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# LABORATORY-SCALE EROSIVE WEAR MEASUREMENTS CONDUCTED WITH A TOROID WEAR TESTER (TWT)

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The prediction of pipeline wear is complicated by the difficulty in obtaining pipe wear data for tests that are hydrodynamically similar to pipe flows. Unfortunately, pipeline testing of wear, which seems as if it would be the ideal approach, is time-consuming and expensive, and the issues of particle degradation and scale-up of the results to larger pipelines greatly reduce the value of such tests. A number of researchers have conducted tests with Toroid Wear Testers (TWTs), in which a slurry sample is loaded into an apparatus that resembles a wheel that is fitted with material samples. The wheel is then rotated such that the walls of the wheel rotate past the relatively stationary slurry sample, and the mass loss of the material samples is measured. Despite the promise of the TWT, very little has been done in the last decade to better characterize TWT performance. In the present study, a TWT was tested to evaluate its (a) hydrodynamics and (b) wear performance in comparison with pipeline flows. A range of particle diameters, solids concentrations and TWT rotational speeds were tested. Wear rates were determined and flow visualization studies were conducted to better understand the slurry flow inside the TWT. The results reiterate the usefulness of the TWT for pipeline wear tests, showing that the wear behaviour aligns quantitatively with trends presented for other test devices in the literature. However, the results also indicate the importance of ensuring the TWT operating conditions allow for useful inter-test comparisons. For instance, to make comparisons to sliding-bed-dominated pipeline wear it is necessary that the particle size and rotation speed is kept in a narrow operating range.

KEY WORDS: Pipeline wear, toroid wear tester, slurry flow

## 1. INTRODUCTION

The mining and minerals processing industries transport large volumes of mined raw materials in the form of slurries from extraction sites to processing plants (Bhabra 2013; Sadighian 2016). For the transportation of these slurries, the standard, cost-effective, and environmentally responsible practice is pipeline transport (Bhabra 2013). The reliability of these pipelines is important, as any premature failure may result in unplanned and prolonged shutdowns and/or serious environmental problems. To evaluate slurry abrasiveness, determine pipeline wear allowances, and develop new wear-resistant materials, significant field testing is necessary (Cooke et al. 2000; Fotty et al. 2010).

Field-scale tests on operating pipelines have strict limits on testing parameters such as solids concentration, flow velocity, and particle characteristics. Bench-scale tests (e.g. impinging jet, slurry pot, and Coriolis testers) are an alternative that allow a more efficient, controlled approach (Gupta et al. 1995; Gandhi et al. 1999; Cooke et al. 2000; Gnanavelu et al. 2009; Sarker 2016). However, in practice, these tests suffer from their dissimilarity to actual pipe flows (Sadighian 2016). Slurry pipeline wear mechanisms depend strongly on the flow conditions and the way the particles and walls interact (Wood et al. 2004; Sadighian 2016), and thus the amount of wear data resembling pipeline wear mechanisms is limited (Cooke et al. 2000). Recirculating pipe loop results have provided reasonable agreement with field-scale pipelines, but such tests suffer from significant particle degradation (Goosen et al. 1999; Fotty et al. 2010; Sadighian 2016).

The Toroid Wear Tester (TWT), is a device that has advantages over existing methods to simulate pipeline wear. The TWT is a hollow wheel to which test specimens (coupons) are attached at the outer circumference (see Fig. 1). The wheel is partially filled with sand-water slurry and rotated. The TWT (or "wheel stand") has a long history in wear tests, beginning with early tests in coal hydrotransport (Worster et al. 1955), early and recent tests by BHRA Fluid Engineering (Henday 1988; Thomas et al. 2007), and also recently by Patterson and Cooke (Cooke et al. 2000). As noted previously, the similarity between TWT and pipe flow hydrodynamics is critical, but the similarity is not as good as it would seem at first glance (Sarker 2016). In a pipe, the slurry flows past the stationary wall, whereas the TWT walls rotate past the slurry. This rotation induces secondary slurry motion along the walls, leading to a tumbling action in the TWT (Sarker et al. 2015). The slurry flow and particle-coupon contact is also complex and suggests that comparing the TWT with pipe geometries is not trivial. Very little has been done since the studies of Cooke et al. (2000) to characterize the TWT's performance by comparing results with those obtained from pipeline testing.

The aim of the present study is to address this gap in knowledge and more extensively evaluate the TWT as a tool for the study of slurry pipeline wear as well as to pave the way for absolute wear predictions in operating slurry pipelines based on TWT tests. In this work, a TWT nearly identical to that described by Cooke et al. (Cooke et al. 2000) was tested to evaluate its hydrodynamics and wear performance in comparison with pipeline flows. A range of particle diameters, solids concentrations, and TWT rotational speeds

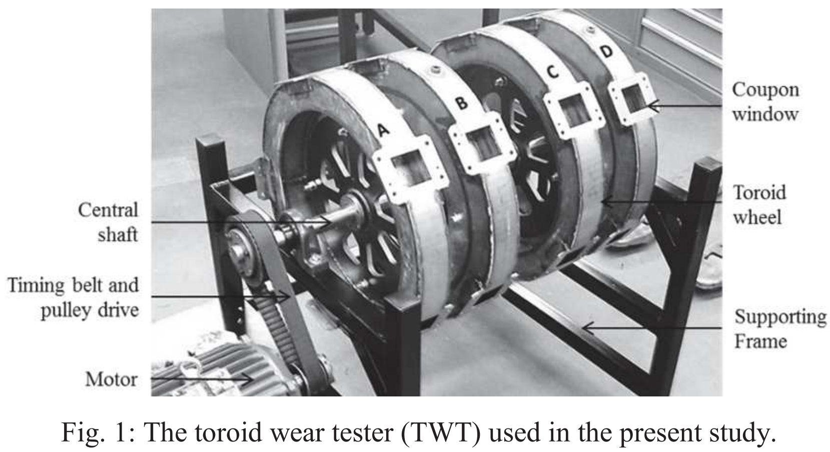



Fig. 1: The toroid wear tester (TWT) used in the present study.

were tested. Wear rates were determined and flow visualization studies were conducted to better understand the slurry flow inside the TWT. The objectives of the current study are:

(a) To visualize and interpret the hydrodynamics within the TWT, and

(b) To characterize the performance of the TWT for measuring wear rates.

## 2. EXPERIMENT

The TWT fabricated for this study has four hollow toroidal shaped wheels (labelled A, B, C and D in Fig. 1) made of stainless steel. Each wheel has five square openings (coupon windows) on the outer circumference. Wheels A, B, and C have identical dimensions, while wheel D is slightly smaller. The dimensions of the coupon windows for Wheels A, B, C are 65 × 65 $mm^2$ and 58 × 58 $mm^2$ for Wheel D. The test coupons are mounted on the coupon windows using stainless steel coupon holders with a 0.5 mm thick paper gasket (Dynoteq Tesnit BA-U) to prevent leakage. The gasket and mating surface are also coated with a layer of lubricant (Rust Check Coat and Protect). A single shaft, powered by a 2.2 kW motor rotates all four wheels. A fifth, removable wheel made of transparent acrylic plastic was also built to allow visualization of the flow inside the TWT. The acrylic toroid wheel (ATW) is dimensionally similar to the actual wear wheels, and is mounted on the overhanging part of the TWT shaft. Instead of having coupon windows, the ATW has two openings on the side walls for slurry exchange.

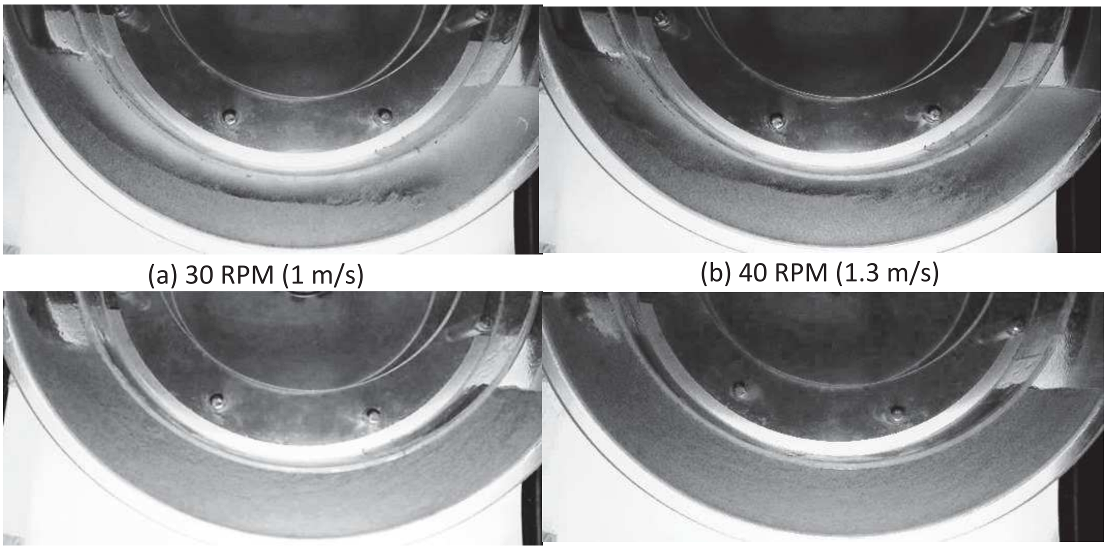
Wear experiments in the TWT were performed using sand–water slurry at room temperature (22 °C). Different particle sizes and solids concentrations were used to investigate the wear performance of the TWT, namely SIL 1 sand ($d_{50} = 0.25$mm), SIL 4 sand ($d_{50} = 0.43$mm) and gravel ($d_{50} = 2$mm). These particles were tested at solids concentrations between 6-20% by vol. and at wheel speeds of 30-60 RPM (1-1.9 m/s linear speed). The nominal duration of all tests was 96 hours (4 days), but the actual run time was closer to 93 hours after accounting for the slurry exchange time. The material loss was measured by mass measurements, the simplest yet proven approach (Summer 1987; Fotty et al. 2010). Coupons were cleaned and weighed before and after testing with a careful cleaning regime (Sarker 2016). Preliminary tests verified that the wear was linear with the number of test days, negating the need for daily mass measurements. The wheels were charged with a volume of slurry equal to one-third of each wheel's total volume, and the remainder of the space was filled with Nitrogen to prevent corrosion. Further, a corrosion inhibitor was used (Hydroguard I-15 from ANGUS Chemicals) in the slurry to prevent erosion fully. To reduce the effect of particle degradation (Cooke et al. 2000; Sarker 2016), the slurry was replaced at 24-hr intervals. At each slurry replacement, the TWT was stopped, emptied, recharged, and purged with Nitrogen.

## 3. RESULTS AND DISCUSSION

### 3.1. SLURRY FLOW BEHAVIOUR UNDER DIFFERENT CONDITIONS

The preliminary work by Cooke et al. (Cooke et al. 2000) indicated that the coarse particles in the TWT form a settled bed at the bottom of the wheel and stay relatively stationary while the wheel rotates. Flow observations made in this study support that observation and indicate that this behaviour is a strong function of the rotational speed, particle size and solids concentration. Here the particles remain settled up only until a critical speed, which depended on the particle (and presumably the carrier fluid) properties.

At higher speeds, the settled bed suspends and eventually becomes fully dispersed. Fig. 2 demonstrates this effect for SIL 1 particles (0.25 mm).



(a) 30 RPM (1 m/s) (b) 40 RPM (1.3 m/s)

(c) 60 RPM (1.9 m/s) (d) 80 RPM (2.9 m/s)

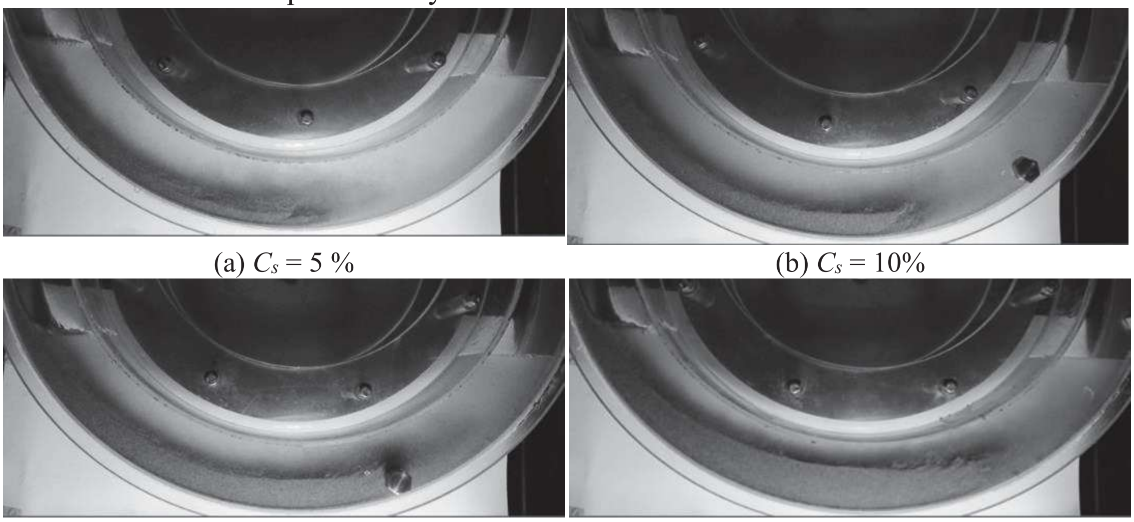
Fig. 2: Effect of wheel speed on 0.25 mm SIL 1 particles; $C_s$ = 20%; The linear speed corresponding to the rotational speed of the AWT is given in parenthesis

At speeds less than 30 RPM (1 m/s linear velocity), the particles form a sliding bed that slowly tumbles at the downstream side of the TWT. The wall friction causes the bed to move toward this side, reaching equilibrium (see Fig. 2(a)). It can be inferred that the sliding bed contains the entire slurry solids concentration under these conditions.

Between 40-50 RPM (1.3-1.6 m/s), the behaviour changes from a completely settled to a partially settled bed due to the increased turbulence and secondary carrier fluid back-flow. In this range, a distinct sliding bed remains, but the thickness and stream-wise span of the bed both increase, indicating that the bed is more loosely packed (Fig. 2(b)). The thickness and stream-wise span of the bed was estimated by post-processing of the images. For example, to assess the stream-wise span, the number of pixels along the entire slurry wetted region and particle-bed-dominated region were measured, and their ratio was used as the approximate normalized span of the bed. Further detail is given in Sarker (2016). At 30 RPM, the stream-wise span of the settled bed is approximately 70% of the slurry wetted area, which increases when the speed changes to 40 RPM. The height of the particle bed also increases, indicating a reduction of the contact load on the TWT surface.

At 60 RPM (1.9 m/s), the induced flow and back-flow of the carrier fluid become stronger and fully suspend the SIL 1 particles. This increases the bed span to approximately 90% of the slurry wetted area. At this point, a portion of the coarse particles still remains settled (Fig. 2(c)). At speeds higher than 60 RPM, the SIL 1 particles appear to be fully suspended (Fig. 2(d)), and a homogeneous slurry is formed.

Based on these results, 30 RPM (1 m/s) was chosen as the best speed for studying the effect of solids concentration and particle size because of the presence of the distinct sliding bed, which is similar to the conditions in a pipeline carrying a heterogeneous, coarse-particle slurry. Figure 3 presents the behaviour of SIL 1 particles in the slurry at varying solids concentrations ranging from 5-20% (by volume) at 30 RPM. It is apparent from Fig. 3 that the normalized bed span ($L_N$; the stream-wise extent of the particle bed along the wheel circumference relative to the immersed channel circumference) and the normalized bed thickness ($L_T$; the height of the particle bed relative to the channel height) increase with increasing solids concentration (data presented in Table 1). Therefore, it is logical to assume that higher solids concentration in the TWT will lead to greater material loss due to an increased normal load. However, the exact trend of the material loss increase is difficult to estimate from the visualization due to other complexities, e.g. the true particle-wall slip velocity, effect of back-flow on the particle bed, and the non-uniform normal load on the coupons as they traverse the settled bed.



(a) $C_s$ = 5 % (b) $C_s$ = 10%

(c) $C_s$ = 15% (d) $C_s$ = 20%

Fig. 3: Effect of solids concentration on 0.25 mm SIL 1 particles; 30 RPM (1 m/s)

Since particle size is an important wear parameter, separate slurries made from the 0.25 mm SIL 1, 0.43 mm SIL 4, and 2 mm gravel were also visualized in the ATW under different conditions. Here, 60 RPM is used as the reference rotational speed for this comparison because, as is clear in Fig. 2(c), this is the speed at which the smallest particles are first fully suspended by the induced flow and back-flow in the system. Figure 4 shows the observations made for the SIL 4 and gravels under similar operating conditions.

Table 1

Effect of solids concentration on 0.25 mm SIL 1 particles; $N$= 30 RPM (1 m/s)

| $C_s$ (% v/v) | Normalized Bed Span, $L_N$ | % $L_N$ increase | Normalized Bed Thickness, $L_T$ | % $L_T$ increase |
|---|---|---|---|---|
| 5 | 0.5 | 0 | 0.35 | 0 |
| 10 | 0.55 | 10 | 0.4 | 20 |
| 15 | 0.65 | 24 | 0.5 | 35 |
| 20 | 0.7 | 30 | 0.65 | 48 |

The SIL 4 slurries displayed a distinct settled bed even at 60 RPM. Under these conditions though, the top layer and the upstream side of the bed were actively drawn out of the settled bed by the stronger turbulence. For the 2mm gravel however (Fig. 4(b)), the carrier fluid turbulence and back-flow in this operating condition are insufficient to suspend the gravel at all, resulting in a very stable sliding bed with negligible change in the bed span with RPM. Thus, larger particles are better to use in a TWT for generating result of a sliding bed (Schaan et al. 2007).

(a) SIL 4 (b) 2mm gravel

Fig. 4: Settled bed of SIL 4 particles and 2mm gravel at $N$ = 60 RPM; $C_s$ = 20% by volume

### 3.2. MATERIAL LOSS EXPERIMENTS

Noting that wear rate in pipeline flow is a strong function of erodent particle size, shape, bulk flow velocity and the solids concentration, previous bench-scale studies (see for example: Karabelas 1978; Elkholy 1983; Gupta et al. 1995; Gandhi et al. 1999; Huang et al. 2010) have incorporated these parameters in a general correlation given by

$$E = k d_P^{n_1} V^{n_2} C_S^{n_3} \quad (1)$$

Here, $E$ is the erosion damage (mm/year), $d_p$ is the particle diameter (mm), $V$ is bulk flow velocity (m/s), and $C_s$ is the solids concentration (% by wt). The coefficient $k$ incorporates the effect of pipe and particle hardness as well as shape; and the exponents capture the hydrodynamic effects that change during the experiments. These can also be affected by material properties. The reported values for these exponents vary significantly between studies. However, if the comparison is limited to a small number of studies, focussing on pipe flows dominated by a sliding-friction wear mechanism as well as studies that have agreed well with such results, reasonable ranges for these exponents can be determined. The particle size exponent, $n_1$, falls between 0.3–0.6 (Elkholy 1983; Gupta et al. 1995; Gandhi et al. 1999; Huang et al. 2010) and the velocity exponent, $n_2$, can be between 2–2.6 (Elkholy 1983; Gupta et al. 1995; Gandhi et al. 1999) for particle size ranging 0.2 to 0.9 mm. For the solids concentration exponent, $n_3$, the range of 0.5–0.8 (Gupta et al. 1995; Gandhi et al. 1999) has also been reported for slurry pot testers.

For the smaller particle sizes, the complex effects described in Section 3.1, in which the presence and geometry of the sliding bed change significantly with wheel speed mean that the quantitative results should be equally confounding. This was clear in the wear results because for SIL 1 and SIL 4, wear rate actually decreased when the speed was changed from 30 to 60 RPM, contrary to literature trends (Karabelas 1978; Elkholy 1983; Gupta et al. 1995; Gandhi et al. 1999; Huang et al. 2010). This is the effect of the changing geometry of the sliding bed for these particle types. Unfortunately, this means that estimation of the value of $n_1$ impossible from the current set of experiments. On the other hand, the gravel remains settled at all speeds, indicating that the gravel particles are better suited for investigating the effects of velocity and concentration.

Using the gravel particles, three different solids concentrations, 6, 12, and 20% by vol. (15%, 27%, and 40% by wt.), were tested at 30, 45, and 60 RPM, totalling nine test points. Since $n_1$ is not presently accessible, the data are fitted via least squares regression to a three-parameter equation with the following form:

$$E' = k'V^{n_2}C_s^{n_3} \ , \quad (2)$$

where the constant $k'$ simply collapses $k$ and $d_P^{n_1}$ (in Eq. 1) into one term and $n_2$ and $n_3$ remain the same. Here $E'$ is the wear rate predicted by the fit. This fit was performed on all nine data points resulting, in a value of 2.5 for $n_2$ and 0.35 for $n_3$. The value of $R^2$ associated with this fit was 0.99 and the data scatter is presented in Fig. 5. For the velocity effect, $n_2 = 2.5$ is in the range reported for other slurry pipeline erosion experiments (2–2.6), which indicates that for the gravel particles, the minor changes in hydrodynamics and bed shape with wheel speed do not affect the results significantly.

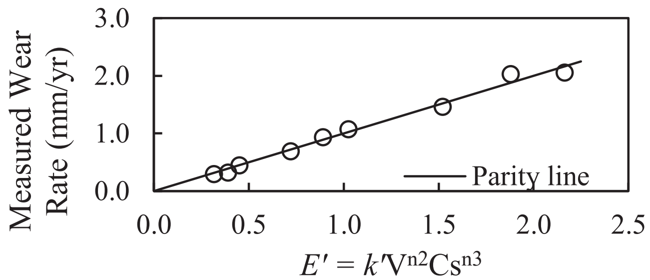



Fig. 5: Effect of wheel velocity and solids concentration on the TWT wear rate

For the concentration effect, $n_3 = 0.35$ is just below the range (0.5–0.8) mentioned in the previous studies by Gupta et al. (1995) and Gandhi et al. (1999). Both studies used slurry pot devices as the bench-scale tester. In slurry pots, the test coupons are connected to a rotating shaft in a cylindrical tank containing the slurry; which means that the particles in the slurry remain suspended during the experiment. Therefore, the contact frequency between the suspended particles and test coupons increases with the solids concentration, leading to a greater material loss. On the other hand, in the TWT, the 2mm gravel particles remain settled, so as the solids concentration increases, the contact frequency and even particle–coupon contact area do not change significantly, but the particle sliding bed thickness section does (see Fig. 3 and Table 1 and the discussion in Section 3.1). Therefore, it is the increase in sliding bed thickness that increases the normal load on the test coupons and results in greater material loss. This is expected to have a smaller effect than the related change for the slurry pot (increased contact frequency). This is reflected in the current result, for which the TWT exponent is slightly less than the reported value. However, it is not yet clear if the TWT result can be directly compared to a pipeline operation because this varying sliding bed geometry effect is potentially unique to the TWT geometry.

# 4. CONCLUSION

Visualization and slurry erosion experiments were conducted to evaluate the usefulness of a Toroid Wear Tester as a tool in the prediction of slurry pipeline wear. The TWT has a significant advantage over other simple wear test devices (slurry pot, impinging jet, etc.) because it better approximates the hydrodynamics of a pipe flow. However, though the TWT is hydrodynamically similar to a pipe flow, the current work demonstrates that there are still significant differences, namely that there is a strong secondary back-flow that helps to suspend the particles and that the effect of the slurry solids concentration and the wheel speed on the sliding bed geometry is not trivial. If these concerns are ignored, confounding trends, such as decreasing wear rate with increasing particle size, are obtained. This is because changes to the TWT hydrodynamics with changing parameters cannot be ignored. To obtain results comparable to sliding-bed-dominated erosion, either larger particle sizes or lower wheel speeds are preferable. With this in mind, attention was paid to results from slurries with 2mm gravel particles. In this case, the power-law exponents describing the relationships between solids concentration and wear rate as well as flow velocity and wear rate are consistent with values in the literature.

These results affirm that the TWT is a promising device for exploring and predicting pipeline wear. This work underlines the importance of understanding the differences between the TWT and pipe flow hydrodynamics in understanding and predicting wear.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