Prediction of uneven wear in a slurry pipeline on the basis of measurements in a pot tester

Rajat Gupta, S.N. Singh, V. Sehadri *

Applied Mechanics Department, Indian Institute of Technology, Hauz Khas, New Delhi-110016, India

Received 4 July 1994; accepted 24 November 1994

Abstract

This paper reports a systematic study conducted on a pot tester to establish the effect of velocity, concentration and particle size on erosion wear. Two correlations have been proposed, based on the data generated for equisized particulate slurries in the pot tester, to predict the expected erosion wear for two pipe materials, namely brass and mild steel. The weighted mean diameter has been established as the best representative diameter for the multisized particulate slurries. The proposed correlations have been used to predict the extent of uneven erosion wear in a slurry pipeline using local concentration, local effective particle size and average velocity. The comparison between predicted and experimental results shows agreement within ±13.5% for brass and ±14% for mild steel.

Keywords: Slurry pipeline; Erosion wear; Pot tester; Uneven wear

1. Introduction

A proper understanding of the phenomenon of wear in slurry pipelines is essential for any designer of a slurry transportation system. Wear is defined as the progressive volume loss of material from a surface due to corrosion and/or erosion. Corrosion in slurry pipeline is a chemical phenomenon strongly dependent on the extent of dissolved oxygen present in the slurry. Erosion wear takes place in pipelines due to two mechanisms, namely "cutting" and "deformation". Wear rate due to erosion is comparatively higher than the corrosion and hence needs more attention from the designer. The extent of wear affects the life span of the pipeline and hence the initial cost. Several studies on erosion wear reported in the literature [1-5] have clearly identified, for any given piping system, the dependence of erosion wear on parameters like velocity, concentration, particle size and relative hardness of the slurry and pipeline materials etc. Rabinowicz [6] established the strong dependence on the particle size of wear. Bain and Bonnington [7] conducted experiments on a simulated drum test rig and showed that erosion wear is proportional to (particle size)$^{n}$. The variation in the power in the particle size dependence reported by different researchers may be due to the fact that the shapes of the various sizes of particles used in different studies were not identical and that the effect of particle size was affected by shape difference. Tarjan and Debreczeni [8] have suggested that erosion wear is directly proportional to velocity but have no extensive evidence to support their suggestions. Studies have found that the absolute erosion rate is proportional to $v^n$, where $n$ can lie between 1 and 3.5 [11]. Karabelas [21] carried out a systematic study with sand-water slurry and showed that the value of $n$ could lie between 2 and 3. The scatter in the values of the power index ($n$) of the velocity obtained by different investigators could possibly be due to the variation in the wear mechanisms occurring in the different experimental situations as well as to other factors such as the properties of the slurry itself.

Altaweel [9] analyzed the phenomenon of wear using a single particle concept and concluded that wear is directly proportional to concentration if each impact is equally effective. James and Broad [10] observed that wear rate varies as (particle size)$^{0.6}$. Elkholy [11] has carried out a systematic study on the phenomenon of abrasion wear in slurry pumps and has shown that wear is dependent on velocity, concentration, particle diameter, impingement angle and relative hardness. The final equation for wear for cast iron has been given by him as,
where \( n \) is a function of \( H_1/H_2 \).

Although there has been considerable research work done by various research groups on wear rate in a slurry pipe line, it has not been so far possible to obtain a universal correlation valid for all types of slurries. Moreover, majority of the studies are confined to equisized particulate slurries and the data related to multisized particles is very limited. In any commercial slurry pipe line the range of particle size distribution is three or more orders of magnitude and at any given operating condition this gives rise to skewed concentration and velocity profiles across the pipe cross section [12] which may be responsible for uneven wear in pipelines. Further, larger sized particles are more unevenly distributed as compared to finer ones and it further enhances the unevenness of the wear rate in the pipeline. The bottom portion of the slurry pipelines is subjected to much higher wear rate as compared to the top portion. A knowledge of the extent of uneven wear at any operating condition is essential to predict the useful life of the pipeline. The actual wear rate tests in pilot plant test loops are very expensive and time consuming. Hence, it would be very useful to develop a methodology for predicting the local erosion rate in a slurry pipe on the basis of measurements in an accelerated wear test rig like a pot tester. The present paper is an effort towards developing an equation on the lines of the pump Eq. (1) for commercial slurries on the basis of data obtained in a pot tester. The pot tester designed and fabricated by Gupta et al. [13] has been used to generate data for erosion wear in an accelerated manner. It is similar to the one used by Tsai et al. [14] and consists of an aluminium cylindrical tank, shaft, stirrer arrangement, set of bearings, motor, rotating arms etc. Fig. 1 gives the schematic diagram of the pot tester.

A steel shaft having a diameter of 10 mm had a mixer propeller attached to it at the bottom. The function of the mixer propeller was to keep the slurry in a suspended state in the aluminium tank. Slightly above the propeller, a brass sleeve of 65 mm length and 20 mm diameter has been provided which has the provision for fitting four flat side arms holding the wear test pieces. This shaft rotated inside a cylindrical tank having a diameter of 205 mm and a height of 135 mm. Four U-shaped baffles are also provided on the cylindrical tank walls in order to keep the slurry in a suspended state and also break the rotational motion created by the propeller. The assembled system had a lid of 12 mm thick perspex sheet to allow visual observation. The shaft was held in position by the two bearing systems provided on the lid and was rotated at different speeds by a variable speed motor.

2.2. Pilot plant test loop

The pilot plant test loop facility in the Fluid Mechanics Laboratory of I.I.T., Delhi (Fig. 2) has been used to generate data on uneven wear. It consists of a closed circuit pipe test loop of 55 mm diameter having 60 m length, a mixing and a measuring tank with stirrer arrangements, a transparent observation chamber and a special test fixture for conducting uneven wear studies. The pilot plant test loop has been described in detail by Gupta et al. [12]. For carrying out the uneven
Stirrer (in horizontal plane)
Wedge flow meter
Observation chamber

Fig. 2. Schematic diagram of the pilot plant.

Block for holding wear pieces at 0°, 90°, 180° and 270°
MS Plate for fixing wear pieces

All dimensions are in mm

Fig. 3. Assembled view of the pipe spool piece for the measurement of uneven wear.

Table 1
Range of parameters investigated

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) For equisized particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Solid concentration (% by wt.)</td>
<td>15, 25, 35 and 45</td>
</tr>
<tr>
<td>2.</td>
<td>Velocity (m/s)</td>
<td>3.92, 5.49 and 8.06</td>
</tr>
<tr>
<td>3.</td>
<td>Particle size (μ)</td>
<td>448.5, 223.5, 112.5 and 37.5</td>
</tr>
<tr>
<td>(b) For multisized particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Solid concentration (% by wt.)</td>
<td>15, 25, 35 and 45</td>
</tr>
<tr>
<td>2.</td>
<td>Velocity (m/s)</td>
<td>3.92, 5.49 and 8.06</td>
</tr>
</tbody>
</table>

For the study of accelerated wear studies, two materials, namely brass and mild steel were selected. Brass was selected for its ductility and stiffness as erosion wear for such materials is faster. Mild steel was selected to represent the commonly used pipe material in the slurry pipelines. Each test specimen was 45 mm long and was cut from a tubing of 3 mm diameter. Table 1 gives the range of parameters over which measurements have been made. For uneven wear studies, test specimens selected were again brass and mild steel. These specimens were cut from a pipe piece of 55 mm internal diameter so that they could be mounted flush with the inside surface of the pipe. The size of each specimen was 32 mm
Table 2
Properties of tailing material. (i) Overall specific gravity of the solids, 2.82; (ii) static settled concentration, 60.56 wt.%; (iii) particle size distribution in the fresh sample (collected from pilot plant, wet sieving over B.S. 200 mesh and hydrometer analysis)

<table>
<thead>
<tr>
<th>Particle diameter (μm)</th>
<th>% finer (wt.%)</th>
<th>Particle diameter (μm)</th>
<th>% finer (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>100.0</td>
<td>75</td>
<td>47.0</td>
</tr>
<tr>
<td>600</td>
<td>99.4</td>
<td>45</td>
<td>35.0</td>
</tr>
<tr>
<td>300</td>
<td>93.4</td>
<td>28</td>
<td>18.0</td>
</tr>
<tr>
<td>200</td>
<td>83.4</td>
<td>14</td>
<td>10.0</td>
</tr>
<tr>
<td>150</td>
<td>77.5</td>
<td>8</td>
<td>6.0</td>
</tr>
<tr>
<td>106</td>
<td>68.9</td>
<td>4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 3
Properties of tailing material. Rheological data on the slurry of tailings (using Weissenberg Rheogoniometer). Notation: \( C_w \), concentration of solids (wt.%); \( T \), temperature of the slurry (°C); \( \tau_y \), yield stress (dynes cm\(^{-2}\)); \( \eta_b \), Bingham–Newtonian viscosity (cP); \( \eta_w \), viscosity of water (cP); \( \eta_0 \), \( \eta_b / \eta_w \).

<table>
<thead>
<tr>
<th>( C_w )</th>
<th>( T )</th>
<th>( \tau_y )</th>
<th>( \eta_b )</th>
<th>( \eta_w )</th>
<th>( \eta_0 )</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>19</td>
<td>0</td>
<td>1.03</td>
<td>1.0</td>
<td>Newtonian</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>0</td>
<td>1.141</td>
<td>1.03</td>
<td>1.108</td>
<td>Newtonian</td>
</tr>
<tr>
<td>20</td>
<td>19</td>
<td>0</td>
<td>1.271</td>
<td>1.03</td>
<td>1.234</td>
<td>Newtonian</td>
</tr>
<tr>
<td>30</td>
<td>19</td>
<td>0</td>
<td>1.509</td>
<td>1.03</td>
<td>1.465</td>
<td>Newtonian</td>
</tr>
<tr>
<td>40</td>
<td>19</td>
<td>0</td>
<td>1.982</td>
<td>1.03</td>
<td>1.924</td>
<td>Newtonian</td>
</tr>
</tbody>
</table>

Table 4
Composition of manually prepared multizized solid samples used in the study

<table>
<thead>
<tr>
<th>Sample</th>
<th>% of solids in each size fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>448.5 μm</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>7.5</td>
</tr>
</tbody>
</table>

<X 15 mm. The specific gravity of brass having a composition of 70% copper and 30% zinc was 8.5 and Rockwell hardness was 68 (scale-B) whereas for the mild steel the specific gravity was 7.860 and Rockwell hardness was 84 (scale-B).

3. Properties of the solid particles used

Tailing material from a processing plant at a copper mine has been used in the study. The overall specific gravity of the material was 2.82. The properties of the solid material are given in Tables 2 and 3. From the tables it is seen that the solids have wide particle size distribution having 83.4% of the particles finer than 200 μm and 47% are even finer than 75 μm. Measurement of relative viscosity of the slurry at different concentrations showed the slurry to be Newtonian at all concentrations tested (Tables 2 and 3).

4. Experimental procedure and data analysis

Erosion wear for brass and mild steel test pieces has been evaluated for equisized and multizized particulate slurry slurries in the pot tester. For the study on equisized particles, the selected B.S. sieve fractions (with average diameters) were -25 + 50 (448.5 μm), -50 + 100 (223.5 μm), -100 + 200 (112.5 μm) and -200 (37.5 μm). For each particle size, experiments have been conducted at four solid concentrations, namely 15, 25, 35 and 45 wt.% and three surface velocities, namely 3.92, 5.49 and 8.06 m s\(^{-1}\). The multizized particulate slurries were prepared by manually mixing different size fractions in different proportions. The various combinations studied are tabulated in Table 4. Sample 5 in the above table corresponds to the size distribution present in the original sample. The experiments were conducted in the pot tester at the same concentration and the three velocities for each of the above five samples. It was established that the effect of particle attrition could be minimised by replacing slurry every half an hour (Table 5). Thus the slurry in the pot tester was replaced during each test after every half an hour. The erosion wear was measured every half an hour for a total of 2 h. Erosion wear was determined using weight loss technique. Weight loss was measured in an electronic balance having a least count of 0.1 mg. This ensured accurate meas-
urement of erosion wear. Proper care was taken to clean the specimens which involved washing with tap water, rinsing in acetone and drying in a hot air oven between each weighing. From the measured weight loss after the specified test run, the loss in wall thickness was calculated using the following relation [10]:

\[
\text{wear rate in mm year}^{-1} = \frac{W_L}{S \times \text{Surface area}} \times \frac{8760}{T} \times 10^3
\]

where \(W_L\) = measured weight loss (kg); \(S\) = relative density of pipe material; \(T\) = duration of test (h).

The uneven wear rate studies in the pipe have been conducted at two velocities for three concentrations, namely 17, 25.5 and 34.5 wt.%. For each concentration, the pilot plant was run for 20 h to have reasonable erosion-wear which could be measured accurately and to avoid particle attrition effect. During the test the efflux concentration and flow velocity were monitored regularly. Efflux samples were analyzed for the particle size distribution (PSD) at regular intervals in order to ensure the absence of any significant attrition. The concentration profile was determined experimentally by collecting concentration samples isokinetically from different heights from the bottom of the pipe (BOP) by traversing a sampling tube with a specially designed traversing mechanism. Samples collected were also sieve analyzed for the determination of percentage of individual size fractions. This was used to calculate the effective mean diameter of the slurry at any given location inside the pipe. After 20 h of run, the wear pieces were washed in acetone, dried and weighed in an electronic balance.

5. Results and discussion

5.1. Functional dependence of erosion rate on various parameters

Results from the pot tester for equisized particles have been used to evaluate the functional relationship for erosion wear. Fig. 4 gives the sample results and shows the variation of erosion with time for two concentrations (namely 25 and 15 wt %) at three velocities (namely 3.92, 5.49 and 8.06 m s\(^{-1}\)) for particle diameters of 112.5 \(\mu\)m and 223.5 \(\mu\)m. It is seen from Fig. 4(a) that for a given concentration, erosion wear increases with increase in velocity and for a given velocity, erosion wear also increases with increase in concentration but this increase is comparatively much smaller. Fig. 4(b) shows similar variation as Fig. 4(a) for a particle size of 112.5 \(\mu\)m. Comparing the two Figs. 4(a) and 4(b), it can be concluded that erosion wear decreases with decrease in particle size. The results follow the expected trend quoted in the literature.

A total of 48 data points for each material have been generated from the pot tester using equisized particulate slurries. On the basis of investigations of Ahmed Elkholy [11] the functional relationship for erosion wear has been assumed to be of the form:

\[
E_w = k V^m d^n C_w^p
\]

where \(k, m, n\) and \(p\) are constants and are to be evaluated for the combination of pipe material and the slurry material. The best values of \(k, m, n\) and \(p\) have been evaluated by making use of the 48 data points generated on the pot tester for brass

![Fig. 4. Variation of wear as a function of time (material, brass).](image-url)
with equisized particles. The above equation is simplified by taking logarithms of both sides as

$$\log E_w = \log k + m \log V + n \log d + p \log C_w$$

(3)

The 48 data points are substituted in the above equation to generate 48 equations and these equations are solved using the method of least squares to get the best values of the constants.

This procedure was repeated for mild steel. The final equations obtained are,

$$E_{w\text{ brass}} = 0.178V^{2.4882}d^{0.291}C_w^{0.516}$$

(4)

$$E_{w\text{ mild steel}} = 0.223V^{2.148}d^{0.344}C_w^{0.556}$$

(5)

In the case of an ideal fit, the plot between the measured wear and the wear predicted on the basis of correlations should be a 45° line passing through the origin. The above correlations have been used to predict the erosion wear. The comparison of measured wear and predicted wear for both the materials is shown in Figs. 5 and 6. It is seen that the points are randomly scattered around the ideal line for both the cases and all the points lie within an uncertainty band of ±8.5% for both the materials, namely brass and mild steel. Thus, it can be concluded that the accuracy of the fit is reasonably good. From the above two equations it is observed that the values of indices for concentration and particle size are much smaller for both the materials as compared to the index for velocity. This implies that erosion wear has a much stronger dependence on velocity as compared to concentration and particle size. Hence one could conclude that the indices for concentration and particle size will have less effect on erosion wear than velocity for any combination of solid and pipe material and this view is supported by other studies [1,10,11]. The significant change in the exponent of velocity and the value of $k$ for brass and mild steel will lead to significant change in erosion wear thereby indicating a strong dependence of the exponent and the value of $k$ on the properties of the pipe material like hardness, fracture, toughness, erosion mechanism, solid material hardness etc. Similar observations have been made by other investigators also [5,10,11]. The functional dependence of $k$ and $m$ on the material parameters can be quite complex and at present the available data is insufficient to derive the exact form of these relationships. One can only conclude that the actual values of $k$ and $m$ are dependent on the properties of the pipe material and solid particles. Actual values of these constants have to be experimentally evaluated.

The above equations have been derived based on the data obtained on equisized particles. However, the commercial slurries are always multisized having particle sizes varying over more than 3 orders of magnitude. It is not possible to
(iii) weighted mean diameter, this is defined as

\[ d_{wm} = \frac{N}{1} \sum_{i=1}^{N} f_i d_i \]

where \( N \) = number of size groups into which the total sample is divided, \( f_i \) = fraction of solid retained in a particular sieve, and \( d_i \) = average diameter of the two successive size sieves one on which the solids are retained and the other through which the solids have passed completely.

Erosion wear data was generated in the pot tester for multisized slurries using the pot tester by mixing various size fractions in different proportions. Using the developed correlations and the different diameters, the erosion wear was predicted and compared with the experimental results obtained from the pot tester. Figs. 7–9 depict these comparisons and it is seen that the data points are randomly scattered about the ideal line in all the cases. The percentage variation is ± 10% for brass and ± 11% for mild steel with weighted mean diameter as the effective mean diameter, whereas this variation for \( d_{median} \) is ± 17% and ± 16% for \( d_{mean} \). Hence it can be concluded that the weighted mean diameter is the most appropriate representative diameter in the case of multisized particulate slurries for the purpose of prediction of erosion wear.

In order to further establish the above findings, experiments were conducted in the pot tester with original slurry (sample 5, Table 4). Using the developed correlations and the weighted mean diameter, the predicted erosion wear compares reasonably well with experimental results obtained from the pot tester (see Fig. 7). The agreement is within a
maximum limit of $\pm 10\%$ which is of the same order as before.

5.2. Prediction of uneven wear in a pipe

Having identified the best representative diameter for multisized particulate slurries, the developed correlation for brass has been used to predict the uneven wear in a slurry pipeline. These predictions have been compared with the uneven wear measurements obtained from the experiments on pilot plant test loop. The measured values of local concentration and local weighted mean diameter are used for the prediction of local wear rate in the pipe surface. Fig. 10 shows a typical result for uneven wear, concentration profile and particle size distribution across the pipe cross section. A comparison of predicted wear and measured wear for brass is shown in Fig. 11. It is seen from the figure that the data points are randomly scattered on both sides of the ideal line and the deviation,
Fig. 10. Variation of different parameters across the pipe cross section ($C_w$, 25.5%, $V$, 2.75 m s$^{-1}$).

Fig. 11. Comparison between predicted wear and measured wear using weighted mean diameter as a representative particle size based on the uneven wear studies in a pilot plant test loop (material, brass).

in the range of $\pm$13.5%. Similar exercise has also been done for the mild steel material, which is depicted in Fig. 12. Here also the data points are scattered on both sides of the ideal line and the deviations are in the range of $\pm$14%. The deviations could be attributed to the experimental uncertainties as well as to the use of average velocity in the absence of any data on velocity profiles. The other reasons could be

(i) the inherent error present in the use of weighted mean diameter as the best representative diameter for particle size distribution;

(ii) the relative motion of solid particles with respect to the wear pieces in the pot tester is not exactly identical to that existing in a slurry pipeline. In particular, the impact angle in the two cases could be somewhat dif-
Fig. 12. Comparison between predicted wear and measured wear using weighted mean diameter as representative particle size based on the uneven wear studies in a pilot plant test loop (material, mild steel).

It is interesting to note that in spite of the above limitations the pot tester data can be used to predict the local wear rate in the pipe surface with reasonable accuracy. The present study has also shown that the local wear rate in a slurry pipe is uniquely correlated to the local values of solids concentration, PSD and velocity.

6. Concluding remarks

On the basis of the present investigation and analysis, it can be concluded that the pot tester can be used successfully to develop correlation for the prediction of wear in the case of equisized particles for any combination of pipe and slurry materials. It has also been established that for multisized particulate slurries, the weighted mean diameter is the best representative diameter for the prediction of wear. Hence two correlations have been developed for the prediction of uneven wear for two materials, namely brass and mild steel. In addition, we can use this correlation to predict the local wear rate in a slurry pipe as long as the concentration and size distribution of the solids across the pipe cross section are known. This will enable the designer to evaluate the rate of maximum wear at the bottom of pipe to the average wear rate in slurry pipe for any operating conditions. This criterion can be used to choose optimum velocity for transportation at any given solids concentration subject to the constraints of pumping cost and life of the slurry pipeline. This parameter can also help to decide the time frame for the rotation of the slurry pipeline to further extend its useful life. Thus, the data in a pot tester can be used as a design tool to determine the optimum operating conditions for a slurry pipe line.

Appendix A: Nomenclature

\[ E \] wear in mm year\(^{-1}\)
\[ W \] wear in g
\[ C_v \] concentration by volume
\[ C_w \] concentration by weight
\[ V \] flow velocity, m s\(^{-1}\)
\[ d \] particle diameter
\[ T \] time over which wear has been measured (h)
\[ H_1 \] solid particle hardness (HB)
\[ H_2 \] pipe material hardness (HB)
\[ \alpha \] impingement angle
\[ \alpha_1 \] angle at which wear develops

References