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Influence of particle attrition on erosive wear of bends in dilute phase pneumatic conveying

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ABSTRACT

Bulk materials like sand particle/alumina, which do not possess good air retention properties or high permeability are generally conveyed in the dilute phase, suspension flow in conventional pneumatic conveying systems. High inlet conveying air velocity is thus necessary to successfully convey such materials. As a result of high air velocity, the particles impact on the bend surface and cause erosion of bends and attrition of particles. The study of bend erosion has been a subject of research for a long time and the influence of various operating parameters has been widely investigated. The authors have carried out an extensive experimental plan to study the influence of recirculation of material on the erosion of bends and attrition of particles. It is expected that the severity of erosion may go down as the particles lose sharp edges due to the recirculation of material. Silica sand having a mean particle size of 435 μm was conveyed in the pneumatic conveying pilot plant. The pipeline test loop is 48 m long and 67 mm bore. The bends were placed in horizontal-horizontal orientation with R/d ratio of 4.0. The solid particle erosion behavior of three test bends (B1, B2 and B3) and particle attrition have been analyzed. A 300 kg batch of sand was recirculated 29 times through the test pipeline, thus conveying a total of 8.7 tonnes. The mass loss and bend wall thickness were regularly monitored. Material sample during each run was collected to assess the extent of particle attrition and changes in the particle morphology.

This paper presents the experimental results of a comprehensive analysis of the erosion and particle degradation with a change in particle morphology. A correlation has been developed between the extent of material recirculated through the test pipeline and its influence on the erosion of bends and degradation of particles.

1. Introduction

Transportation of powdered and granular materials through pipelines using a carrier gas, normally air, is termed Pneumatic Conveying. It is widely used in the industry to handle a range of powdered and granular materials through closed loop pipelines. There are principally two modes of conveying viz. dilute phase suspension flow and dense phase non suspension flow. Since the particles are conveyed in suspension in the dilute phase, higher gas velocity is required at the material feed point [1]. On the other hand, when the conveying gas velocity is relatively low, the particles drop out of suspension resulting in a layer at the bottom of the pipeline. Hence, the particles flow in dunes or as pulsating moving bed flow which is referred to as fluidized dense phase [2]. The material must have good air retention property for being successfully conveyed in fluidized dense phase flow. Particles having good permeability like plastic pellets, are transported in slug flow as full-bore plugs separated by gas pockets [3]. In case of dilute phase conveying, the particles impact on the bend surface at high velocity. If the material being conveyed is hard and abrasive like silica sand, the bends are subjected to erosion due to the high velocity impact of the particles. As a result, the particles also suffer attrition leading to changes in particle size and shape.

Erosive wear of bends is influenced by many variables such as particle size, shape, hardness, conveying conditions like conveying air velocity, air to solids ratio and bend geometry and its material properties. The effect of many of these parameters on erosive wear of bends in pneumatic conveying has been investigated by many researchers [4]. Particle size has a significant influence on both the mass of material removed and depth of penetration in the bend surface [5]. The smooth surface with no steps or ridges was observed during the conveying large

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sand particle of 230 μm mean diameter. In contrast, the small particles of 70 μm caused erosion in a narrow, concentrated zone. The depth of penetration for the same amount of mass loss was thus very different with variation in particle size. In addition, the particle shape also plays a significant role in the erosion behaviour [6]. The erosion rate caused by angular particles was significantly high by as much as four times compared to those of spherical particles. However, the shielding effect resulting from an increase of particle concentration in the gas stream does help reduce mass and thickness loss in pneumatic conveying of Olivine sand [7]. Macchini et al. [8] revealed that the specific erosion rate dropped with an increase in volumetric solids concentration. The bend orientation is another feature which influences the location of maximum depth of penetration and failure of the bend [9].

The useful life of the bends when subjected to erosion is influenced both by the mass loss and depth of penetration in the outer bend surface. Fine particles tend to cause erosion in a narrow zone thus leading to failure of bends even when the mass loss is relatively small. An array of sixteen ultrasonic sensors mounted to the outer surface of bend were used for measuring the reduction in wall thickness [10]. The sixteen transducers gave information about distribution and patten of erosion under different conditions in multiphase flow. Solnordal et al. [11] examined the distribution of erosion depth profile (erosion scar) on the surface of the elbow after conveying a specific quantity of material by using a profilometer. Symmetrical distribution of erosion on the extrados of the surface was observed with maximum erosion depth at the center. Non-intrusive Acoustic method showed good promise for monitoring erosion in dilute phase pneumatic conveying [12].

The attrition of particles due to impact on the bend surface results in generation of finer particles which further affects the change in the flow pattern of the material in the pipeline. Conveying air velocity and impact angle (defined as the angle between the straight path of the particle and the tangent line on the wall at impact point) are the most significant variables affecting particle degradation [13]. The degradation of powders increased at lower solids loading ratio which defined as the mass flow rate of material to mass flow rate of air [14] or at higher conveying air velocity [13]. Kalman [15] presented that the attrition rate in pneumatic conveying could be decreased or controlled by either conveying material in dense phase mode of flow or reduction in the air velocity in the dilute phase to slightly above the saltation velocity of the particles. Particle attrition or degradation can also be minimized by choosing a suitable bend geometry (to change the angle of impact) or by selection of an appropriate bend material. For example, the bends could be constructed with resilient materials to absorb a portion of the impact energy such as rubber [16]. Salman et al. [17] found during transporting fertilizer particles in pneumatic conveying pipeline that the number of broken particles increased with an increase in air velocity. The strength of conveyed particles also effects the attrition rate. Lower attrition level was observed for particles with higher hardness [18].

Erosive wear of bends and particle attrition are operational problems in dilute phase pneumatic conveying that are inherently connected because both these problems are attributed to high velocity impact of conveyed material on the bend surface. In this paper, the degradation of conveyed particles and erosion wear of three test bends have been studied in detail in the pneumatic conveying pilot plant.

2. Experimental details

2.1. Experimental test rig

Silica sand was conveyed in dilute phase through a 48 m long and 67 mm bore pipeline at air velocity 20 m/s and solid loading ratio (SLR) 1.0, as illustrated in Fig. 1. The experimental pilot plant consisted of a supply hopper, rotary feeder, conveying pipeline, storage hopper and a bag air filter to separate the particles from conveyed air. Compressed conveying air at 1 bar gauge pressure was supplied to the conveying system through a two-stage Roots type blower. Rotameter positioned in the compressed air line was used for measuring air flow rates. Supply hopper was mounted above a variable speed rotary feeder that was utilized for feeding materials against high pressure of air in the conveying pipeline. The storage hopper was installed above the supply hopper, which was separated by a butterfly valve. The storage hopper was mounted on the load cells to measure solid mass flow rates since the conveyed material was offloaded into this hopper for recirculation.

2.2. Pipeline test loop

The 48 m long pipeline test loop was entirely in the horizontal plane, with a short vertical pipeline and eight bends having a 268 mm radius of curvature (R/d ratio of 4). The concentricity and alignment of the pipeline joint in the test loop were ensured via clamp couplings for avoiding the disturbance in particle flow. The erosive wear behavior of three test bends labeled as B1, B2 and B3 in Fig. 1 was monitored. The

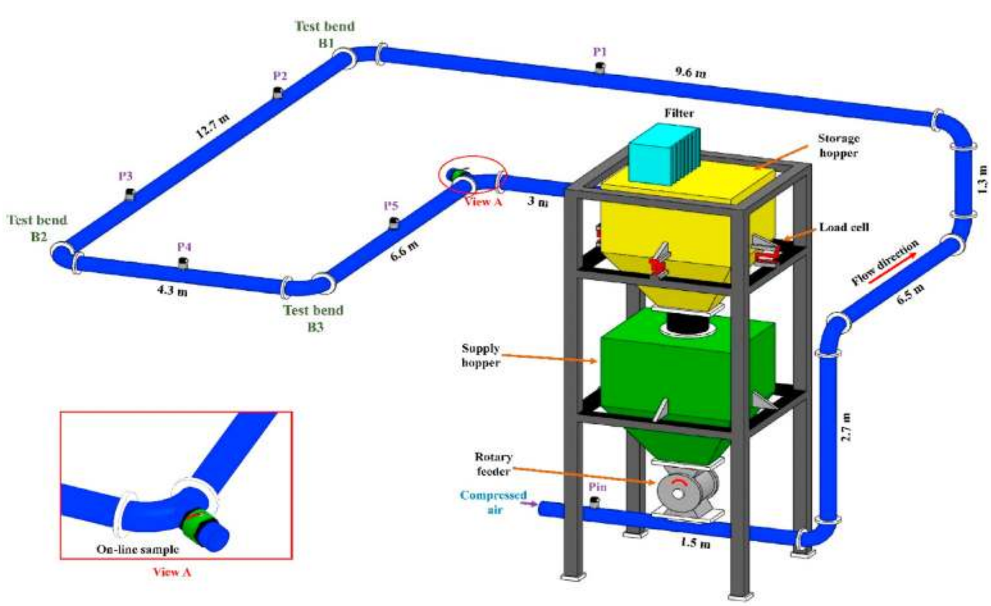

Fig. 1. Schematic diagram of the experimental test rig.

test bends (except for test bend B3) placed at the end of the long horizontal pipeline were proceeded by a sufficient long distance to ensure that the particles reaccelerated to their steady state velocity. The required length for the re-acceleration of particles downstream of the bend is between 30 d and 100 d [19]. Since the mean particle size of the fresh sand was high, it is expected that the acceleration length would be between 80 d and 100 d.

2.3. Experimental plan

Silica sand having a particle density of 3000 kg/m^3 and mean particle size of 435 μm was recirculated through the test pipeline. Fig. 2 shows the particle size distribution of the silica sand. The shape of the erodent particle was examined under the SEM micrograph as seen in Fig. 3. It is seen that the fresh sand consisted of angular-shaped particles with sharp corners and edges.

One batch of 300 kg Silica sand was recirculated through the test pipeline at the same conveying conditions. The air velocity at the inlet was 20 m/s and the solid loading ratio was 1.0. The measurements of weight loss and the wall thickness of bends were recorded after every 5 runs (i.e., after conveying 1500 kg of sand). The wall thickness of the bends was measured using an ultrasonic thickness probe at 15^0 section along the outer circumference of the bend. The online sample method is used as a means of obtaining the representative sample to monitor the extent of degradation and to establish a co-relation between the particle attrition and bend erosion. During the steady-state period of conveying, 100 g sample was collected for particle size distribution and SEM analysis. The material was recirculated 29 times to artificially reduce the mean particle size. It could not be conveyed any further due to erosion of the rotary feeder blade tips. Where after every 10 runs, the rotary feeder was opened for visual inspection of the rotor blade tip. During the course of this program, erosion of the rotary feeder blade tip was observed and monitored, and hence it is expected that the air leakage was not increased. Since some fluctuation in the flow was observed in 29 runs, the rotor blade tip was checked again for erosion. Because the blade tip was observed to have eroded, the experimentation was terminated.

3. Results and discussions

As indicated in the earlier sections, 300 kg batch of material was recirculated 29 times. Thus, a total of 8700 kg material was conveyed through the same set of pipeline bends. The results of erosion and particle degradation are presented in the following sections.

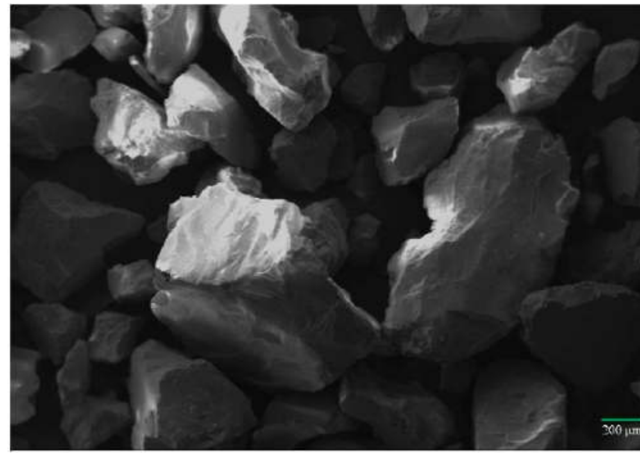

Fig. 3. SEM microphotographs of Fresh erodent material (Silica sand).

3.1. Overall erosion of bends

The mass loss of test bends (B1, B2 and B3) were measured at regular intervals. A graphical representation of the cumulative mass loss of each test bend against the quantity of sands conveyed is shown in Fig. 4. The mass loss during the initial runs was more as compared to subsequent runs. This is expected because initially the sand particles had sharp

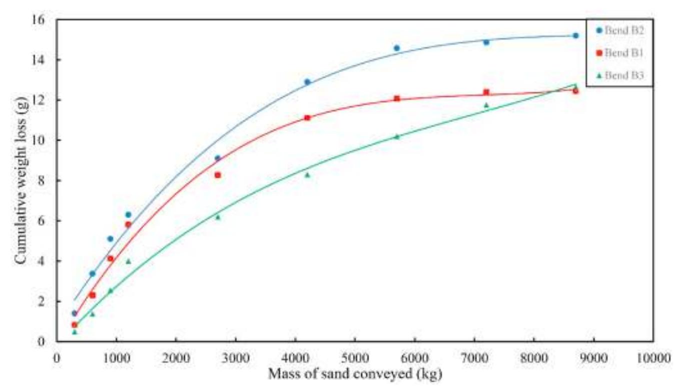

Fig. 4. Mass loss of test bends against the total mass of sand conveyed.

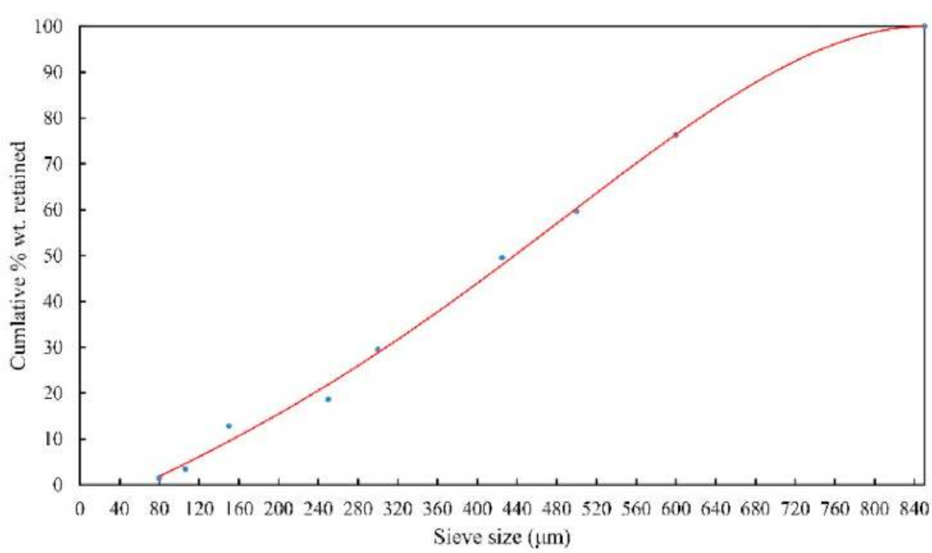

Fig. 2. Particle size distribution of fresh erodent particle.

edges which led to a higher rate erosion of the target surface of bends. With recirculation, the sand particles got disintegrated (degraded), loose sharp edges, got rounded off and thus caused lesser loss of material. It has also been noticed that the test bend B2 had a higher specific erosion rate in comparison to the other two test bends (B1 and B3). The length of the straight pipeline between bends B1 and B2 is more than 12 m. This ensures that after impacting at the bend B1, the particles could reaccelerate to their steady state velocity. Due to air expansion effect, it is expected that the erosion of bend B3 should be more than that of bend B2, but the straight length of the pipeline between B2 and B3 may not be sufficient for the coarse particles to reaccelerate to their steady state velocity. This would result in particles impacting at a lower velocity and hence lower magnitude of erosion of bend B3. In other words, the length between bend B2 and B3 was not sufficiently long for particles to re-accelerate to their steady state velocity. This means that the particles did not impact at bend B3 with the velocity at which they would have impacted if the distance between bend B2 and B3 was longer. This is the reason that the wear of bend B3 was lower than that of bend B2. If the particles had reaccelerated to the steady state value, the velocity of impact at bend B3 would have been higher, and accordingly, the wear of bend B3 would have been more than that of bend B2.

3.2. Depth of penetration

The reduction in wall thickness of test bends (B1, B2 and B3) was measured and shown in Fig. 5. The maximum erosion and hence the depth of penetration was observed at around 30° bend angle from inlet. It is expected since mild steel is a ductile material and maximum erosion would be observed at lower values of impact angle. It was further observed that as the material was recirculated, the magnitude of penetration in wall thickness reduced. The experimental results presented here is an average of four measurements.

Fig. 6 shows the reduction in maximum wall thickness of the test bends at 30^0 with continuous re-circulation. It has been found that the reduction in wall thickness was higher for test bend B2 as compared to the other bends resulting in rapid failure for the bend. It has been observed that the reduction in wall thickness of bend B2 was 5.77% for the first four runs and 5.38% for the next 25 runs run. This reinforces the point that the material lost sharp edges and caused much less erosion as compared to the fresh sand. Similar values for the bend B1 were 3.54% and 3.63% respectively.

3.3. Particle attrition

The mean particle size and the particle size distribution of the conveyed particles are essential parameters of bulk materials which play a vital role in the flow behavior of powders during the conveying. Hence, it is necessary to monitor particle degradation rate during the experimental work because the degraded particles also affect the erosion rate as well as the wall thickness penetration of the test bends. It is depicted from Fig. 7 that the particle degraded rapidly for the first four runs but in the subsequent runs, the rate of particle degradation was much lower. The mean particle size reduced by 31.0% of initial size after four runs and 12.3% for the remaining 25 runs. This leads to an important conclusion that for the first 4 runs, erosion rate as well as wall thickness regression, was higher as compared to rest of conveying cycles. This clearly establishes that the rate of erosion of the bends and particle attrition are inter linked.

Both erosive wear and particle attrition result from the high velocity impact on the bend surface, and hence the mechanism of erosion and attrition is common to a large extent. Fig. 8 shows the trend of erosive wear and particle size with the number of the test. It has been observed that particles degraded faster for the first four-run and this corresponding with a high mass reduction in test bends. The slope of the trend in particle size reduction and the reduction in the rate of erosion was of similar. It is thus important to analyze the relationship between the rate of erosion and particle attrition.

Fig. 9 shows the influence of particle size on specific erosion of test bends. Specific erosion is a dimensionless ratio of the mass loss of test bend to mass conveyed through it. It is revealed that when particles were fresh and their size was large with sharp edges, the erosive wear was significant. With recirculating the particles, the edges were broken and consequently degraded. As attrition continued, the shape of the particles became more rounded off and reduction in mean particle size and hence deceleration of erosive wear. This is because the smaller particle size was, the lesser kinetic energy of erodent particles was, and hence a relatively lower impact force to erode the surface. In addition, the shape of the particles also affects the magnitude of erosion. On the other hand, the smaller size of erodent particles was much influenced by hydrodynamics and turbulence of the continuous phase. This means that the particles responded to fluctuations in the flow more easily with higher attrition, and hence the majority of particles followed the airflow path rather than impacting on the bend wall.

3.4. Particle shape

Fig. 10 shows the SEM image of sand particles after the first conveying run and the third conveying run. It has been observed that the particles degraded fast and resulting in a significant reduction in the mean particle size and sharp edges getting rounded off. Particles of the

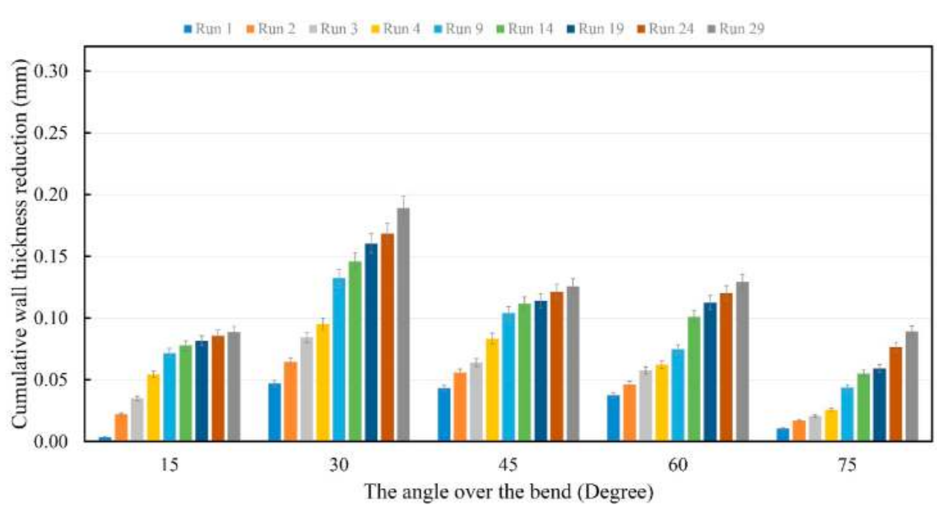

Fig. 5. History of wall thickness reduction with number of run for test bend B1.

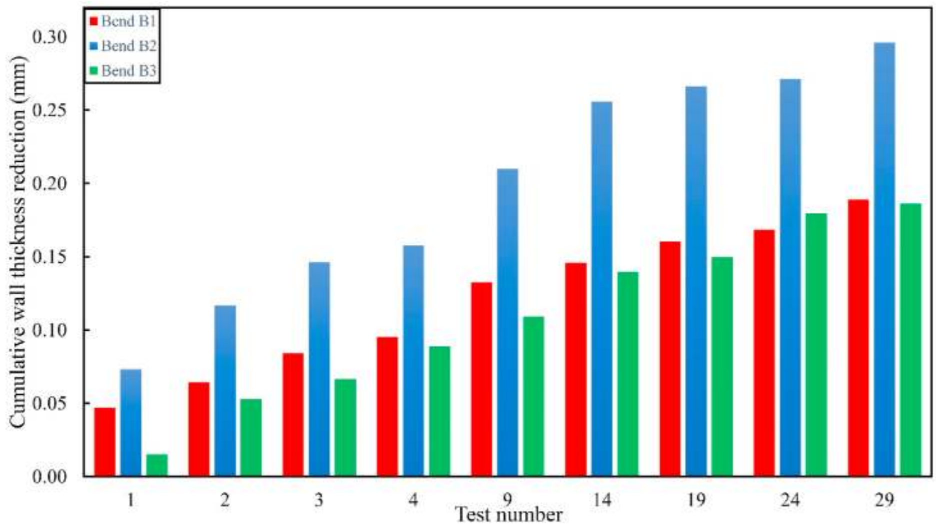

Fig. 6. Maximum wall thickness reduction at 30^0 against test number for all the test bends.

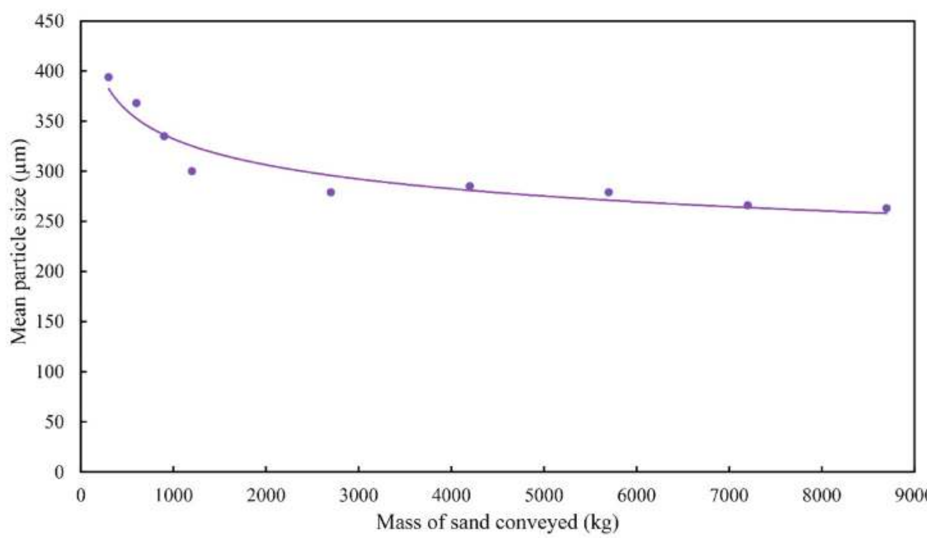

Fig. 7. Particle degrades with commutative mass conveyed.

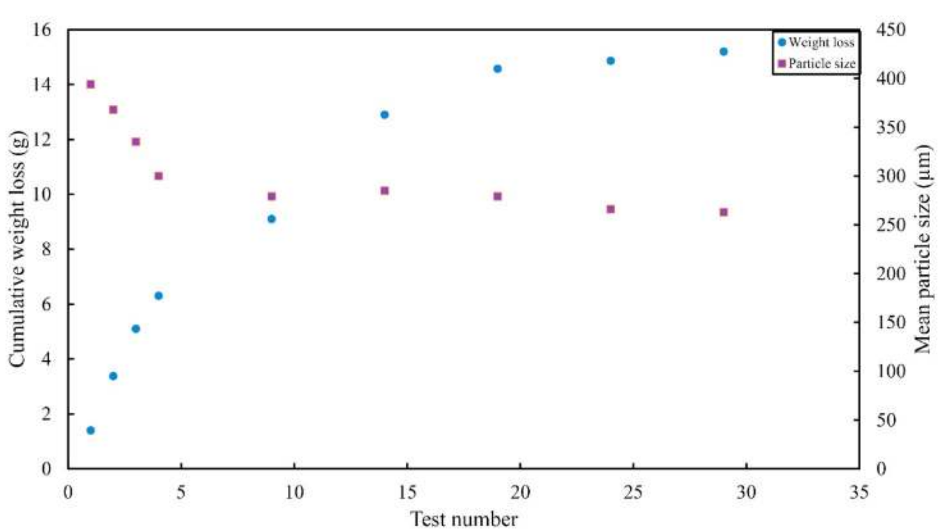

Fig. 8. Particle degrades and mass loss with test number for test bend B2.

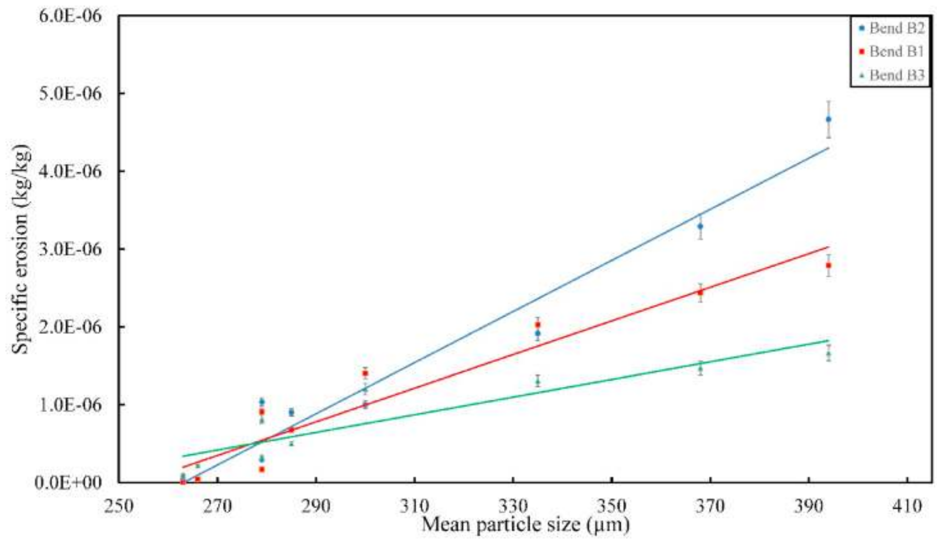

Fig. 9. Relation between Specific erosion rate with particle size for test bends.

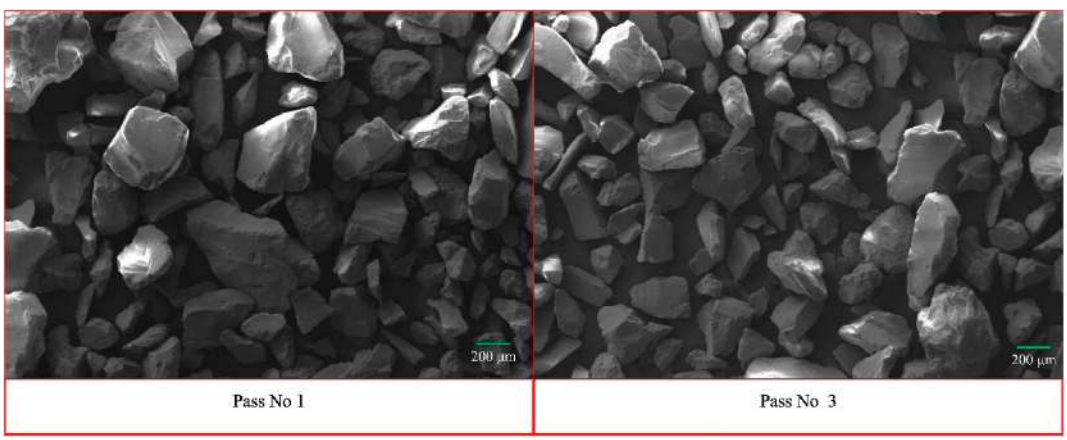

Fig. 10. Particle shape changes during conveying.

Fig. 11. Worn surfaces of test bends.

fresh sand were sharp and angular but subsequently, after pass no. 1 to pass no. 3 the edge of particles got rounded off.

3.5. Wear profile

At the end of conveying process, the bends used during the experiments were cut into two halves along the centerline to examine the wear profile of the bend surfaces. These are shown in Fig. 11. The wear pattern on all the test bends was different depending upon the impact velocity. It is also observed that the material removal from the bend 2 was limited over a concentrated area resulting in higher depth of penetration. Moreover, the wear marks for the test bend 2 was symmetric about the extrados compared to wear marks of the other bends indicating the particles was fully suspended over the carrier gas and the flow reaches steady-state condition before entering the bend 2. Finally, all worn surfaces of tested bends were smooth with no steps or ridges formation.

4. Empirical relation for erosion

From the above experimental observations, it is seen that at identical conveying conditions, the particle degradation and the erosive wear of bends are interlinked as the quantity of material (or the number of batches recirculated) through the bends increases. So,

$$\boldsymbol{Er} = \boldsymbol{f}(\boldsymbol{d}, \boldsymbol{N}) \tag{1}$$

Particle degradation is also influenced by the number of times the same batch of material is recirculated. In order to develop an empirical relation for erosive wear (*Er*), two dimensionless parameters: number of runs (*N*) and particle degradation factor ($\boldsymbol{\beta_n}$) are used. The equation is presented as follows:

$$\boldsymbol{Er} = \boldsymbol{C}(1 - \boldsymbol{\beta_n})^{a}(\boldsymbol{N})^{b} \tag{2}$$

Where:

C is coefficient and a, b are exponents.
Particle degradation factor $\boldsymbol{\beta_n} = dn_{50}/d_{50}$.
dn_{50}: Mean particle diameter at run n.
d_{50}: Mean particle diameter at the initial run (for fresh sand).

The unknown coefficient and exponents are found by using experimental data. For that reason, the equation is written in the form of logarithmic function as follows:

$$\text{Log}\ (Er) = \log\ (C) + a*\log\ (1\text{-}\beta n) + b*\log\ (N) \tag{3}$$

Experimental data of erosion with the number of runs and mean particle size are used to the above equation in order to find the coefficient and exponents. The number of equations will be established based upon the number of tests used. In this case, 9 cases of experimental data have been used. These equations can be presented in matrix as follows:

$$\begin{Bmatrix} \text{Log}(\boldsymbol{Er}1) \\ \text{Log}(\boldsymbol{Er}2) \\ . \\ . \\ \text{Log}(\boldsymbol{Er}n) \end{Bmatrix} = \begin{bmatrix} 1 & \log(1-\boldsymbol{\beta}_1) & \log(\boldsymbol{N}=1) \\ 1 & \log(1-\boldsymbol{\beta}_2) & \log(\boldsymbol{N}=2) \\ . & . & . \\ . & . & . \\ 1 & \log(1-\boldsymbol{\beta}_n) & \log(\boldsymbol{N}=\text{n}) \end{bmatrix} \begin{Bmatrix} \log(\text{C}) \\ \text{a} \\ \text{b} \end{Bmatrix} \tag{4}$$

The above equation represented in matrix form has been solved for the unknown in MATLAB software. The calculated unknowns are given as below:

$C = 11.5355;\quad a = 1.0363;\quad b = 0.3545$

So, the final form of the equation is written as:

$$Er = 11.5355(1 - \beta_n)^{1.0363}(N)^{0.3545} \tag{5}$$

Fig. 12 shows good prediction of mass loss of bend from the above model. The predicted mass loss varies from the experimental data within the boundary ±15% of the error margin.

It is observed in Fig. 4 that the maximum wall reduction occurred at 30° from the bend inlet. So, similarly, the proposed model for prediction of wall thickness reduction (w) at 30° is written as follows:

$$w = \text{d}\ \ (1 - \beta_n)^{\text{m}}(N)^{\text{k}} \tag{6}$$

The unknown coefficient (d) and exponents (m and k) are found by using experimental data. So, the final form of the equation is written as

$$w = 0.1746(1 - \beta_n)^{0.3445}(N)^{0.2567} \tag{7}$$

Fig. 13 shows good prediction of maximum wall reduction from the above model. The predicted maximum wall reduction varies from the experimental data within the boundary ±15% of the error margin. The above-developed equations are only applicable for Silica sand conveyed material. However, using the same methodology for developing a correlation between the erosion and particle degradation for other conveying materials the coefficient and exponents will be changed, and the equations will be accordingly modified.

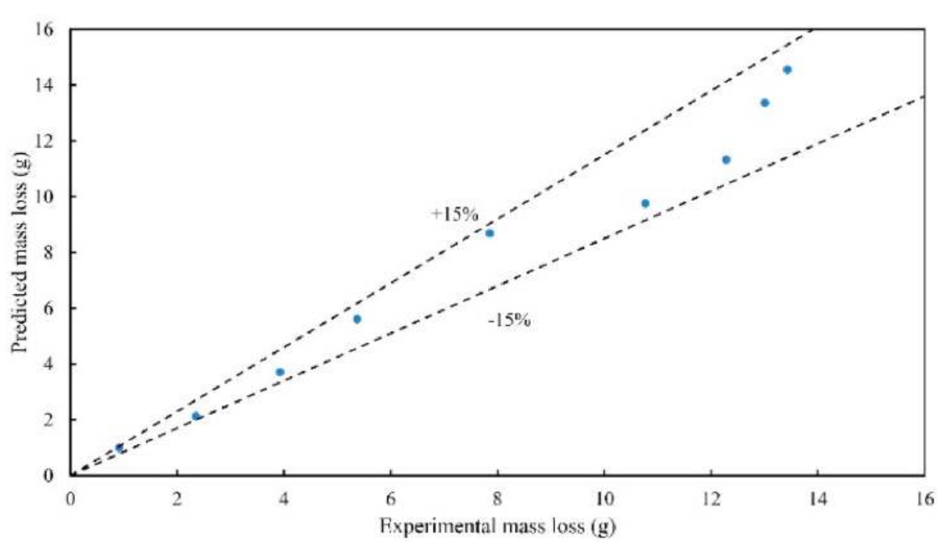

Fig. 12. The relation between predicted and experimental mass loss.

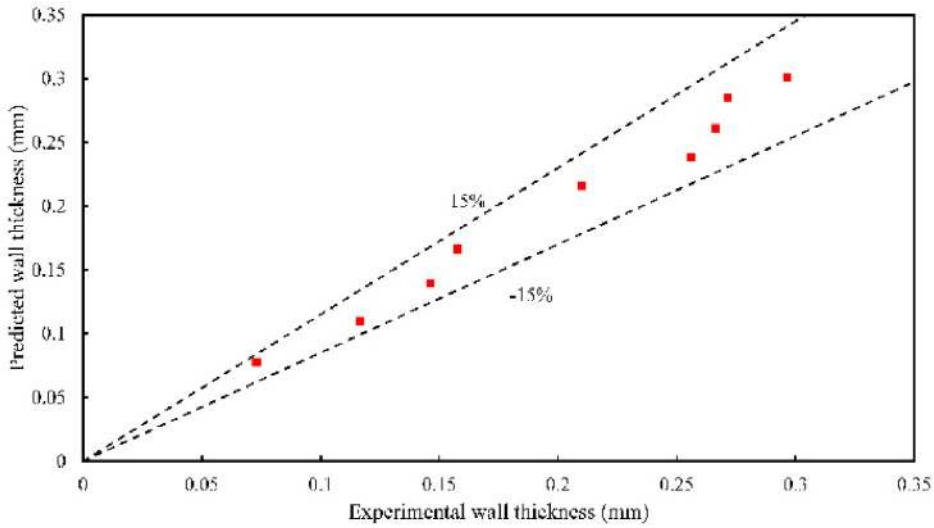

Fig. 13. Relation between predicted and experimental maximum wall reduction.

5. Conclusions

Solid particle erosion behavior of three test bends (B1, B2, and B3) and particle degradation in dilute phase pneumatic conveying were analyzed. Sand as erodent particle (mean particle size of 435 μm) was recirculated 29 runs in a test loop at conveying velocity 20 m/s. The analysis revealed that the maximum depth of wear occurred at an angle 30° around the bend irrespective of the number of recirculation of eroded particle. The mass loss of test bends at the first four-run was observed to be high in comparison to the remaining runs as well as accompany rapid degradation in the erodent particle. In addition, the bend B2 exhibited excessive erosion compared to the others because the erodent particle reached steady-state condition prior enter the bend and higher particle velocity due to air expansion effect. On the other hand, the degradation rate of particles became more stable with further recirculation indicating their shape got well rounded. The impact event on eroded surface material revealed interrelation between erosive wear and particle attrition. The larger the particle size was, the higher erosion rate was. As particle shape being more rounded, the erosion rate and particle attrition as well became less. Finally, the predicted results from developed model based on non-dimensional factors such as the number of run and particle degradation factor show a reasonable accuracy with experimental ones.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

List of symbols

d	*Pipe diameter, m*
R	Radius of bend curvature, *m*
Er	Erosive wear (i.e., mass loss), *g*
N	Number of runs
Bn	Particle degradation factor
dn50	Mean particle diameter at run n, μm
d50	Mean particle diameter at the initial run, μm
w	Wall thickness reduction, mm

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