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Numerical investigation of a new pipe wall design to reduce elbow erosion

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Abstract. *Pneumatically conveyed particles are commonly responsible for triggering the erosion process by impacts on the wall. Those impacts result from the fluid-particle interaction and understanding their mechanisms is the key to mitigate the erosion damage in engineering applications. In this paper, a novel pipe wall design is proposed in order to reduce the erosion on a 90° elbow. This design consists of twisting a pipe wall along the flow streamwise direction. Basically, such configuration generates a swirling flow upstream of the elbow and consequently re-disperses the transported particles, preventing them from focusing on a single point at the elbow. An accurate CFD model based on the Euler-Lagrange approach is used for evaluating the erosion depth. Experimental data on a standard pipe elbow is employed for validating the numerical results (Solnordal et al., 2015). Further, simulations are run for the new pipe geometry. In general, the changes in the two-phase flow brought about by the twisted pipe wall are effective for reducing elbow erosion. The simulations show that a reduction of erosion peak up to 33% can be achieved in a pipeline equipped with the twisted pipe wall in comparison to the baseline configuration.*

Keywords: *New pipe wall design; CFD; Solid particle erosion modeling; Erosion reduction; Air-sand erosion.*

1. INTRODUCTION

When particles have to be transported, elbows are prone to erosion because of the high conveying velocities necessary to keep the solid motion. In such situation, the particles constantly impinge the elbow outer wall and remove surface material. The secondary flow downstream of the elbow increases the particle impact frequency with the wall, resulting in higher erosion rates. Despite being a relatively simple geometry, the erosive wear elbows experience has drawn the attention of many researchers over decades. Many experimental investigations have been carried out to provide data on the erosion distribution in a 90° elbow (Mazumder et al., 2005; Kesana et al., 2013; Solnordal et al., 2015).

In this respect, constant effort has been put in the accurate prediction of the erosion in standard 90° elbows. Nevertheless, very few studies have focused on geometric modifications that increase the elbow lifetime by reducing the erosion rate (Mills, 2004). In essence, such configuration generates a swirling motion of the flow upstream of the elbow, which consequently re-disperses the transported particles, preventing them from repeatedly impacting a single region at the elbow. The effects of the turbulent flow generated by the twisted pipe wall on the particles are then investigated in one twisted pipe design (i.e., containing 4 in the radial direction) and the mechanisms responsible for mitigating elbow erosion are scrutinized.

2. Pipe wall design proposal

The new pipe wall design is presented in Figs. 1 with 4 undulations. Visibly, the pipe wall concept is simple. Based on the untwisted pipe diameter (D, where D is equal to 102.5 mm), smaller circles (with radius equal to D/4) are inscribed and rotated by an angle α_1 (Fig. 1c). For the present cases, $\alpha_1 = 90°$ leads to a wall with 4 undulations (4 inscribed circles). It is important to bear in mind that depending on the value of α, the swirl generated by the undulations will be more intense or not.

Once the undulations are set, they are turned along the axial direction. For this case, the undulations were turned once (360°) along 1333.5 mm (13D) according to Fig. 1b. The twisted wall length is also important to determine the swirl generated. In fact, a correct combination of the undulations with the twisted length will dictate how strongly the fluid interacts with the walls. For instance, fewer undulations in a short space can generate the same swirl as a long twisted wall with more undulations. Such parameters are strictly related to each pipeline plant and should be defined according to the desired erosion reduction to be achieved at the elbow.

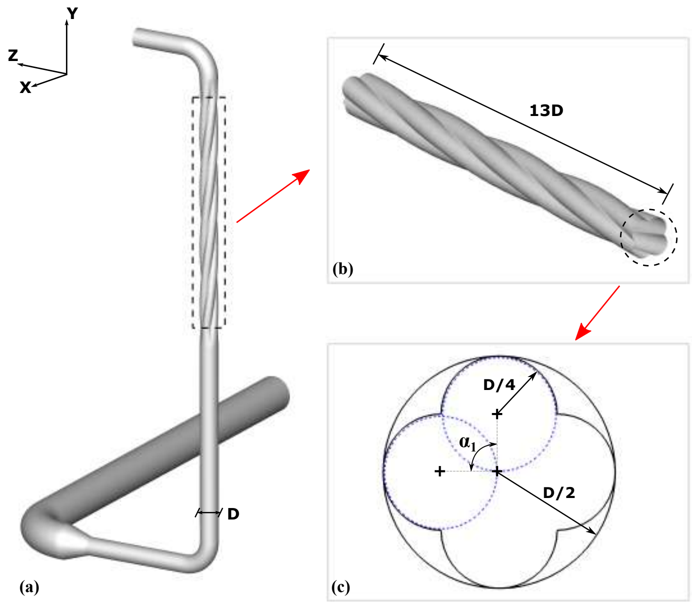

Figure 1. Schematics of the proposed pipe wall with 4 undulations.

3. Methodology

3.1 Eulerian-Lagrangian approach

In order to simulate the multiphase flow, the Unsteady Reynolds Average Navier-Stokes (URANS) equations are combined with a stochastic Lagrangian particle tracking technique to numerically predict the erosion phenomenon on a 90° elbow pipe. The former is connected with a Reynolds stress turbulence model and the contribution of the particulate phase on the fluid was taken into account by appropriate source terms in the momentum equations.

The numerical solution of the conservation equations for the momentum and turbulence is accomplished by the computational code UNSCYFL3D (Martins et al., 2014).

3.2 Erosion model

Among the various empirical models available for predicting the erosion rate, the one developed by Oka and Yoshida (2005) and Oka et al. (2005) is used in this work. It is based on wear measurements of different materials in a wide range of impact angles, particle diameters and impact velocities and yields results that agree with the measurements by Solnordal et al. (2015).

In the model developed by Oka et al. (2005), the erosion damage reads:

$$E_\alpha = 81.714\,(\mathrm{Hv})^{-0.79}\left(\frac{\mathrm{u}_p}{\mathrm{u}_{ref}}\right)^{k_2}\left(\frac{\mathrm{D}_p}{\mathrm{D}_{ref}}\right)^{k_3}(\sin\alpha)^{n_1}\left(1+\mathrm{Hv}\,(1-\sin\alpha)\right)^{n_2} \tag{1}$$

In this work, the rebound model proposed by Grant and Tabakoff (1975) is employed:

$$e_n = 0.993 - 1.76\,\alpha - 1.56\,\alpha^2 - 0.49\,\alpha^3 \tag{2}$$

$$e_t = 0.988 - 1.66\,\alpha + 2.11\,\alpha^2 - 0.67\,\alpha^3 \tag{3}$$

Regarding friction, $\mu_s = 0.45$ and $\mu_d = 0.30$ were used for the static and dynamic coefficients, as they best match the experimental results in Duarte et al. (2017); Pereira et al. (2014).

3.3 Boundary conditions

The air velocity at the inlet is prescribed as U_f = 21.01 m/s with a turbulence intensity of 0.1%. A gauge pressure of 0 Pa is set at the domain exit. The diameter for particle inlet is 40 mm. The sand particles are introduced with a velocity of U_p = 1.0 m/s in crossflow with the air. Their size distribution was represented by 21 classes following the experimental distribution (see Table 2 of Solnordal et al. (2015)), with a mean diameter of 184 μm. 550 parcels are injected at each timestep. Under steady state conditions, nearly 11 million particles were used for the statistics. The fluid and particle timesteps were 1.0×10^{-4} s and 1.0×10^{-5} s, respectively.

The boundary conditions used in this investigation were as those used in the experiments (Solnordal et al., 2015) (Table 1).

Table 1. Simulation conditions.

Air flow rate ($\dot{m}_f$)	0.78 kg/s
Air density (ρ_f)	1.18 kg/m^3
Air viscosity (μ_f)	1.8×10^{-5} Pa.s
Sand flow rate ($\dot{m}_p$)	0.030 kg/s
Sand density (ρ_p)	2650 kg/m^3
Mass loading (η)	3.846%
Amount of sand passing	300 kg
Mean volume fraction (α_p)	1.746×10^{-5}

4. Results and discussion

4.1 Influence of the pipe design on the elbow erosion

The goal of this numerical experiment is to assess the erosion patterns for the 4-spiral pipe. Fig. 2 shows all the erosion-related variables for the 4-spiral pipe. The erosion depth contours for the 4-spiral pipe (Fig. 4.1) shows a shift of the maximum erosion region to the right side of the elbow. In fact, this displacement of the maximum erosion spot to the right side of the elbow was expected since the pipe was twisted clockwise. The opposite behavior in the erosion profile would possibly be observed if the pipe was twisted counter-clockwise. Moreover, the maximum value of the erosion depth for the twisted pipe is lower than the one obtained for the untwisted pipe. This is the first evidence that the proposed pipe acts positively towards mitigating the elbow erosion.

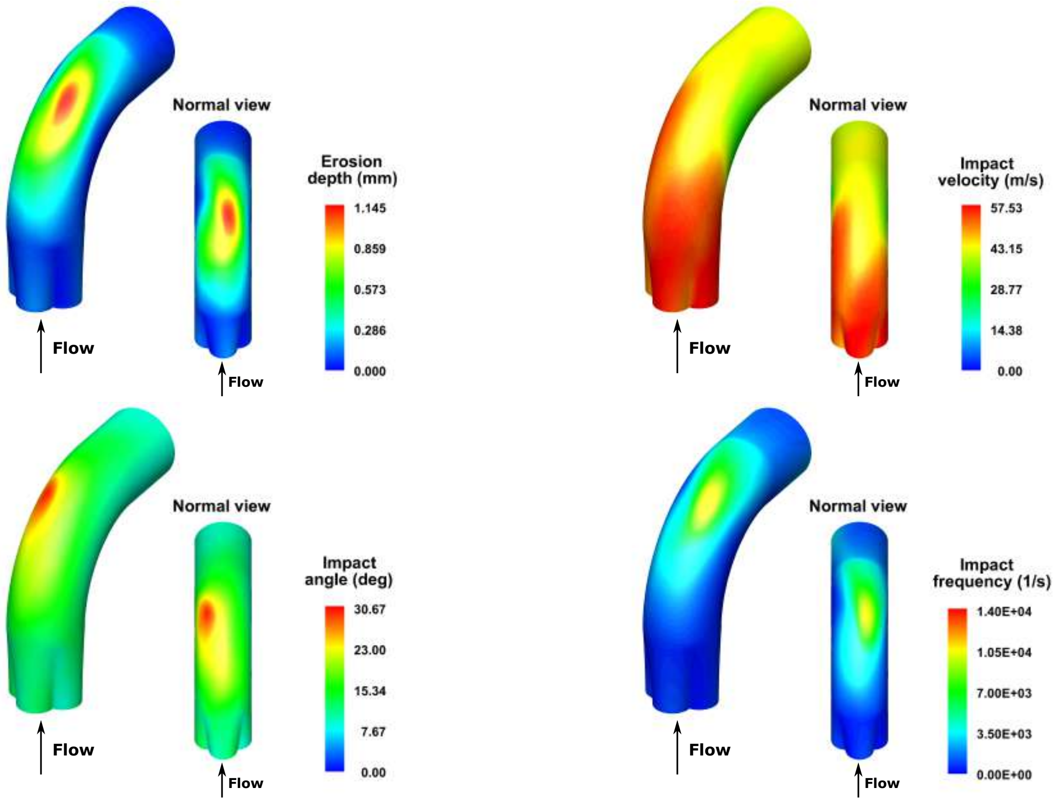

Figure 2. Contours of the erosion-related variables for the 4-spiral pipe. (a) Erosion depth, (b) impact velocity, (c) impact angle and (d) impact frequency.

The contours of the particle impact velocity for the 4-spiral pipe is presented in Fig. 4.1 In this case, the impact velocity was substantially reduced in the central part of the elbow. Notwithstanding, this reduction is also present in the untwisted pipe case, but to a lesser extend. In the latter, such impact velocity reduction is achieved by the constant interactions between the particles and the outer elbow wall. Such effect has been studied by the authors (Duarte et al., 2015, 2017) and is named cushioning effect. Basically, the inter-particle collisions become so important in regions of high particle concentration that a "virtual barrier" is created near the eroded wall, reducing the frequency at which the particles interact with it. As a consequence, the impact velocity is also reduced. In both twisted pipes, besides the cushioning effect, the swirling motion upstream of the elbow contributes to the impact velocity reduction at the central part of the elbow. These combined effects also cause modification in the impact angle. A slight reduction of the impact angle on the right side of the elbows for both twisted pipes can be observed (see, e.g., Fig. 4.1) while higher impact angles are concentrated on the left side of them.

The contours of the particle impact frequency for the present design is shown in Fig. 4.1 Again, locations with higher impact frequency are defining the erosion depth patterns although less impacts occur on elbows with the twisted pipe. In fact, the twisted region is redirecting the particles to new locations (e.g. elbow intrados), preventing them from focusing onto a single spot at the elbow.

To quantify the erosion depth on the elbow wall and relate it to each pipe type, all the erosion-related variables are presented in Fig. 3. The profile in the symmetry plane of the elbow was extracted in order to compare with the experimental result.

The erosion depth profile (Fig. 3a) confirms the reduction observed in the contours. The erosion magnitude is decreased for curvature angles between 30° and 65°. On the other hand, a slight increase is observed for curvature angles higher than 65°. Such behavior can be explained by the stronger swirl experienced by the particles in this case. In terms of the elbow lifetime, this configuration would ensure greater durability compared to the others because it has the lowest peak of erosion depth. The 4-spiral pipe reduced the peak of erosion by approximately 33% when compared to the untwisted pipe.

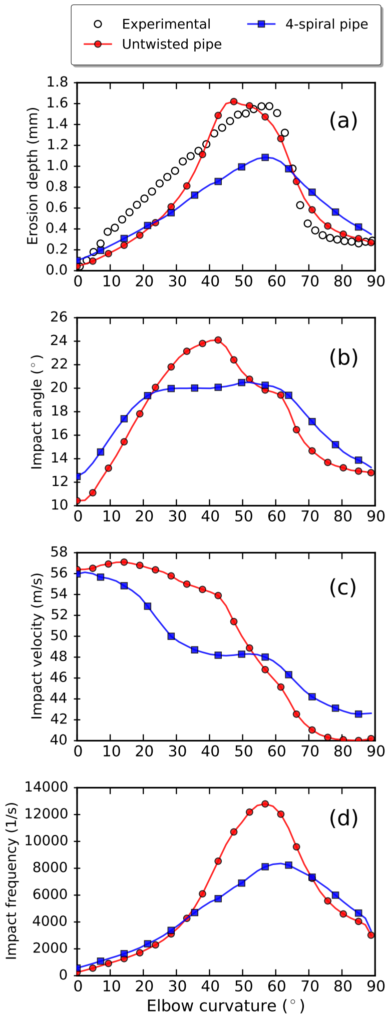

Figure 3. Influence of the pipe wall type on the erosion-related variables. (a) Erosion depth, (b) impact angle, (c) impact velocity and (d) impact frequency. Profiles extracted from the elbow extrados of symmetry plane.

To further understand the mechanisms of erosion reduction in the simulated cases, the impact angle and impact velocity are presented in Figs. 3b and 3c, respectively. The impact angle profile was flattened for curvature angles between 20°

and 65° when compared to the untwisted pipe (Fig. 3b). Additionally, the impact velocity (Fig. 3c) was reduced for curvature angles between 0° and 50° while an augmentation for curvature angles larger than 55° is clearly visible. Such increase in the impact velocity is partially related to the erosion depth increase at the same location. However, the impact frequency (Fig. 3d), again, contributes in defining the erosion depth profile. The combined effect of both for curvature angles larger than 70° reflects in the erosion accretion on the 4-spiral pipe.

5. Conclusions

The gas-solid flow in a new pipe wall design was investigated herein. Its influence on the flow was analyzed and related to the elbow erosion reduction. In this sense, the present work highlights the benefits of the twisted pipe wall design in order to mitigate elbow erosion.

The main results of this study are:

- The flow modifications brought about by the twisted pipe walls are crucial on the particles dynamics.
- The maximum value of the erosion depth at the elbow for both twisted pipes are lower than the one obtained for the untwisted pipe.
- The 4-spiral pipe reduced the peak of erosion on the elbow by approximately 33% when compared to the untwisted pipe.

6. Acknowledgment

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