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Reducing bend erosion with a twisted tape insert

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ABSTRACT

Due to the ongoing problem related to erosion caused by the impingement of solid particles in many engineering fields, parts such elbows, for instance, are particularly prone to erosion issues. In this work, the insertion of a twisted tape at different positions upstream of a bend is investigated numerically with the intent of reducing the elbow erosion. To ensure the reliability of the numerical calculations, experimental data were used to validate the CFD model for the standard elbow. Subsequently, simulations considering one, two and four-way coupling were evaluated for both the standard and the twisted tape-equipped elbows. Simulations were run to evaluate the average particle impact angle, impact frequency and impact velocity and the penetration ratio for each geometry. It was found that the swirling motion imparted to the particles by the twisted tape reduces the maximum penetration ratio in the bend. Another important finding is that the farther the insert is placed upstream of the elbow, the lower the erosion in the elbow, although the tape itself becomes more prone to erosion. In general, it was noticed that the fluid-particle and particle-particle interactions are very important and cannot be neglected. Consequently, depending on the mass loading and geometry configuration, elbow erosion can be dramatically reduced.

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1. Introduction

Erosion, as defined by ASTM International G40-13 [1], is the progressive loss of the original material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, an impinging liquid, or impinging solid particles. Nonetheless, the term erosion can be very broad generating the requirement of more specific terms. According to Crook [2], erosion wear can be divided into four distinct terms, solid particle impingement erosion, slurry erosion, liquid droplet impingement erosion and cavitation erosion. Particularly in the first situation, if the hardness of the particles to be conveyed is higher than that of the system components, such as feeders and pipeline bends, then erosive wear will occur at all surfaces against which the particles impact. 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, pumps, inlet nozzles and choke valves, it can be particularly more serious in pneumatic conveying systems [3].

Generally speaking, erosive wear is a problem which industry has learned to coexist with. The cost of abrasion wear has been estimated as ranging from 1 to 4% of the gross national product of an industrialized nation [4]. As a consequence, the mitigation of the wear magnitude is also a matter of primary importance to the country's economy. Proven to be one of the critical factors for some machinery components, erosive wear is frequently a key factor in defining or restricting the proper lifetime of a component. 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. Due to the nature of the conveying process, piping systems are prone to wear when abrasive particles have to be transported.

There are many principles and ideas that can be used to reduce bend wear due to particles, as stated by Mills [3]. One of the methods is the insertion of a twisted tape or a spiral inside the pipe, upstream of the bend. Mills [3] noticed a considerable reduction in the bend erosion, indicating that the method can be effective. Other works related to the erosion mitigation in pipelines using twisted tape insert were carried out by Ionescu [5] and Wood et al. [6], where the authors found potential benefits generated by the swirl created by the insert. In 2013, Kadyirov [7] investigated only the swirl flow in detail. On the other hand, inserts are commonly used in heat transfer equipments [8–10] to improve heat transfer rates.

Despite the apparent benefits of the twisted tape insert, there is virtually no data on its performance in the open literature related to erosion in elbows. Thus, the main goal of this work is to quantitatively investigate the erosion reduction brought about by the twisted tape placed at four different positions upstream of the bend. The standard elbow at the same mass loading is used as a reference. The effects of the insert are studied in order to identify a potential reduction in the penetration ratio in the bend.

To validate the CFD model and add confidence to the models employed, the numerical results for erosion on the standard elbow are

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compared to the data measured by Mazumder et al. [11]. Subsequently, a twisted tape 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 twisted-elbow results is performed as well as a detailed analysis of the particles impact angle, impact frequency and velocity on the flow within the geometries. The role of interparticle collisions in both cases is investigated. The physical mechanisms responsible for the reduction in the erosion rate in the twisted-elbows are also explained.

Many correlations can be used to calculate erosion in standard elbows [12,13]. Pereira et al. [14] and Duart et al. [15,16] suggest that the Oka model [17] 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.

By gaining a better understanding of the effects of the twisted tape insert in pipelines systems, it is possible to implement it as a passive controller to reduce the undesirable elbow erosion, besides reducing maintenance costs or even preventing more expensive measures, such as replacing the curve part worn by erosion.

2. Numerical approach

The Euler-Lagrange approach is employed in this investigation. The modeling of both phases is described below.

2.1. Gas phase model

An Unsteady-Reynolds-Averaged Navier-Stokes (URANS) approach is adopted in this investigation:

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

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

where ρ is the fluid density, u_i is the Reynolds-averaged velocity component, p is the mean pressure, μ the gas dynamic 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 [18]. 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 element face. The discretization procedure described above generates a linear system of equations for each variable at each element center. The biconjugate gradient and the algebraic multigrid (AMG) methods are used to efficiently solve the linear system resulting from the discretization of the conserved and turbulence properties. The main advantage of this approach is that it does not 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. More details of the solution method can be found in De Souza et al. [19].

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.

The standard k-epsilon model is the most widely known and extensively used two-equation eddy viscosity model [20]. It was originally developed to improve the mixing-length model and to avoid the algebraic prescription of the turbulence length scale in complex flows. Transport equations are solved for two scalar properties of turbulence, the turbulence kinetic energy, k, and its dissipation rate, epsilon:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial(\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j} + P - \rho\varepsilon\right] \tag{3}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial(\rho u_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j} + C_{\varepsilon 1}\frac{\varepsilon}{k}P - C_{\varepsilon 2}\ \rho\ \frac{\varepsilon^2}{k}\right] \tag{4}$$

where P is the production term, given by:

$$P = (\mu_t + \mu)\left[\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}\right]. \tag{5}$$

The eddy-viscosity in the standard k-epsilon model is defined as a function of the turbulent kinetic energy and the turbulent dissipation rate as:

$$\mu_{t,standard} = C_\mu \rho\,\frac{k^2}{\varepsilon}. \tag{6}$$

Although widely used, the standard k-epsilon displays some weaknesses, such as the assumption that the flow is fully turbulent. To circumvent this issue, the 2-layer k-epsilon model was employed, as it can handle well both the core flow and the near wall region. Essentially, it consists in solving the standard model for the turbulent flow region and a one-equation model for the region affected by the viscosity. In the one-equation k-epsilon model, the conservation equation for k is retained, whereas epsilon is computed from:

$$\varepsilon = \frac{k^{3/2}}{l_\varepsilon}. \tag{7}$$

The length scale that appears in Eq. (7) is computed from:

$$l_\varepsilon = yC_l\left(1 - e^{-Re_y/A_\varepsilon}\right). \tag{8}$$

In Eq. (8), Re_y is the turbulent Reynolds number, defined as:

$$Re_y = \frac{\rho y\sqrt{k}}{\mu} \tag{9}$$

where y is the distance from the wall to the element centers. This number is the demarcation of the two regions, fully turbulent if $Re_y > Re_y^*$, $Re_y^* = 200$ and viscosity-affected, $Re_y < 200$. For the one-equation model, the turbulent viscosity is computed from:

$$\mu_{t,2layer} = \rho C_\mu l_\mu \sqrt{k}. \tag{10}$$

The length scale in the equation above is computed as below:

$$l_\mu = yC_l\left(1 - e^{-Re_y/A_\mu}\right). \tag{11}$$

In UNSCYFL3D, both the standard k-epsilon and the one-equation model described above are solved over the whole domain, and the solutions for the turbulent viscosity and the turbulence kinetic energy

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