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Mitigating elbow erosion with a vortex chamber

Carlos Antonio Ribeiro Duarte, Francisco José de Souza *, Vinicius Fagundes dos Santos

School of Mechanical Engineering, Federal University of Uberlândia, Av. João Naves de Ávila, 2121 Bloco 5P, 38400-902 Uberlândia, Minas Gerais, Brazil

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ABSTRACT

Wear due to particles is often the key factor for pipeline failure. Parts such as elbows, for instance, are particularly prone to erosion issues. In this work, the erosion in a bend equipped with a vortex chamber is investigated numerically. Initially, experimental data are used to validate the CFD model for the standard elbow. Subsequently, a vortex chamber is added to the original geometry, preserving its geometric characteristics (e.g., diameter and curvature radius) as well as the simulation parameters (e.g., boundary conditions, density, viscosity). Based on four-way coupled simulations of the gas–solid flow in both geometries, the comparison between the standard and vortex-chamber elbow results is performed and a detailed analysis of the mass loading influence on the flow and on the penetration rate is carried out. In general, it is found that even at low mass loadings, inter-particle collisions play an important role in the overall flow behavior. The maximum penetration ratio gradually diminishes as the mass loading increases for both geometries. This phenomenon has actually been observed in experiments and is named cushioning effect. Another important finding is that the vortex chamber significantly improves the efficiency of the cushioning effect, reducing the peak of penetration ratio up to 93% when compared to the standard elbow. In both standard and vortex chamber elbows, a layer of particles builds up adjacent to the elbow wall, protecting it from direct particle collisions. By virtue of the vortex motion in the vortex chamber, the shielding effect of the inter-particle collisions is potentialized, mitigating the erosion rate as the mass loading is increased.

1. Introduction

Pneumatic conveying systems are constantly exposed to abrasive wear issues. The most common mechanism responsible for this kind of surface damage is classified as erosive wear. In many industrial processes, this type of wear arises from the impingement of solid particles against the surface and has noticeable consequences on equipment reliability and safety. While abrasive wear can be a problem in cyclone separators, propellers and pumps, it can be particularly more serious in pneumatic conveying systems [1].

Generally speaking, erosive wear is a problem which industry has learned to coexist with. Although there are many ways to mitigate its magnitude, relating it to the conveyed material and the system itself requires that a number of variables be taken into account. In addition, maintenance time and operating costs are also important factors that lead companies to decide on the best method for minimizing erosion in their equipment. For an entire pipeline plant, the effects of different elements (e.g., constrictions, pipe shapes and pipe fittings) have to be considered. Due to the nature of the conveying process, piping systems are prone to wear when abrasive particles have to be transported. When particulates are carried by an airstream, high conveying velocities are required to keep the material moving in order to prevent pipeline obstruction. In such a situation, pipe fittings such as bends provide pneumatic conveying systems with their flexibility to change the flow direction. On the other hand, such parts become more susceptible to repeated particle collisions and rapid wear can occur.

Following the first concepts of the standard elbow fitting [2–4], many efforts have motivated the scientific community to understand the physics behind the erosion process in this geometry. Experimental investigations [5–9] supported the development of empirical correlations and models capable of predicting the erosion [10–14]. In this sense, progress in understanding erosion due to particles has been achieved by the utilization of CFD models that can accurately simulate the fluid and particle motion through pipelines and bends [15,16]. Experimental results reveal that the erosion rate is directly related to the particle impact velocity and, to a lesser extent, the particle impact angle. For brittle materials, any reduction in either or both of these variables will result in a decrease in the erosive damage. Based on these findings, several practical solutions have been proposed, as summarized by Mills [1]. Increasing the bend curvature radius, for instance, provides for a smoother transition between directions, and consequently lower impact angle on the bend inner surface. Among these solutions, a particularly ingenious one is the vortex chamber. According to Mills [1], the rotating fluid motion promoted by this chamber keeps the particulate

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* Corresponding author.
E-mail address: fjsouza@mecanica.ufu.br (F.J. de Souza).

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material constantly moving inside, providing a so-called cushioning effect. Consequently, the inner surface of the chamber is protected from the otherwise direct particle collision, as it occurs in the standard elbow. It is important to emphasize that this shielding effect might also occur in the standard bend geometry. A recent study from Duarte et al. [17], showed that the maximum penetration ratio gradually diminishes as the mass loading increases in a standard bend. Although this seems counterintuitive, the physical explanation for such a decrease in the erosion rate is related to intensified inter-particle collisions. As the mass loading increases, more inter-particle collisions occur and less particle-to-wall collisions take place. As a consequence, a layer of particles immediately adjacent to the wall damps the impact of incoming particles to the standard elbow surface, reducing the magnitude of the penetration. This phenomenon has been evidenced experimentally [18] as well.

There have been a number of patents based on the vortex chamber concept [19–22]. The principle is the same as described above: a cluster of particles rotate in a vortex manner inside the chamber deflecting the subsequently passing particles.

Despite the apparent benefits of the vortex chamber principle, there is virtually no data on its performance in the open literature. Thus, the main goal of this work is to quantitatively investigate the erosion reduction brought about by a vortex chamber. The standard elbow is used as a reference. The effects of different mass loadings are studied in order to identify the limits for a potential reduction in the penetration rate. Many correlations can be used to calculate erosion in standard elbows [10–14] but recent studies from Pereira et al. [16] and Duarte et al. [17] suggest that the Oka model [23] appears to be the most accurate, robust approach, as it is based on measurable properties of both eroded and erodent materials. The computational code UNSCYFL3D, which solves the particle-laden gas flow using the fully coupled Euler–Lagrange approach, was used. The two-layer k-epsilon was used to model turbulence effects.

To validate the CFD model and add confidence to the models employed, the numerical results for erosion on the standard elbow are compared to the data measured by Mazumder et al. [9]. Subsequently, a vortex chamber is added to the original geometry, preserving its characteristics (e.g., diameter and curvature radius) as well as the simulation parameters (e.g., initial velocity, density, and viscosity). Based on four-way coupled simulations of the gas–solid flow in both geometries, the comparison between the standard and vortex-chamber elbow results is performed and a detailed analysis of the mass loading influence on the flow and on the penetration rate is carried out. The role of inter-particle collisions in both cases is scrutinized. The physical mechanisms responsible for the reduction in the erosion rate in the vortex chamber are also explained. A complete analysis of the flow and particle dynamics is presented in Sections 3 and 4, respectively. To the best of the authors's knowledge, this is the first published work in which the efficiency of the vortex chamber is evaluated.

2. Numerical approach

2.1. Gas phase and particle motion models

In order to simulate the fluid flow in both elbow geometries, the Euler–Lagrange approach was employed. The continuous phase was calculated by solving the Reynolds-Averaged Navier–Stokes (RANS) equations in connection with the 2-layer k-epsilon turbulence model. The contribution of the particulate phase on the fluid was taken into account by appropriate source terms in the momentum equations. For a general, steady-state flow, the above-mentioned equations can be written in tensor notation as:

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

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

where ρ is the fluid density, u is the Reynolds-averaged velocity component, p is the mean pressure, μ the gas viscosity and μ_t is the turbulent viscosity. The additional source terms due to phase interaction is represented by Su_{ip}.

The numerical solution of the conservation equations for the momentum and turbulence, is accomplished by the computational code UNSCYFL3D [24]. 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. The collocated arrangement is used for all variables, with the conventional Rhie–Chow interpolation scheme for the computation of the mass flow rate through each volume face. The main advantage of this modeling is that it does depend on the element shape, as the data structure is based on element faces. For storing the coefficients of the linear systems for the velocity components, pressure correction and turbulence variables, the CSR (Compressed Sparse Row) format is used.

In all the simulations carried out in this work only the steady-state solution for fluid was sought. The second-order upwind scheme was employed for the advective term, whereas the centered differencing scheme was used for the diffusive terms of the momentum equations and turbulence model equations.

It is very important to refine the grid so as to have $y+ < 1$ in the first element away from the wall and ensure accurate results for the fluid flow. The models for both the fluid and particle have been validated in another publication [25]. All the details of the solution method can be found in previous publications [17,16,24–26].

The simulation of the particulate phase is treated in a Lagrangian framework, in which each particle is tracked through the domain and its equation of motion is based on Newton's second law. The trajectory, linear momentum and angular momentum conservation equations for a rigid, spherical particle can be written, respectively, as:

$$\frac{dx_{pi}}{dt} = u_{pi} \tag{3}$$

$$m_p\frac{du_{pi}}{dt} = m_p\frac{3\rho C_D}{4\rho_p d_p}(u_i - u_{pi}) + F_{si} + F_{ri} + \left(1-\frac{\rho}{\rho_p}\right)m_p g_i \tag{4}$$

$$I_p\frac{d\omega_{pi}}{dt} = T_i \tag{5}$$

In the above equations, $u_i = U_i + u_i'$ are the components of the instantaneous fluid velocity. The average fluid velocity U_i is interpolated from the resolved flow field, whereas the fluctuating component u_i' is calculated according to the Langevin dispersion model. d_p is the particle diameter and $I_p = 0.1\ m_p\ d_p^2$ is the moment of inertia for a sphere. Unlike most commercial CFD codes, UNSCYFL3D solves for the particle rotation. This is particularly important when dealing with large particles, which frequently collide with walls.

Inter-particle collisions are modeled by a stochastic, hard-sphere model. As described by Oesterlé and Petitjean [27] and Sommerfeld [28], for each computational particle, a fictitious collision partner is generated, and the probability of a collision is checked based on an analogy with the kinetic theory of gases. This in turn requires that the average and RMS linear and angular velocities, as well as the particle concentration in each control volume, be sampled and stored during every Lagrangian calculation.

Because an unstructured grid is used in this work, there is the need for a specific algorithm to locate the particle after its final position is calculated by the integration of Eq. (3). For that purpose, the particle-localization algorithm proposed by Haselbacher et al. [29] was used.