



Reduction of pipe wall erosion by creating a vortex flow in anthracite powder pneumatic transport for power plants

Dorina Ionescu¹

¹ Department of Mechanical Engineering Technology, Faculty of Engineering, University of Johannesburg, South Africa
Phone: +27 11 559 6509, e-mail: dorinai@uj.ac.za

Abstract. From the total electricity generated in South Africa, about 85% is coal based. Coal powder is a solid fuel used in injectors for electricity production. The coal powder is extremely abrasive therefore it is important to maintain a minimum admissible flow speed. As the most severe pipe wall erosion takes place in bends, the most significant factor influencing wall erosion is the solid particle velocity. The aim of this research was to reduce the wall erosion through flow velocity control. Computational fluid dynamics (CFD) simulations, showed that for the same velocity, the erosion is dependent on flow direction change and the ratio between the radius of the bend and pipe diameter. The reduction of flow velocity was achieved by subtracting a spiral volume, from the inner volume of a horizontal pipe, just before an upward or downward bend. The modified volume geometry generated a vortex flow in the bend, achieving a more even distribution of maximum erosion points over the bend surface. The wall erosion, expressed in mm-wall thickness loss/hour, in the modified volume decreased by about 28,8 % while the installation life expectancy increased significantly. Furthermore the bend radius was proved to influence the erosion magnitude and location.

Key words

Optimization techniques, Fossil-fuel power stations, injection of coal powder, Anthracite powder transport.

1. Introduction

The South African industry is energy and carbon intensive, depending mainly on fossil fuels for its total energy needs [1]. Fossil fuels supply nearly 90% of the country's total primary energy needs, with coal providing about 75% of the total national energy needs. The electricity generating sector is the single largest consumer of coal (about 43% of the total national amount of coal consumed in 1997), with about 15% of the GDP spent on energy [2]. Eskom, the largest energy producer in South Africa (95%) had a total generating capacity of 50,229 GW in 2008, of which 85% was coal based. Hence the increase of pneumatic transport installations life expectancy is vital for South African economy.

2. Coal Fired Power Generation Technologies:

A. Pulverized coal systems

The coal pulverized into a fine powder will burn almost as intensely as a gas [3]. The feed rate of coal suited for the boiler demand as well as the amount of air available for drying and transporting the pulverized coal fuel is monitored by computers. The raw coal is fed into the pulverizer along with air heated to about 650^o F from a boiler. As the coal gets crushed, the hot air dries it and blows the usable fine coal powder out to be used as fuel. The powdered coal from the pulverizer is directly blown to a burner in the boiler. The burner mixes the powdered coal in the air suspension with additional pre-heated combustion air and forces it out of a nozzle similar in action to fuel being atomized by a fuel injector in modern cars [3]. Under normal operating conditions, the heat in the combustion zone will ignite all the incoming fuel.

B. Cyclone Furnaces

Cyclone furnaces can burn poorer grades coal with higher moisture contents and ash contents as much as 25%. The furnace is basically a large cylinder jacketed with water pipes that absorb some of the heat to make steam and protect the burner itself from melting down [3]. The hot combustion gases leave the other end of the cylinder to enter a boiler that produces steam. All the fuel that enters the cyclone burns when injected once the furnace is at its operating temperature. The ash drains through a trench in a collection tank where it is solidified and disposed off. This ability to collect ash is the biggest advantage of the cyclone furnace burning process. Only 40% of the ash leaves with the exhaust gases compared with 80% for pulverized coal burning. One of the major disadvantages of Cyclone furnaces is the required annual replacement of its liners due to the erosion caused by the abrasiveness of the coal [3].

2. Erosion prediction

Solid particle impact velocity has been recognized by researchers as the most significant factor influencing erosion. Experimental results showed that the erosion rate is proportional to the exponent of the solid particle velocity or the fluid velocity surrounding the particles [4]. Depending upon the experimental conditions, the

values of the velocity exponent may vary from a minimum of 0, 8 up to 8, 0.

A. Location of maximum pipe erosion for bend radius to pipe diameter ratio of 2,5 (Volume 1 and Volume 2 for vertically upward and downward bends respectively).

Experimental investigations of erosion in multiple phase flows done by Deng [5], using sand as solid phase, showed that the maximum pipe mass loss is in the elbow and the location of maximum wear due to erosion is different for horizontal flow compared to vertical flow, with maximum damage in the horizontal to vertical downward bends. It is well known that pipe erosion is sensitive to the characteristics of the solid particles, therefore a generalised conclusion would be unwise. The present study, where anthracite powder was used as solid phase, showed that the erosion in the elbow is more significant for a vertical upward bend. Figures 1 and 2 show details of the maximum erosion magnitude and the points where it occurs for upward and downward bends respectively.

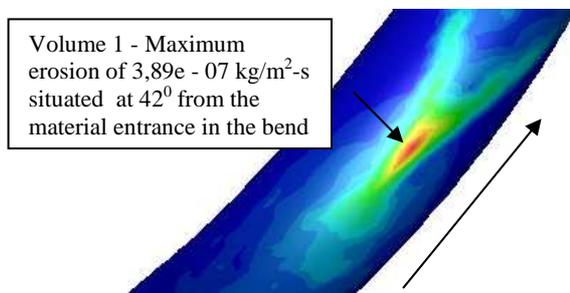


Fig. 1 - Volume 1; DPM Erosion (auto range) horizontal / vertical upward bend, R/D = 2,5

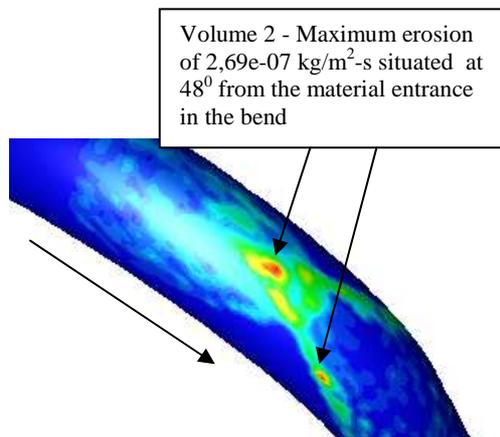


Fig. 2 – Volume 2; DPM Erosion (auto range) horizontal / vertical downward bend, R/D = 2,5

The maximum erosion values for the downward vertical bends are approximately 30% less than that of vertically upward bends.

B. Location of maximum pipe erosion for bend radius to pipe diameter ratio of 5 (Volume 3 and Volume 4 for vertically upward and downward bends respectively).

For bends with a ratio of R/D ranging from 4 to 6, the CFD results showed the presence of two maximum erosion points in the bend as shown in figures 3 and 4.

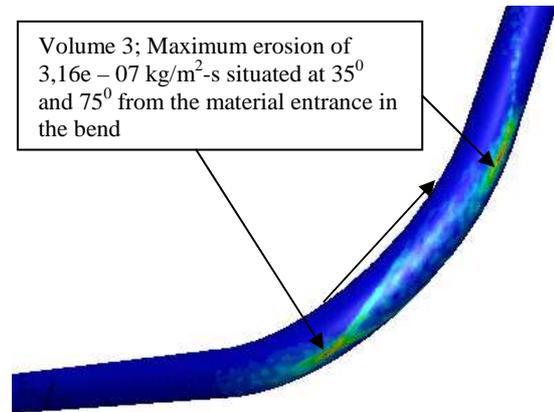


Fig. 3 – Volume 3; DPM Erosion (auto range) horizontal / vertical upward bend, R/D = 5

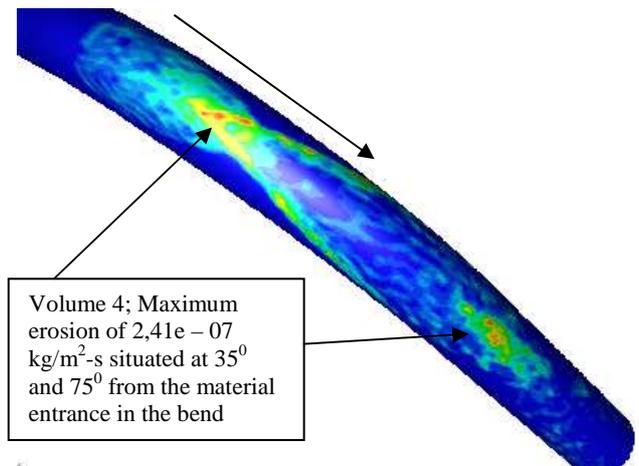


Fig. 4 – Volume 4; DPM Erosion (auto range) horizontal / vertical downward bend, R/D = 5

The maximum erosion values for the downward vertical bends are approximately 47% less than that of vertically upward bends. Also the increased bend radius decreased the maximum erosion from 3,89e-07 kg/m²-s to 3,61e-07 kg/m²-s. This conclusion is contrary to Bradley's results [6] that the bend radius is of no consequence for pressure drop and wall erosion.

3. Erosion reduction – Research done at the University of Johannesburg

To reduce the wall erosion in the bend via flow velocity control, the reference volumes 1, 2, 3, and 4 were modified. A spiral shaped volume of 1, 5 turns, rectangular cross-section of 12 mm depth x 10 mm width and a pitch of 100 mm was subtracted from the horizontal pipe adjacent to the bend, thus Volumes 1-M, 2-M, 3-M and 4-M were created. The starting point of the spiral volume is at 600 mm from the beginning of the horizontal section, and ends at 750 mm along the horizontal, for all modified volumes.

Due to a flow velocity decrease by an average of 9% the maximum and average erosion rates decreased. Furthermore the distribution pattern of the erosion points is completely changed. The concentrated erosion points were replaced by erosion points uniformly distributed over the whole surface of the bend. Although there are

some high erosion points the overwhelming majority of erosion points are of average value, hence greatly increasing the installation life expectancy. Figures 5, 6, 7 and 8 show the erosion points distribution for the modified volumes 1-M, 2-M, 3-M and 4-M respectively.

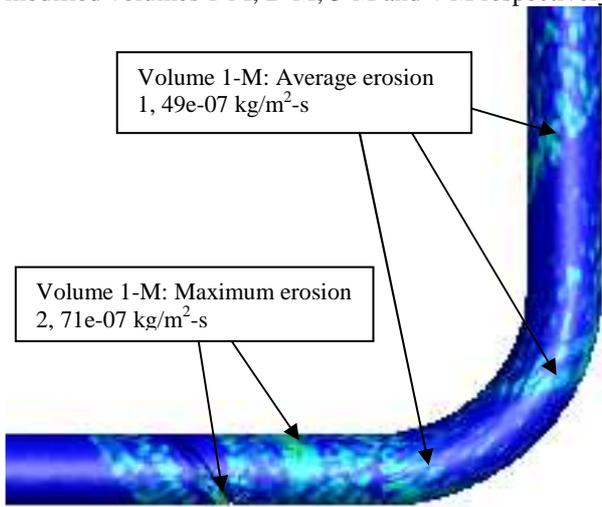


Fig. 5 - Volume 1-M DPM Erosion (auto range) horizontal / vertical upward bend, R/D = 2,5

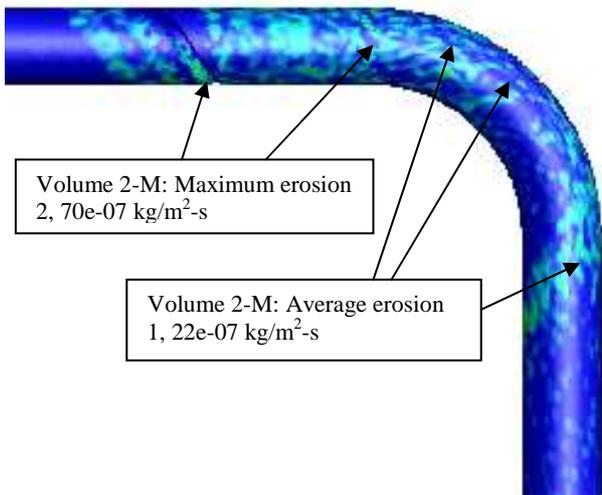


Fig. 6 - Volume 2-M DPM Erosion (auto range) horizontal / vertical upward bend, R/D = 2,5

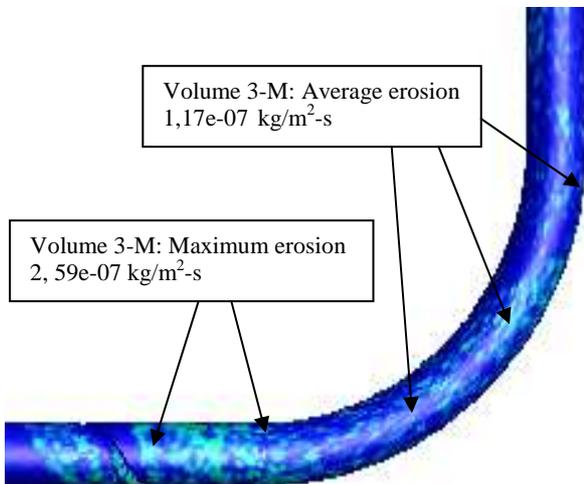


Fig. 7: Volume 3-M DPM Erosion (auto range) horizontal / vertical upward bend, R/D = 5

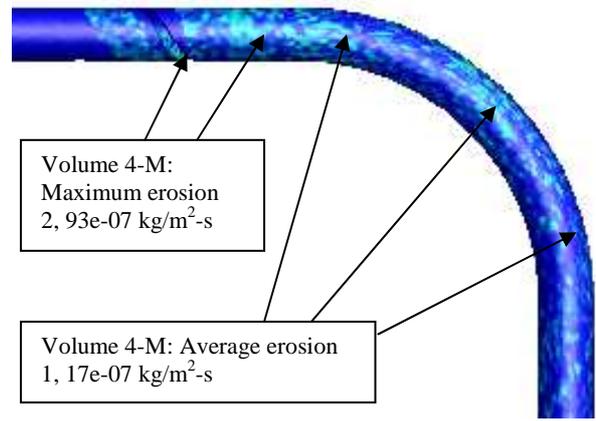


Fig. 8: Volume 3-M DPM Erosion (auto range) horizontal / vertical upward bend, R/D = 5

For all modified Volumes 1-M, 2-M, 3-M and 4-M the maximum erosion points are very few and are concentrated mainly in the spiral groove, while the majority of bend wall is subjected to average erosion values. Figure 9 shows a detail of erosion points distribution for the modified volume 4-M, where the maximum erosion values showing, are of average value (1,17e-07 kg/m²-s) As can be seen, the average erosion points have a relatively uniform distribution. However full wall penetration will still occur in the few maximum erosion points, therefore for the mass loss calculations of modified volumes the maximum erosion values were considered.

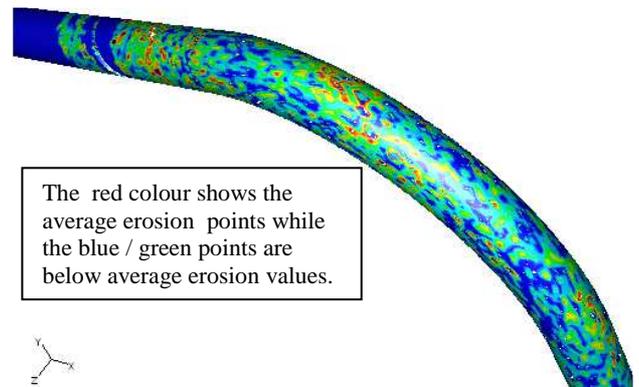


Fig. 9: Volume 4-M horizontal / vertical downward bend, R/D = 5; DPM Erosion (maximum range 1,17e-07 kg/m²-s)

4. Calculation of mass loss through erosion and the installation life expectancy

To calculate the mass loss in the bend for Volume 1 and Volume 2, the area considered was half the pipe circumference multiplied by 1/3 of bend length .

A. Erosion area and life expectancy for control Volumes 1 and 2

$$\frac{2\pi \times r_{pipe}}{2} = \frac{2\pi \times 0,025}{2} = 0,0785 \text{ m}, \quad (1)$$

$$\frac{2\pi(R_{bend})_{outer}}{4} = \frac{2\pi \times 0.15}{4} = (0.2356m)/3 = 0.0785 \text{ m} \quad (2)$$

$$Erosion \text{ area} = 0.0785 \times 0.0785 = 6.16 \times 10^{-3} \text{ m}^2 \quad (3)$$

For Volume 1 the maximum erosion rate was $3,89 \times 10^{-7}$ kg/m²-s resulting in an erosion rate of $14,004 \times 10^{-4}$ kg/m²-hour. Assuming the steel density to be 7850 kg/m³:

$$Volume \text{ eroded} = \frac{mass \text{ eroded}}{density} = \frac{14,004 \times 10^{-4}}{7850} = \quad (4)$$

$$= 1.784 \times 10^{-7} \text{ m}^3 / \text{hour}$$

$$Vall \text{ thickness eroded} = \frac{Volume \text{ eroded}}{Erosion \text{ area}} = \frac{1.784 \times 10^{-7}}{6.16 \times 10^{-3}} = \quad (5)$$

$$= 0.29 \times 10^{-4} \text{ m} / \text{hour} = 0.029 \text{ mm} / \text{hour}$$

$$Pipe \text{ wall thickness} = 3.91 \text{ mm}$$

$$Time \text{ for full penetration} = \frac{3.91}{0.029} = 134.83 \cong 135 \text{ hours} \quad (6)$$

If the installation is running an average of 4 hours per day, for Volume 1:

$$Time \text{ for full penetration} = \frac{135}{4} = 33.75 \cong 34 \text{ days} \quad (7)$$

For Volume 2 the maximum erosion rate was $2,69 \times 10^{-7}$ kg/m² – s. All values used in calculations are the same as for Volume 1 except the maximum erosion rate. The full penetration time for Volume 2 can be calculated using the maximum erosion rates ratio.

$$\frac{Volume \text{ 1 max. erosion rate}}{Volume \text{ 2 max. erosion rate}} = \frac{3.89 \times 10^{-7}}{2.69 \times 10^{-7}} = 1.446 \quad (8)$$

$$Time \text{ for full penetration} = 34 \text{ days} \times 1.446 = 49 \text{ days} \quad (9)$$

B. Erosion area and life expectancy for control Volumes 3 and 4

As for Volumes 3 and 4 there are two maximum erosion areas, the mass loss in the bend for Volume 3 and Volume 4 was calculated using the following approximation of the erosion area:

- 1) First dimension is the half pipe circumference;
- 2) To obtain comparable erosion areas the second dimension is the bend length divided by 2.75 i.e.

$$\left[\frac{2\pi(R_{bend})_{outer}}{4 \times 3} \right]_{\text{volume 1 and 2}} = \left[\frac{2\pi(R_{bend})_{outer}}{4 \times n \times 2} \right]_{\text{volume 3 and 4}} \quad (10)$$

$$\frac{150}{3} = \frac{275}{n \times 2} \Rightarrow n = 2.75$$

$$\frac{2\pi \times r_{pipe}}{2} = \frac{2\pi \times 0,025}{2} = 0.0785 \text{ m};$$

$$\frac{2\pi(R_{bend})_{outer}}{4} = \frac{2\pi \times 0,275}{4} = (0.432m)/2.75 = 0.157 \text{ m} \quad (11)$$

$$Erosion \text{ area} = 0.0785 \times 0.156 = 12.33 \times 10^{-3} \text{ m}^2 \quad (12)$$

Although the large radius bends have two maximum erosion points, the erosion area situated toward the end of the bend is smaller; hence the total maximum erosion

area can be approximated to about 0.8 of the calculated value:

$$12.33 \times 10^{-3} \times 0.8 = 9.864 \times 10^{-3} \text{ m}^2 \quad (13)$$

Considering the maximum erosion rates of $3,61 \times 10^{-7}$ kg/m²-s for Volume 3 and $2,41 \times 10^{-7}$ kg/m²-s for Volume 4 and following the same calculation pattern as for Volumes 1 and 2, the installation life expectancy was calculated as 58.24 days for Volume 3 and 87 days for Volume 4 respectively.

C. Erosion area and life expectancy for modified Volumes 1-M, 2- M, 3-M and 4-M

As the bend geometrical characteristics are identical to those for control Volumes the installation life expectancy can be calculated using the corresponding maximum erosion ratios:

$$\frac{Volume \text{ 1 max. erosion rate}}{Volume \text{ 1-M max. erosion rate}} = \frac{3.89 \times 10^{-7}}{2.71 \times 10^{-7}} = 1.435 \quad (14)$$

$$Time \text{ for full penetration} = 34 \text{ days} \times 1.435 \cong 49 \text{ days} \quad (15)$$

$$\frac{Volume \text{ 2 max. erosion rate}}{Volume \text{ 2-M max. erosion rate}} = \frac{2.69 \times 10^{-7}}{2.70 \times 10^{-7}} = 0.996 \quad (14)$$

$$Time \text{ for full penetration} = 49 \text{ days} \times 0.996 \cong 48.82 \text{ days} \quad (15)$$

$$\frac{Volume \text{ 3 max. erosion rate}}{Volume \text{ 3-M max. erosion rate}} = \frac{3.16 \times 10^{-7}}{2.59 \times 10^{-7}} = 1.22 \quad (16)$$

$$Time \text{ for full penetration} = 58.24 \text{ days} \times 1.22 \cong 71 \text{ days} \quad (17)$$

$$\frac{Volume \text{ 4 max. erosion rate}}{Volume \text{ 4-M max. erosion rate}} = \frac{2.93 \times 10^{-7}}{2.41 \times 10^{-7}} = 1.216 \quad (18)$$

$$Time \text{ for full penetration} = 87 \text{ days} \times 1.216 \cong 106 \text{ days} \quad (19)$$

With the exception of Volume 2-M where is a slight life expectancy decrease the rest of modified volumes induce a significant increase in installation life expectancy.

4. Flow velocity reduction

The modified volumes life expectancy increased by on average of 29, 33 %. This was mainly due to the velocity decrease in the modified volumes. Table 1 shows the values of maximum flow velocities in the bend and the percentage velocity reduction.

Table 1 – Percentage solid particle velocity reduction

	Maximum velocity m/s		Maximum velocity m/s	Reduction %
Volume 1	32.8	Volume 1-M	28.6	12.8
Volume 2	32.5	Volume 2-M	28.8	11.4
Volume 3	30.1	Volume 3-M	28.3	6.0
Volume 4	30.1	Volume 4-M	28.5	5.3

Figures 10 and 11 show the velocity path lines defined by velocity magnitude in the bend area for the modified volumes. As can be seen from figures 10 and 11 the core

exhibits higher velocity flow in the straight portion of the pipe, where the flow space modification occurred, right before the solid – air mixture engages in the bend. Once in the bend the flow velocity is reduced to the values listed in table 1, implicitly decreasing the wall erosion. It has to be observed that the particles path lines coloured by velocity magnitude engage in the bend in a vortex flow.

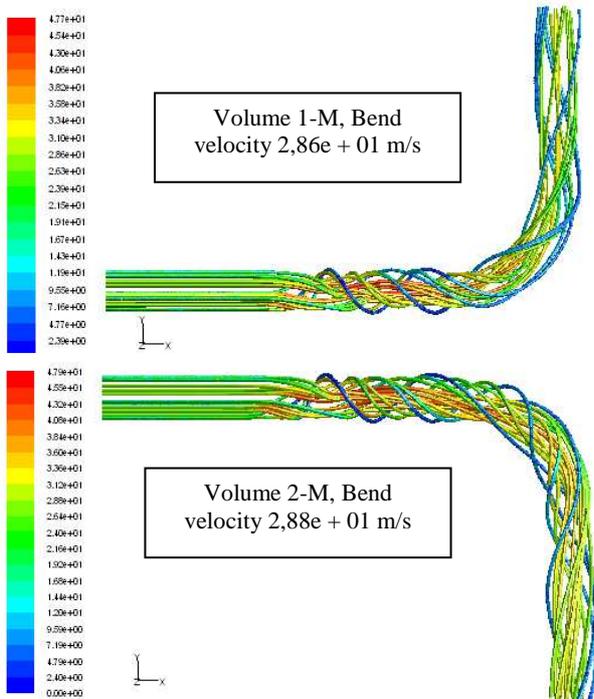


Fig. 10: Velocity path lines defined by velocity magnitude for the modified Volume 1-M and 2-M

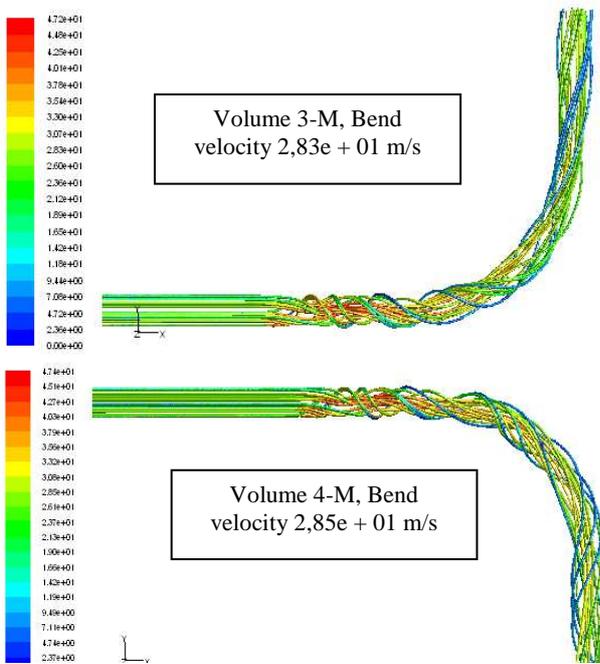


Fig. 11: Velocity path lines defined by velocity magnitude for the modified Volume 3-M and 4-M

Tables 2, 3, 4 and 5 list some flow parameters that influence the installation life expectancy.

Table 2: Installation life expectancy for reference volumes

	Volume 1	Volume 2
Overall static pressure loss	17,08 kPa	17,56 kPa
Maximum velocity	32,8 m/s	32,5 m/s
Maximum mass loss through erosion [kg/m ² – s]	3,89 x 10 ⁻⁷	2,69 x 10 ⁻⁷
Installation life expectancy	34 days	49 days

Table 3: Installation life expectancy for reference volumes

	Volume 3	Volume 4
Overall static pressure loss	17,34 kPa	17,76 kPa
Maximum velocity	30,1 m/s	30,1 m/s
Maximum mass loss through erosion [kg/m ² – s]	3,16 x 10 ⁻⁷	2,41 x 10 ⁻⁷
Installation life expectancy	58,24 days	87 days

Table 4: Installation life expectancy for modified volumes

	Volume 1-M	Volume 2-M
Overall static pressure loss	22,5 kPa	29,1 kPa
Maximum velocity	28, 6 m/s	28, 8 m/s
Maximum mass loss through erosion [kg/m ² – s]	2,71 x 10 ⁻⁷	2,70 x 10 ⁻⁷
Installation life expectancy	49 days	48,82 days
Installation life expectancy increase / decrease compared to control volumes	44 %	- 3,69x10 ⁻³ %

Table 5: Installation life expectancy for modified volumes

	Volume 3-M	Volume 4-M
Overall static pressure loss	28,4 kPa	28,6 kPa
Maximum velocity	28, 3 m/s	28, 5 m/s
Maximum mass loss through erosion [kg/m ² – s]	2,59 x 10 ⁻⁷	2,9 x 10 ⁻⁷
Installation life expectancy	71 days	106 days
Installation life expectancy increase compared to control volumes	22 %	22%

5. Conclusions

- The DPM modelling of the reference volumes show a heavy erosion concentrated on a well defined area in the bend. This will result in complete penetration after a minimum of 34 days for volume 1 and a maximum of 87 days for volume 4.
- The DPM modelling of the modified volumes show a significant bend life expectancy ranging from 49 days for Volume 1-M to maximum of 106 days for Volume 4-M. With the exception of Volume 2-M where there is a slightly negative growth, all modified volumes show an average life expectancy increase of about 29,33 %.
- All volumes showed a severe pressure drop.
- For all volumes the particle velocities are within comparable values and above saltation velocity.

E. Careful consideration should be given to the pressure drop as there is the risk of pipe clogging. A sensible balance should be maintained between a higher output pressure compressor, energy costs and velocities increase.

References

- [1] Digest of South African Energy Statistics; 1998; Department of Minerals and Energy.
- [2] (First National Communication on Climate Change to UNFCCC, by South Africa, DRAFT report. 2000)
- [3] Coal Fired Power Generation Technologies
<http://starfire.ne.uiuc.edu/~ne201/1996/kawka/history.htm>
!-History and Background
- [4] BRADLEY, M.S.A.-U.K.: Pressure Loss Caused by Bends in Pneumatic Conveying Pipelines - Effects of Bend Geometry and Fittings; *Powder Handling & Processing*, Vol. 2, No. 4, November 1990, pp. 315-321
- [5] DENG, T., PATEL, M., HUTCHINGS, BRADLEY, M.S.A., "Effect of Bend Orientation on life and puncture point location due to solid particle erosion of a high concentrated flow in pneumatic conveyors", *Wear*, Vol. 258 (2005), pp 426-4
- [6] BRADLEY, M.S.A. AND REED, A.R.-UK: An Improved Method of Predicting Pressure Drop Along Pneumatic Conveying Pipelines; *Vol.2, No. 2, September 1990*, pp.223-227