

NUMERICAL EROSION PREDICTION COMPARING STANDARD AND VORTEX-CHAMBER ELBOWS

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Abstract. Erosive wear is usually a decisive factor for failure of pipelines plants. Industrial processes which require conveying of erosive particles are directly exposed to problems of contamination or leakage. As a result, unnecessary costs are needed by maintenance operations. This industrial concern is responsible for leading researchers to develop new pipe fitting geometries which can reduce the problem of erosion. With this in mind, the erosion prediction in both standard and vortex-chamber elbow with a 90-degree curvature angle are investigated numerically. In order to assess the quality of the numerical predictions of the erosion rate, experimental data were primarily used to validate the erosion and restitution models for the standard elbow. After that, these models were extended to the vortex-chamber elbow. The input parameters for the empirical erosion correlation were obtained from accurate CFD models for the gas-solid flow within the bend. Four-way coupling were evaluated for both elbows. In general, it was found that the effects of inter-particle collisions on the flow and on the penetration ratio cannot be disregarded. Another important finding is that the maximum penetration ratio on the vortex-chamber elbow reduces drastically when compared to standard elbow, indicating that the flow dynamics directly contributes to this reduction. The presence of the vortex chamber at the elbow reinforces the effect that has actually been observed in experiments and is named "cushioning effect". Based on the analysis of the simulation results, it can be concluded that a layer of particles actually protects the elbow from direct particle collisions. Conversely, the inter-particle collisions damps the erosion damage to the surface. This effect is present in many particle conveying systems and, for the vortex-chamber elbow, can be used as a positive mechanism.

Keywords: Elbow Erosion, Vortex Chamber, Mass Loading, Inter-particle Collisions, Cushioning Effect

1. INTRODUCTION

Erosion is a serious problem in piping systems, especially in the oil and gas conveying. Its intensity is closely connected to poor process efficiency and reduced component lifetime. Conveying systems usually require particular attention, especially regarding piping fittings, which are normally the parts responsible for abrupt changes in flow direction. Elbows, tees and cross plugs are some examples of vulnerable conveying system components in erosive environments. Erosion in these parts can cause unexpected failures, resulting in fluid leakage, contamination, production downtime among other problems. In pneumatic conveying systems, in particular, the high velocities required for particulate materials transportation can be a serious problem. Erosive wear is probably the main reason why industry is often reluctant to install pneumatic conveying systems, particularly when abrasive materials have to be handled (Mills, 2004). On the other hand, erosion has interesting practical uses and advantages, such as in manufacturing processes which employ waterjet cutting, drilling and surface cleaning.

2. MATHEMATICAL MODELS

The Euler-Lagrange approach is employed in this investigation. Below the modeling is described, accordingly.

2.1. Gas phase model

A Reynolds-Averaged Navier-Stokes (RANS) approach is adopted in this investigation. For a general, steady-state flow, the above-mentioned equations can be written in tensor notation as:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \quad (2)$$

The numerical solution of the conservation equations for the momentum and turbulence is accomplished by the computational code UNSCYFL3D (Souza *et al.* 2012). This in-house tool is based on the finite volume method in unstructured three-dimensional grids. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is used to couple the velocity and pressure fields. More details of the solution method and the particle motion model can be found in Souza *et al.* (2014).

2.2. Erosion prediction model

The erosion rate is defined as the mass of removed material per unit of area per unit of time. It is calculated on the walls by accumulating the damage each particle causes when colliding against the wall surface. It is given by:

$$E_f = \frac{1}{A_f} \sum_{\pi(f)} \dot{m}_\pi e_r \quad (3)$$

in which A_f is the face area, $\dot{m}_\pi$ is the particle mass flow rate represented by each computational particle that collides with the face and e_r is the erosion ratio, which consists in the ratio of mass of eroded material over mass of erodent material and must be computed by a correlation.

The predictive equation for erosion damage proposed by Oka *et al.* (2005) can be expressed as:

$$E(\alpha) = g(\alpha) E_{90} \quad (4)$$

where $g(\alpha)$ is the impact angle dependence expressed by two trigonometric functions and by the initial eroded material Vickers hardness number (Hv) in unit of GPa. Is important to emphasize that this function is for the pair sand-aluminum and may change for other materials. As a result, E_{90} can be expressed as follows:

$$E_{90} = 81.714(Hv)^{-0.79} \left(\frac{u_p}{u_{ref}} \right)^{k_2} \left(\frac{D_p}{D_{ref}} \right)^{k_3} \quad (5)$$

u and D are the impact velocity and particle diameter, respectively, and u_{ref} and D_{ref} are the reference impact velocity and the particle diameter used in the experiments by Oka *et al.* (2005). k_3 is an exponent which take an arbitrary unit and is determined by the properties of the particle. k_2 exponent can be determined by eroded material Vickers hardness and by particle properties.

3. CASE DESCRIPTION AND RESULTS

As previously mentioned, the investigation of erosion prediction performed in this work adopted the experiment conducted by Mazumder *et al.* (2008) as database validation, which aluminum elbow specimens were used. By applying the above described CFD procedure, erosion predictions were performed in elbows for the flow conditions listed in Tab. (1).

Table 1. Simulation conditions for erosion prediction.

Fluid	Air
Fluid density	1.225 Kg/m ³
Fluid viscosity	1.79 × 10 ⁻⁵ Pa.s
Fluid velocity	34.1 m/s
Material of specimen	Aluminum (6061-T6)
Material density	2,700 Kg/m ³
Particle type	Angular SiO ₂ -1
Particle density	2,900 Kg/m ³
Average particle size	182 μm
Mass loading	0.0013 kg _p /kg _s

Sand particles were injected in the line at about 1.22 m below the test piece. The test piece was a 90° standard elbow (Fig. (1)) and a vortex-chamber elbow (Fig. (2)) with a diameter of 0.0254 m and a curvature radius of 0.0381 m. In order to represent more realistic behavior at the specimen location, the whole domain was included on the calculation. This configuration attempts to better reproduce the experimental conditions.



Figure 1. Standard elbow domain

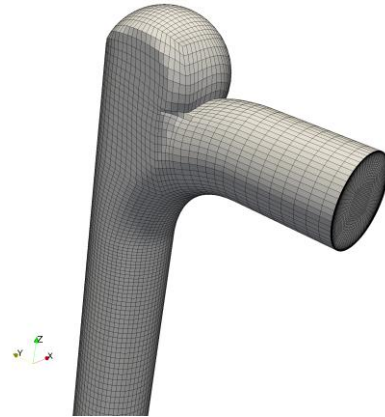


Figure 2. Vortex-Chamber elbow domain

Figures (3) and (4) shows the fluid velocity field for both elbow types, the streamlines illustrates how the flow dynamics behave on both cases. The presence of the vortex chamber creates a high rotation region where incoming fluid is forced to deviate to the exit. This intensifies when particles are injected in the field. The vortex-chamber “traps” the particles inside, creating a rotating particle shield responsible to deflect or prevent incoming particle to directly collide to the wall. On the other hand, the structural design of the standard elbow cannot generate this active protection, creating a well-defined erosion region.

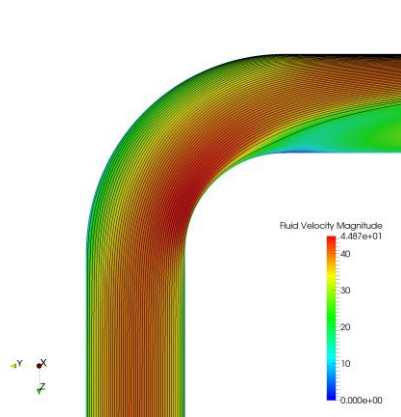


Figure 3. Fluid field for the standard elbow.

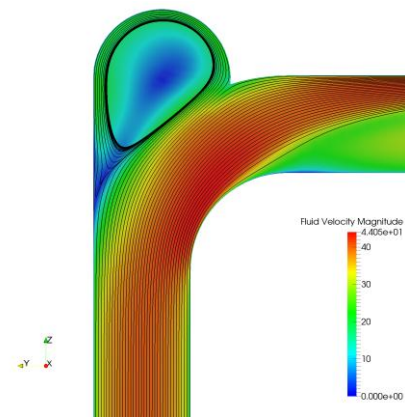


Figure 4. Fluid field for the vortex-chamber elbow.

Despite the low mass loading simulated ($\phi = 0.0013$) the interparticles collisions cannot be disregarded on this type of analysis so a four-way coupling approach was used. Figures (5) and (6) illustrates the particle concentration in both configurations. The preferred particles location on standard elbow reinforces the idea of the direct impact to the wall. On the other side, the vortex-chamber elbow mainly concentrate the particles on the first portion of the elbow curvature and on the semi spherical region of the vortex chamber.

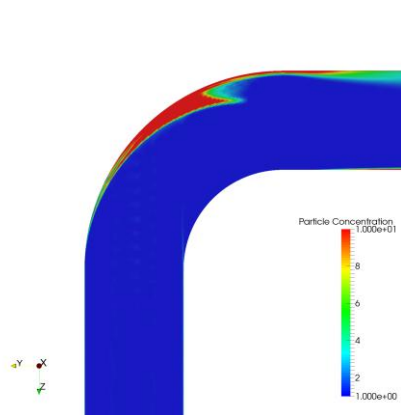


Figure 5. Particle concentration for the standard elbow.

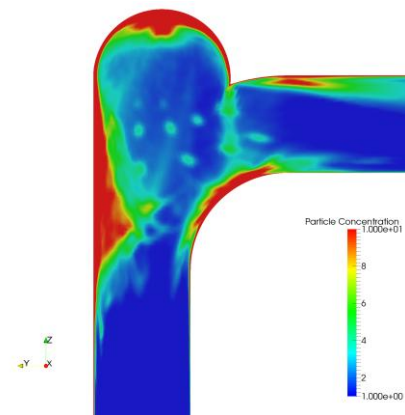


Figure 6. Particle concentration for the vortex-chamber elbow.

The erosion region analyzed on the standard elbow was extracted from the bend wall from the opposite side of the inlet domain which have 90° of curvature angle, in the case of the vortex-chamber elbow, the region of erosion was extracted from the semi sphere which have 180° of curvature angle. Figure (7) compares the penetration ratio profile for both elbow configuration. Remarkably, the penetration ratio is reduced when the vortex chamber is used. The peak reduction of erosion was approximately 36.5%. This clearly justifies the deflective protection created by the vortex chamber. In addition to the deflection by rotation, as previously mentioned, a layer of particles also protects the semi spherical part of the vortex chamber through a mechanism called cushioning effect.

The physical explanation for this reduction is entirely related to the inter-particle collisions. The layer of particles immediately adjacent to the wall damps the impact of incoming particles to the eroded surface, reducing the magnitude of the penetration.

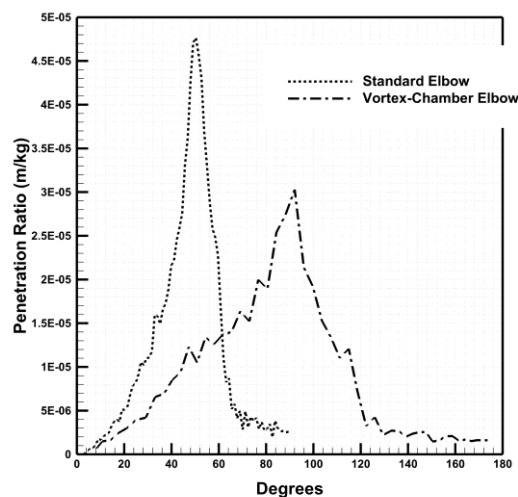


Figure 7. Penetration ratio versus bend curvature angle for standard and vortex-chamber elbow.

4. CONCLUSIONS

Based on the simulation results, it can be concluded that even at low mass loadings, the effects of inter-particle collisions on the penetration ratio cannot be disregarded. The main contribution of this work is the prediction and evaluation of the cushioning effect in standard and vortex-chamber elbows erosion. It is noteworthy that such effect has been detected experimentally and can be present in several industrial situations. It may also be the key to understanding erosion-related problems.

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