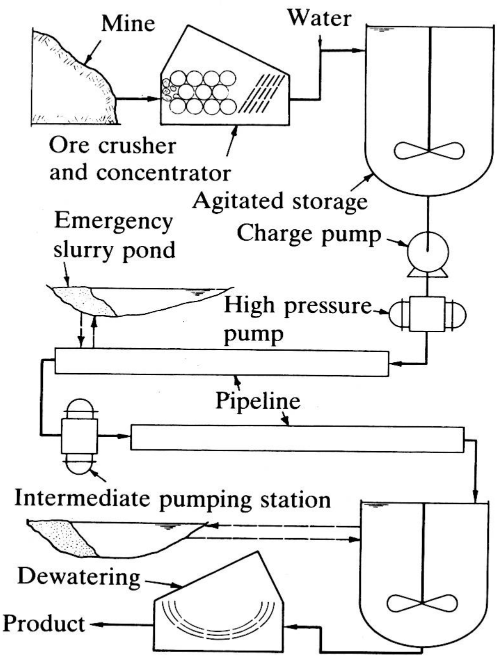

Figure 1. Schematic flow diagram of a long distance slurry pipeline (10)

crushed and concentrated. It is then fed into a mixing hopper where the water is added and the resulting slurry delivered to an agitated storage vessel. From here, it can be pumped into the pipeline by a high pressure pump, avoiding the need for frequently spaced pumping stations. High pressure slurry pumps, however, usually require a pressurised feed, supplied in this instance by a priming pump. Emergency slurry ponds must be provided at the end of each section of slurry line, if blockage at one portion of the line is not to be propagated along its entire length. In the case of iron ore concentrate, dewatering of the slurry is required before the fines can be pelletised in readiness for the blast furnace. From the above description, the following tasks might reasonably be assigned to the design team:

- Select, if the option is open, a size distribution to be used for slurry transportation. If the size is fixed by process requirements, this should be monitored and taken into account for the transportation system.
- Determine the design throughput of solids, and find a source of water capable of handling it at the desired concentration, also to be fixed by the designer.
- Select an agitated storage system to ensure a constant throughput for intermittent

production. Agitation must maintain a well-mixed suspension for minimal cost in power or agitator wear.

- Design the pipeline for its internal diameter, wall thickness and length between pumping stations. This requires the selection of a pumping system of suitable flow and head capability.
- Protect the system as much as possible from wear, corrosion, blockage, leakage, cavitation and pressure surges. Minimise the extent of any damage resulting from failure of such protection.

Clearly, design of the pipeline itself is one component of the total problem. Nevertheless, it is central and impinges upon the design of other parts of the system. Much of the technology relevant to slurry lines can be borrowed from that developed by the water supply and petroleum industries. Indeed, Sandhu and Weston (11) considered the feasibility of conversion of existing crude oil or natural gas lines into coal slurry lines. They concluded that in many cases it could be done at a cost fourfold less than that required for a new system. New pumps would have to be installed at the pumping stations, but only 2 per cent of the line length would have to be replaced to cope with slurry service.

The basic features of a long pipeline with a downward sloping ground profile between mine and outlet are now described. The line must be capable of handling the pump head plus a surge allowance. Its wall thickness is, therefore, required to be greatest just downstream of the pump. The hydraulic grade line falls linearly along the pipe to the next pumping station needing progressively less wall thickness to cope with the pressure. It makes sense, however, to vary the thickness in stages rather than attempt to follow the hydraulic grade too closely. It is worth pointing out that an upwards slope makes more severe demands upon the pipe section downstream (up slope) of a pumping station.

The above process depends upon reasonably accurate predictions of head gradient for the design flow and concentration of slurry. Some savings can be made if small-scale loop tests can be scaled up to prototype. Thomas (12) reviewed a number of scale-up methods, some involving a simple power correlation of pipe diameter and others of a more complicated polynomial form. For semi-heterogeneous non-Newtonian slurries, five constants were required to be determined, demanding numerous tests. It may be possible, however, to split the non-Newtonian and heterogeneous aspects in such a way that the analysis is simplified. Formulations attempting to deal with everything at once have rarely been proven successful.

At a Symposium of the Canadian Society of Chemical Engineers, two papers were presented highlighting another way in which pipeline design can be subdivided for clarity. Stevens (13) focused on long-distance pipelines, defining them as anything longer than ten miles. Shook (14) looked at short-distance pipelines, defining them as anything that could be designed without an extensive test programme. He concluded that there was no such thing as a 'short-distance pipeline' at the time of writing (1969)! Now that test loops are beginning to look like commercial projects, it is worth considering how money might be saved for the design team, ultimately for their clients and all those associated with the product being shipped.

1.3 NOMENCLATURE

In an attempt to save the tedium of continually needing to refer to a list of terms and subscripts, these are defined in the text when the occasion arises. Common usage is employed where possible, such as u or V for velocity, ρ for density, S for specific gravity, μ or η for viscosity, and commonly accepted symbols for dimensionless numbers such as Reynolds number (Re) and Froude number (Fr). Variables may be prefixed with a 'delta' (Δ) to denote difference or a 'del' (∇) to denote gradient, a feature applying principally to pressure (p). Although the use of ∇ stems from the mathematics of vectors, this is the nearest the reader will be subjected to vector mathematics. Head gradient (J) may be taken to refer to the carrier fluid (water) rather than the mixture, unless otherwise specified. Departures from common usage include m for pseudoplastic consistency coefficient, in preference to K, one of the more overworked constants in the English alphabet. Friction factor is always f, not λ, and usually interpreted as Darcy, rather than Fanning, friction factor. Section 2.1 explains this in more detail. In any situation where the symbols are not explicitly defined in the text, the reader can refer to the nomenclature given in an appendix. This is set out chapter by chapter to overcome the problem of multiple definitions with the range of subjects covered.

2. SLURRY PIPELINE FLUID DYNAMICS

Fundamental to the problem of slurry transportation are the principles of fluid mechanics for single-phase Newtonian systems. Despitë he fact that new theories of turbulence and creeping flow, are continually being published, enough is understood about fluid flow in pipes for it to be considered a textbook subject. A brief presentation of it is given here for its value as a basis for looking at more complex systems. Settling and stable suspensions of solid particles each depart in a special way from single-phase Newtonian behaviour. The dynamics of a settling slurry can be most readily understood by treating it as a two-phase mixture of liquid and solids. In a manner similar to that of gas-liquid two-phase flow, there arise numerous flow regimes, each representing a distinct distribution of liquid and solids within the pipeline. Such systems also behave differently in vertical and horizontal flow, and are otherwise sensitive to pipeline slope. Without the two-phase complications, stable slurries often display a non-Newtonian response to shear, requiring two or more parameters to replace viscosity. The Reynolds number must be reformulated and the laminar-turbulent transition is frequently altered. Considering that some industrial slurries consist of coarse solids unstably suspended in a non-Newtonian medium, the need for a sound fluid mechanical basis becomes obvious.

The reader of this section is to look at single-phase, steady-state, Newtonian flow in pipes. Departures from this ideal are then taken in turn, beginning with settling mixtures and the flow regimes they generate. Non-Newtonian media follow, with attention given to basic definitions and practical examples of substances displaying the various properties. Departures from the steady state are represented by pressure surges (water-hammer), generated either by a pump trip, a sudden valve closure, or a burst pipeline. They are of engineering significance, in that measures must be provided to deal with them without damage to the pipeline or its ancilliary components. The fluid transients of interest are treated first in basic terms and then in the context of solids suspensions.

2.1 FLUID FRICTION

Fluids inside pipelines invariably require a pressure gradient to maintain them in steady flow. The pressure gradient (∇p) can be determined from the shear stress (τ) developed by the fluid at the pipeline wall. For a Newtonian fluid, this is in turn governed by fluid viscosity (μ) and wall shear rate ($\dot{\gamma}$). Pressure gradient is usually expressed non-dimensionally, known as the Darcy friction factor (f), for which the normalising scale is the product of velocity pressure ($\frac{1}{2}\rho u^2$) and the inverse of pipeline diameter (D), where ρ and u represent the density and mean velocity of the fluid concerned. For laminar flow through a pipe of circular section, the parabolic velocity profile form can be used to calculate wall shear rate and close the problem:

$$\dot{\gamma} = 8uD^{-1} \qquad \text{Application of parabolic velocity profile} \qquad (1)$$

$$\nabla p = 4\tau D^{-1} \qquad \text{Force equilibrium of pressure and shear stress} \qquad (2)$$

$$\tau = \mu\dot{\gamma} \qquad \text{Definition of Newtonian viscosity} \qquad (3)$$

From equations 1, 2 and 3, we can develop an expression for pressure gradient in terms of mean velocity, pipe diameter and fluid viscosity. In dimensionless form, this becomes an expression of friction factor in terms of a Reynolds number, the ratio of inertial to viscous fluid forces:

$$\nabla p = 32\mu u D^{-2} \qquad \text{Combination of above three equations} \qquad (4)$$

$$f = 2D\nabla p \rho^{-1} u^{-2} = 64\ \mathrm{Re}^{-1} \qquad (5)$$

where $\mathrm{Re} = \rho u D \mu^{-1}$

Equations of the form of equation 5 have great universal significance in nearly all fluid mechanical phenomena. Drag effects on bodies in flight, power requirements for fluid mixing equipment and the flow of non-Newtonian substances are all described by formulae like equation 5. The form of the Reynolds number may vary, as may that of the friction factor and the value of the numerical coefficient. The equation is only valid, however, for laminar flow. It is worth noting at this point that some researchers prefer the Fanning friction factor (f'), defined in terms of the wall shear stress instead of pressure gradient:

$$f' = 2\tau\rho^{-1}u^{-2} = 16\ \mathrm{Re}^{-1} \qquad \text{for laminar flow} \qquad (6)$$

It has been argued that the Fanning friction factor is more fundamental in concept, as it relates shear stress directly to velocity and fluid properties. The Darcy definition, however, is more convenient in terms of pipe flow.

Most practical commercial pipelines operate in the turbulent flow regime, for which momentum transfer takes place by means of a spectrum of eddies. Much bulk mixing takes place across the diameter of the pipe and fluid inertia becomes significant. An approximation for the friction factor in smooth pipes is given by the Blasius formula:

$$f = 0.316\ \mathrm{Re}^{-0.25} \qquad (7)$$

if $\mathrm{Re} \geqslant 3000$

It is of interest to note that a Reynolds number of 3000, equation 5, gives a friction factor of 0.0213, half that of the prediction of equation 7 of 0.427. It is typical of the transition from laminar to turbulent flow that the friction factor increases. Turbulence in pipes is essentially born of instability; eddies formed at the wall tend to grow rather than decay. As the Reynolds number is increased beyond the transition value, the friction factor will continue to fall (equation 7), though at a slower rate than in laminar flow.

Equation 7 is not quite accurate, especially at Reynolds numbers above about 30 000. An improved formula for turbulent friction factor is the Karman–Nikuradse equation:

$$f^{-0.5} = 2 \log_{10} (\mathrm{Re}.f^{0.5}) - 0.80 \qquad (8)$$

Unfortunately, equation 8 gives an implicit expression for friction factor, difficult to evaluate on a pocket calculator. Furthermore, it is only valid for smooth pipes. As the Reynolds number is increased, the significance of pipe roughness increases as the thickness of the laminar boundary layer at the wall decreases. For a given scale of roughness (k), an approximate formula may be given for friction factor, in terms of a new dimensionless parameter, the relative roughness (k/D):

$$f = 0.25\ (\log\ (0.27\ k/D + 5.74\ \mathrm{Re}^{-0.9}))^{-2} \qquad (9)$$

Equation 9, taken from Miller (15), is an improvement on equation 8 in that it takes account of roughness, gives friction factor directly and is more accurate over the full parameter range. A more rapid alternative may be to use the 'Moody Chart', a friction factor graph as plotted in Figure 2. It gives the friction factor over a wide range of Reynolds numbers and pipe roughnesses and has been developed by iteration of the Colebrook–White equation, to which equation 9 is a close approximation. Figure 2 also gives approximate uD values for air and water at ambient temperature and pressure.

Most pipelines consist not only of straight lengths of pipe, but also bends, valves, tees and other assorted fittings. Miller (15) gives a comprehensive compilation of the pressure drop (Δp) across such components, usually expressed in the following terms:

$$\Delta p = K\rho u^2/2 \qquad (10)$$