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A Discussion on Modeling Abrasive-Wear in Slurry Systems

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ABSTRACT

Slurry systems are used for processing and transportation of mined ore, mineral or metal concentrates, tailings, solid wastes, etc. in the oil and gas, mining and wastewater industries. The handling, processing and transporting of these slurries can result in significant equipment wear. Depending on the solid concentrations and equipment geometry, there are different kinds of wear that can occur, such as impact or erosion and abrasion. Understanding the types of wear or damage mechanisms will aid in selecting and/or developing appropriate models to predict wear rate. In this work, we discuss abrasive wear in the context of slurry flow conditions, available models and their shortcomings, and application of computational fluid dynamics (CFD) to predict abrasive wear. In addition, some suggestions for modeling strategies have been presented and discussed.

Key words: Wear; Pipeline; Slurry; Abrasion; CFD; modeling

INTRODUCTION

Slurry systems can be found in several industrial applications. For example, they are used for bitumen extraction and transporting tailings to deposit in Canada's oil sands industry. In the mining and mineral industry, they are part of transporting system for mineral or metal ore concentrates and tailings. Dredging, aggregates, oil and gas, wastewater, solid wastes, and other soft-rock mining industries also use slurry systems for transporting and/or processing of their products. The handling, processing and transporting of these slurries can result in significant equipment wear. Admittedly, wear in slurry systems is so important that a large amount of scientific and engineering literature already exists on this subject in the

public domain. In general, wear affects the hydraulic and mechanical performances of slurry systems, reduces their reliability and, above all, their operational life. Most slurry applications are either open to atmosphere resulting in significant air ingress and entrainment or the process may require air or gas as in the case of short length oil sands hydrotransport pipelines and carbon dioxide-based tailings consolidation technologies. In addition, in such systems, the liquid phase may have its own natural dissolved gases. The presence of these dissolved gases in the slurry can lead to corrosion and/or erosion-corrosion if the system wall material is corrosion susceptible. There is a lot of literature on corrosion related damage mechanisms including some of our previous works¹⁻⁷.

There are several mitigation strategies available to designers, engineers and operators for these damage mechanisms. One obvious strategy is to employ wear resistant materials. This strategy at best only extends the wear life of the system and does not necessarily remove damage mechanisms. For systems where particles are nuisances and not part of the process, technologies such as effective sand management technologies can be implemented as in the case of some oil and gas facilities. The total cost of ownership for both these strategies can be prohibitive. Another strategy is to utilize a tool or model to predict the system wall material loss, identify risk, aid in material selection and/or development of a process-based maintenance schedule. Through an informed design decision, both capital expenditures (CAPEX) and operation and maintenance (OPEX) costs can be reduced. Models can also be employed for technology assessment and product evaluation. These benefits are realized if the models are based on underlying mechanics or phenomena in the real systems. Therefore, understanding the types of wear or damage mechanisms will aid in selecting and/or developing appropriate models to predict wear rate.

SLURRY FLOWS AND WEAR MECHANISMS

Slurry Flows

Slurry pipelines are used in many industries. These pipelines can be grouped as: (i) short hauling transportation or process, e.g. dredging (< 300 m long), process plants (< 300 m long) and tailings (~3 km long), and (ii) long-haul duties which are mostly for transporting mineral products which can be many hundreds of kilometres long. Although the information about global slurry pipelines are somewhat scarce it is expected that the total installed length will be much lower than that of hydrocarbons long distance (> 1 km) pipelines. Our uncomprehensive review estimated that, there are at least 5,000 km total installed length of slurry long distance pipeline globally. A typical pipe diameter ranges from 178 mm (7 inches) to 813 mm (32 inches) for transporting various products. Industrial slurry pipeline systems consist of several components such as straight pipes, pumps, and fittings including elbows/bends, expanders, expansion barrels, laterals or wyes, valves, impact spools, *et cetera*. All these components are prone to wear. Pumps, especially centrifugal type, have several wet wear parts including impeller, casing and throatbush with each having different damage mechanisms. The wear mechanisms in fittings are also different from straight sections of the pipeline due to curvature effect and flow disturbance. While the wear rate might be higher than straight section, the total length is a small portion of a typical slurry pipeline of several kilometers, and therefore, this discussion will tend to focus on damage mechanism in horizontal straight pipeline. It is worth mentioning that, because of relatively higher wear rate in these fittings, they are known to pose higher risk to asset integrity than that of the straight section. Therefore, it comes as no surprise that most of the previous literature and models on wear have focused on these components.

Slurry flow is generally an incompressible two-phase flow consisting of solids and liquid. The solids range in sizes from low as sub-microns to as large as 200 mm (8 inches). This wide range of solid sizes have led to some classifications as non-settling and settling slurries. Usually, non-settling slurry contains fine solids such that the mixture can be considered a “continuum” and assumed to behave like a fluid. For turbulent non-settling slurry flows, usually the ratio of gravity particle settling time and particle residence time in the pipe flow is used, or alternatively, Stokes number. Thus, turbulence fluctuation velocity is significantly larger than particle settling velocity. For silica-based solids and most industries, this corresponds to particles smaller than 44 μm , and as such slurries are considered as non-settling.

Normally the rheology of settling slurries cannot be measured due to settling nature of the solids. For complex slurries such as non-segregating slurry, the solids size distribution is so broad such that the coarse solids will settle through the fine solids-liquid mixture. This type of slurry can be treated as two-phase flow where fine solids-liquid mixture is considered as continuous phase (fluid) and the coarse particles are considered dispersed phase. One can then easily characterize this continuous fluid. Also, it is worth mentioning that, the *in-situ* rheological behavior of this slurry type may not be the same as that obtained from off-line rheological characterization.

In addition, slurry can also be classified as dilute or dense. Many authors, especially, Elghobashi⁸ have approached it from modeling perspective using phase coupling. The demarcation between dilute and dense is typically given as 0.1 v/v%. However, in practice, when the volume concentration of the dispersed phase is less than 5% it is considered dilute and dense otherwise. In a dilute slurry system particle-particle interaction is minimal and can be neglected. For dense (solids concentration > 5 v/v%), particle-particle interaction is important as well as fluid-particle, fluid-wall and particle-wall interactions.

For dense settling slurry pipelines, slurry flows have several flow patterns and where possible, a designer or an operator adopts a specific regime to meet system reliability and power consumption objectives. Nowadays, slurry piping systems are designed with a holistic approach to achieve the optimal cost-effective and environmentally responsible manner. Unfortunately, in some situations, there is no choice in deciding on flow patterns. Depending on the slurry flow regime, the flow and material interaction mechanisms will be different which in turn affects the pump power consumption and pipeline wear life. Figure 1 shows a schematic representation of the slurry flow regimes commonly found in practical applications. The regimes are driven by operating velocity relative to deposition velocity of the solids. Figure 1 (a, b) tends to occur when operating velocity is less than or around deposition velocity whereas higher operating velocity gives rise to Figure 1 (c, d). The demarcation of these regimes is somewhat subjective although other works such as D'Souza et al.⁹ and Wasp et al.¹⁰ attempted to quantify them. For some medium to broad distribution of solid particles, all the four flow regimes can exist in a single piping system.

The regimes shown in Figure 1 are valid when solids are transported via flow turbulence momentum exchange. For very large solids, they tend to be transported by pressure difference across them and/or incoming eddies in the outer region of the flow, therefore, solids will be transported in stratified regime akin to Figure 1b. Wilson & Sellgren¹¹ indicated that any "particle" larger than $0.018D$ with D being pipe inner diameter will be transported as fully-stratified flow regime. Note that, this value is somewhat anecdotal and based on the assumption that the pipeline operating velocity is about 25-50% higher than the deposition velocity since our experience shows that fully-stratified flow regime does not exist for particles larger than $0.07D$ when operating higher than 200% of the deposition velocity. For smaller silica-based solids, usually less than 200 microns will be transported fully suspended flow (Figure 1d). Similarly, this upper value of particle size resulting in fully suspended flow may be empirical since solids density and/or fluid viscosity will affect settling velocity. However, one can estimate the corresponding value by accounting for solids density and/or fluid viscosity deviation from silica (2650 kg/m^3) and water viscosity, respectively. The above notes also indicate that, the use of solids concentration 5 v/v% or any value to distinguish between dilute and dense may also have limitation. A system may be dilute globally but locally it will have particle-particle interaction as a result of operating conditions. A typical Canadian diluted-bitumen crude in pipeline contains about 1.0 wt.% sediments with particle size usually less than 100 microns which can be considered as diluted slurry system. However, due to relatively less flow turbulence and geometric effect, these particles tend to collect at the pipe bottom increasing local concentration significantly higher than this 5 v/v% value. Similar observation has also been found in once-through-steam-generator (OTSG) boiler tubes at a Canadian *in-situ* oil sands operation. Such change in flow regime will affect local particle-particle, fluid-particle, fluid-wall and particle-wall interactions, consequently the wear magnitude and pattern.

Wear Mechanisms

Slurry flow is a two-phase flow of solids and liquid or fluid, where the latter is considered a carrier (continuous phase) of the former (dispersed phase). These phases interact with each other. There are four main interactions: particle-particle, fluid-particle, fluid-wall and particle-wall. The particle-wall interaction defines the damage mechanism at the wall. However, this interaction is also a function of particle dynamics in the near wall region. This dynamic is influenced by particle-particle and fluid-particle interactions in that region. Fluid-wall interaction is influenced by fluid viscosity. As the fluid viscosity increases the boundary layer thickens, and near-wall fluid velocities and turbulence intensity reduce. Therefore, there will be retardation of particles occurring in this near-wall because of cushioning effect of the fluid between the approaching solid particle and the wall surface. For dense slurry which tends to consist of very fine solids that usually modify the liquid properties, wear due to impact may be less important. This is because the film of fluid separating the advancing particle from the surface must be displaced and will need a certain amount of energy thereby resulting in a smaller angle of impact and deceleration of the advancing particle. Depending on the particle concentrations and/or equipment geometry, there are different kinds of wear mechanisms that can occur, such as impact or erosion, adhesion, and abrasion. Figure 2 shows relationship among the wear mechanisms.

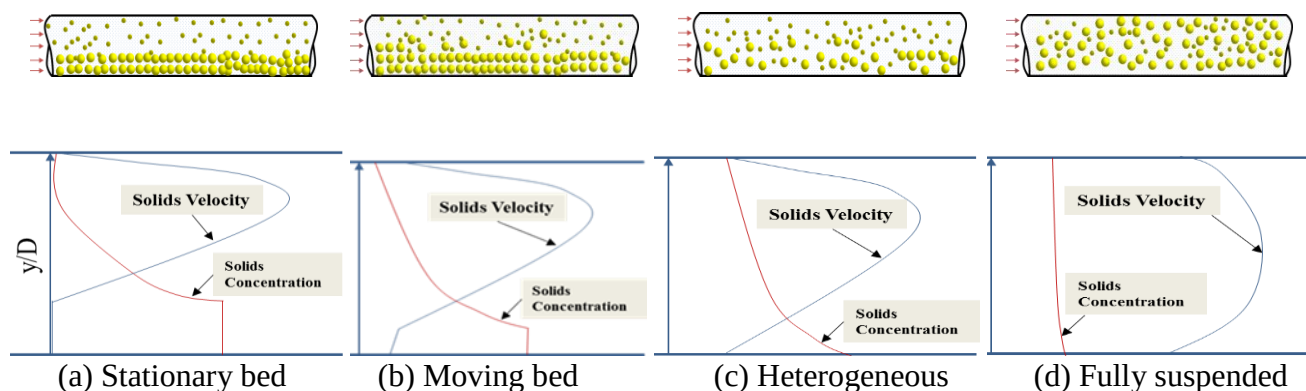


Figure 1: Schematic representation of reported flow patterns in horizontal slurry pipeline

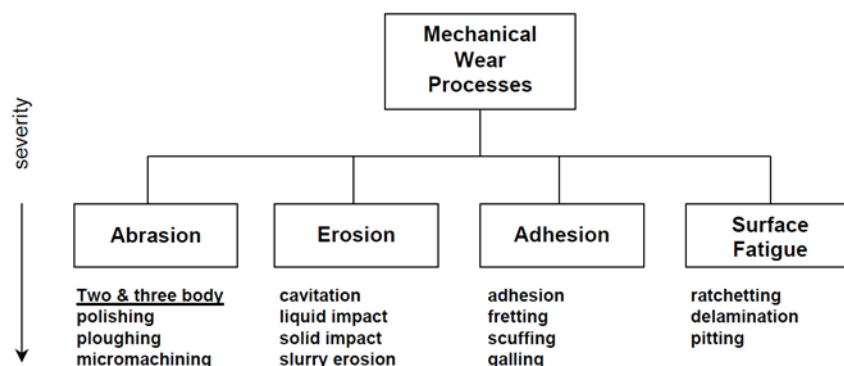


Figure 2: Different wear mechanisms¹²

For dense slurries, Shook and Roco¹³ stated that there are three different types of wear mechanisms: directional impingement from solid particles, random impingement as a result of the fluctuating turbulent motion, and friction of a sliding bed pressing onto the wall. Both directional and random impingements are erosive processes which will be called erosive wear whereas the sliding bed is more typical of abrasion. These mechanisms are demonstrated in the Figure 3. Erosive wear depends predominantly on

the angle of particle impingement with the material surface and the impact velocity. Particle impingement angles vary between 0 and 90 degrees and depend on both fluid-particle and particle-particle interactions. For dilute systems, particle-particle interaction is less important, and particles interact only with the carrier fluid before impact. Therefore, fluid drag and/or lubrication forces define the particles trajectories and velocities. Abrasive wear on the other hand is controlled by the normal force and amount of solids in contact with the pipe wall. The sketch in Figure 3b shows sliding-abrasion in the context of slurry flow which usually involves a bed of contact-load particles bearing against a surface and moving tangent to it. This mechanism can occur anywhere around the pipe circumference. However, due to the direction of the gravitational force, usually the wear rate is significantly lower at the pipe top than the pipe invert. Both erosive and abrasive wear tend to be characterized by several damage mechanisms such as micro-cutting, grooving or ploughing, plastic deformation, fatigue, surface indentation, et cetera as shown in sample scanning electron microscope images in Figure 4.

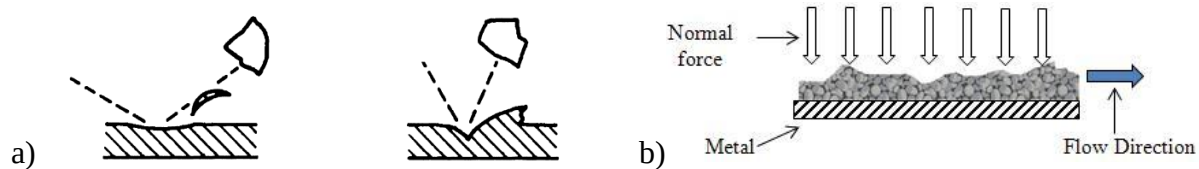


Figure 3 – Conceptual sketch of wear mechanism in dense slurry: (a) erosion¹³ and (b) abrasion

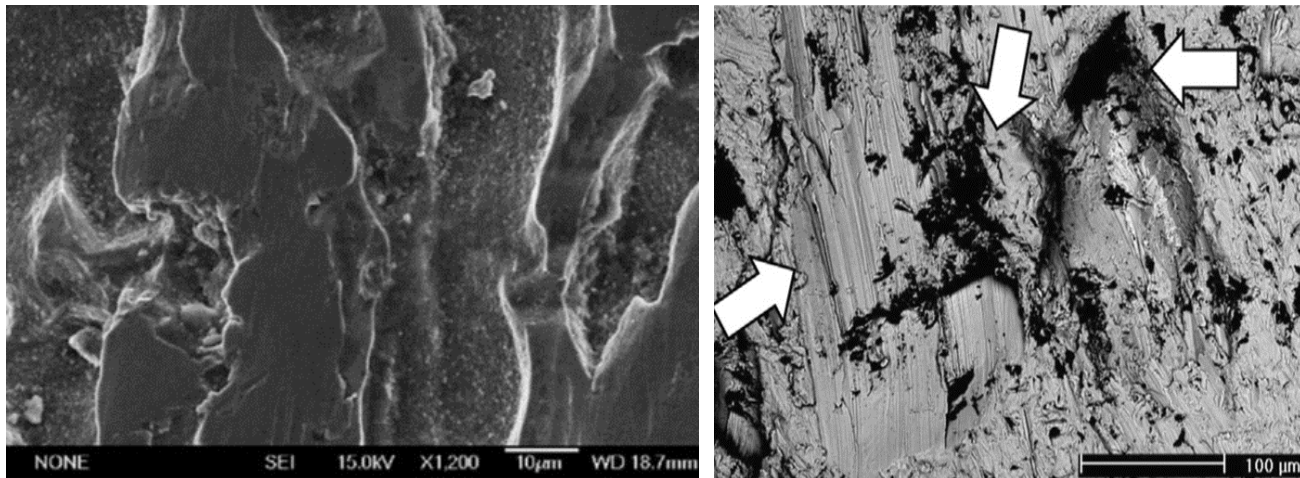


Figure 4 – Samples of damage mechanism: erosive¹⁴ and b) abrasive¹⁵ wear

Both of these wear mechanisms occur simultaneously in most slurry systems, however, which one is dominant is system specific. For dense horizontal slurry pipeline, the particle dynamics near wall depend on particle-particle, fluid-particle, fluid-wall and particle-wall interactions. These interactions also relate to slurry flow regimes discussed in previous paragraphs for Figure 1, and therefore define wear magnitude and pattern. Particle-wall interaction mainly determines wear, but this interaction is also influenced by particle-particle, fluid-particle and to a lesser extent fluid-wall interaction. Slurry flow regimes associated with suspected wear patterns are presented in Figure 5. From risk perspective, where one is interested in a peak wear magnitude, it is worth the effort to perform analysis of effect of any process condition changes on the wear. This is because changing the flow regime from moving bed through fully suspended may increase peak wear magnitude, change peak wear location, and/or decrease of wear life in some instances.

Slurry pipeline systems can have many piping orientations such as vertical or inclined depending on ground topography, in plant equipment, space, cost, and/or owner's preference. It is common to have all these orientations in a typical piping system. The solids distributions are not the same in each orientation

thereby affecting wear pattern and magnitude. Usually, vertical piping including risers tends to have an even or uniform wear pattern whereas horizontal piping generally has those shown in Figure 5. Vertically oriented piping tends to have lower wear rates than that in horizontal orientation. The inclined piping wear pattern is typically in between these two wear patterns. Normally, the angle of inclination, positive or negative affects the magnitude of the wear with higher wear rate in negative (downhill or negative elevation change) than positive (uphill or positive elevation change).¹⁶ This difference is mainly due to slip between the phases as a result of phase density difference and gravity. Note that this might not always be the case, especially for systems which have solids inertia force at near or below gravitational force. This is because large solids can stay and tumble in place, consequently leading to higher wear in this region which can be higher than that in horizontal orientation.

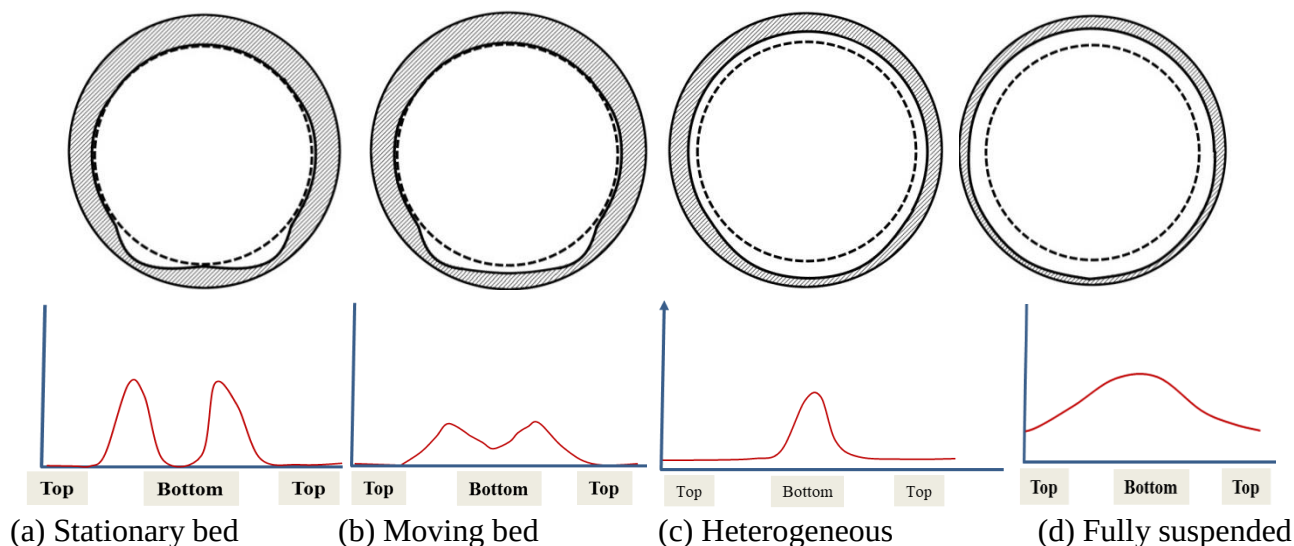


Figure 5: Conceptual representation of wear patterns in horizontal slurry pipeline based on suspected slurry flow regimes

Understanding the dominant wear mechanisms introduced here for slurries, erosion and abrasion, in application will guide both material and model selection. According to previous works (e.g. Finnie and co-authors¹⁷⁻²⁰ and Brach²¹), brittle materials may not be considered for erosive dominant wear because of high potential of plastic deformation and fatigue damage mechanism. Similarly, for abrasion dominant wear where damage mechanisms are cutting and gouging, one may not consider ductile or elastomer materials. These damages are significant for elastomer materials when slurries contain sharp and/or large solids.

It is clear from the discussion given in the previous paragraphs that, there are several parameters that will influence the wear, and any tool development should incorporate them. In literature several parameters have been identified, and Table 1 and Table 2 list them. In general, the factors listed in both tables are not only interrelated but intimately entangled such that they cannot be investigated independently, and those observations, comments or notes in the tables should be treated with caution. Similarly, any tool based on their independent investigation may not provide accurate results. For modeling, one can use dimensionless parameters to reduce any effect on inter-relation.

Table 1: Effect of Slurry Flow Parameters

Variable	Effect on Wear with Variable Increase	Comments (all other variables held constant)
Solids Concentration (bulk)	Wear Increase	- Wear increases with bulk solids concentration (dilute to dense) due to more particles interacting with the wall at higher concentrations - Wear tends to be independent or even decrease at higher concentrations (> 25 v/v% for silica sands)
Solids Concentration (local)	Wear Increase	- Particle settling results in a vertical concentration gradient over the pipe diameter: lower at pipe top and higher pipe invert - Vertical concentration distribution correlates strongly with the wear pattern
Velocity (bulk)	Wear Increase	- Generally, average wear rate increases with bulk velocity raised to some exponent n ✓ Ratio of average wear rate to peak wear rate tends to increase as bulk velocity to deposition velocity ratio (V/V_C) increases - Peak wear is pronounced when V is only slightly higher than V_C - Wear becomes evenly distributed for $V \gg V_C$
Velocity (local)	See Comments	- Local wear rates are determined in part by the local velocity distribution - Particle settling behavior affects local wall velocities ✓ Tends to counteract the effect of the vertical concentration gradient - In general, local velocities at all locations increase with bulk velocity
Pipe Diameter	Wear Decrease	Wear tends to decrease because turbulence level decreases and deposition velocity increases. Peak wear rate might increase but average wear rate might decrease governed by V/V_C
Viscosity	Wear Decrease	For turbulent flow, higher viscosity fluid enhances particles suspension with reduced particle-wall interaction
Temperature	See Comments	- Temperature will only affect viscosity dependence which in turn affect particle-wall interaction, see viscosity effect - For some elastomers, wear resistance will depend on its specifically designed formulation temperature
Pressure	See Comments	Pressure does not seem to affect wear in metallic materials, may affect some of the elastomers
Flow Regime	See Comments	- Many different slurry flow regimes exist which result in many different wear mechanisms - Transition between flow regimes can significantly alter the shape of wear pattern
Pipe Orientation	See comments	- Wear decreases from horizontal to vertical piping - Wear increases from positive elevation to negative elevation when solids inertia force (large particles) is greater than gravitational force