Numerical analysis of erosion pattern on pipe elbow bend with swirling flows

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Abstract. Abrasive solid erosion is a common issue faced in many industrial applications and can incur significant loss to production efficiency. In a piping system, the bends are generally the most vulnerable to the abrasive erosion due to the abrupt change of flow. Reducing the erosion at the bend is key to industries for safety purpose and ensure equipment longevity. This research focusses on the effectiveness of utilizing the swirling flow in reducing the erosion rate at the elbow bends. Numerical approaches are adopted to systematically evaluate the impact of the degree of swirling in the flow on the erosion reduction at the elbow. The results demonstrate the promising prospect of the swirling flows as a mechanism to control the erosion at the pipe elbow.

1. Introduction

Abrasive erosion are common issues encountered in numerous manufacturing and processing industries that employs pneumatic system to transport granular material. Abrasive erosion has detrimental effect to the industries as it causes more frequent production downtime for maintaining equipment. Abrasive erosion left unchecked can result in severe consequence, such as leakages of processing materials from the system that damages the equipment and contaminates the surrounding environment. Minimising erosion is important to industries due to the impact it has on the maintenance cost, and the risk management.

Typically, the pneumatic system’s elbows are identified to be the component that is most vulnerable to abrasive erosion. As a result, numerous investigations were conducted to understand the mechanism of erosions at the elbow, and the factors that could impact the erosion rate. Various strategies were proposed to control the erosion rate. The previous studies focussed on the impact of the operating conditions on the erosion rate at the elbows, such as how the erosion is controlled by the pipe curvature ratio and diameter by El-Beherly et al. [5], the effect of particle size and pipe material [6], the influence of particle impact angle and the material properties [10,13], impact velocity [11].

Researchers also have proposed various designs to alter the shape elbows and manipulate the flows at the bend. An overview of the designs was comprehensively summarized by Dhodapkar, Solt, and Klinzing [2]. The common fittings such as Tee-bends were proposed to counter erosion by creating a particle-particle impact zone. However, the design was less effective in reducing erosion [1]. The specialized bends are the latest innovative designs that exerts better control on the erosion. Gamma bend, pellbow bend and smart elbow bend are examples of the recently proposed models. Each offers unique physical mechanism on erosion reduction. The smart elbow bend utilizes a spherical chamber to form rotating particle shield that deflect incoming particles from impinging directly on the wall. There are evidences from the recent studies [2,11] on the effectiveness of the designs in reducing erosion compared...
to the standard elbow. Gamma bends and pellbow designs utilizes their customized shape to increase the area of the particle-particle impact zones.

This paper investigates the use of swirling inlet as a mechanism to reduce the erosion. Most previous investigations assume uniform flow inlets. Swirling flows as mechanism to reduce erosion was investigated recently [4], but a systematic study into the effect of swirling degree on the erosion was not performed before. The objective of this study is to numerically investigate the effect on the erosion pattern on a common elbow bend when the inlet flows are angled at a range 10 to 30° from the normal inlet.

2. Methodology
A common elbow pipe bend with particulate air flows from the inlet as shown in Fig. 1 is considered. The pipe has a diameter D of 0.0254m and the elbow has a radius to pipe diameter ratio of 1.5. The length of the inlet pipe was assigned to be twelve times the pipe diameter to allow the flow to be fully developed before it enters the bend. The flow is turbulent with a velocity of 34.1m/s and Reynolds number of over 60,000. The particulate mass flowrate is 0.0217 kg/s and the corresponding mass loading is 0.013. Four cases are considered here, namely a common uniform inlet that is parallel the pipe, and three swirling inlets that are angled at 10, 20 or 30° from the normal direction, as shown in Figure 2.

Figure 1 Geometry and meshing employed for the elbow pipe bend.

(a) Top View
2.1 Computational Approaches

The analysis were performed using computer approaches. Commercial Computational Fluid Dynamics (CFD) code StarCCM v13 were employed to simulate the problem. In this computational method, the governing equations of the fluid flows were treated using the finite volume method whereby the equations are numerically integrated on a control volume basis into a set of discrete algebraic equations that are then solved iteratively using computer algorithm. The governing equations of the model used in this study is summarized in the Table 1. In this simulation, the second order discretization schemes are employed to numerically discretize the Reynolds-Averaged Navier Stokes (RANS) and the Turbulence model equations. The SIMPLE algorithm is chosen to iteratively solve the governing equations in the domain until the solver convergence criteria is achieved. The transport of the solid particles are resolved separately from the fluid flow transport. After the calculation on the airflows is completed, the transport of the solid particles is then solved using the particle Lagrange equation. Giving the low mass loading of the flow (less than 2%), one-way coupling is assumed between the particle and the air flows. Particles impacting on the wall are assumed to always rebound from the wall at the angles following Grant & Tabakoff model. The strength of the impact is estimated using the Oka et al. erosion model.

| Physics                  | Mathematical Model                                      |
|--------------------------|---------------------------------------------------------|
| Airflow Transport        | Reynolds-Averaged Navier Stokes (RANS)                  |
| Flow Turbulence          | Standard K-Epsilon                                     |
| Near Wall Treatment      | Two-layer All y+                                       |
| Particle Transport       | Lagrange with 1-way coupling                            |
| Particle Drag Correlation| Schiller-Naumann                                        |
| Particle Shear Lift      | Sommerfeld [13]                                         |
| Erosion model            | Oka et al. [10]                                         |
| Impact model             | Grant-Tabakoff [7]                                      |

3. Model Validation

Simulations of different mesh density were simulated in order to determine the mesh independent solution. The effect of mesh density was analyzed based on the erosion profile along the pipe bends. Figure 3 shows that the erosion profile predicted using a lower mesh count of 1.2 million closely matches with the simulation with almost triple mesh cells. This demonstrates that the simulation configuration using 1.2 million is sufficiently fine for the current problem. Also included in Figure 3 is the experimental result from previous study [9] for verifying the simulation model’s accuracy. The overall comparison of the simulation model prediction with the experimental result is fairly good. The overall characteristics are well captured, i.e. an increasing erosion from the initial location, followed by an abrupt increase of erosion near to the peak at 50-degree position, and then a drastic drop of erosion after the peak.
4. Result & Discussion

In a common configuration where there is no swirl, the erosion pattern is characterized by a small area of peak erosion at the middle of the pipe, with much lower erosion around the peak. This pattern is the result of the abrupt change of direction of the pipe that forces the solid particle to concentrate into a smaller stream and impact on the small area on the pipe as depicted by the particle trajectories plot on Figure 4(a). On the other hand, the continuous flows exhibit different profile from that of particle trajectories, i.e. the flows along the bend is more uniformly distributed. This observation is quite typical in gas-solid flows with high Reynolds number due to the weak coupling between the continuous flow and the solid particles. Solid particles cannot follow the continuous flow when there is abrupt change of direction.

When swirl of 10 degree is imposed on the flows, the flows along the bend are slightly changed and the erosion pattern on the bend is significantly changed. It can be seen that the peak is slightly diffused and is shifted slightly downstream and away from the centerline. The erosion around the peak is significantly reduced and the prominent V-shaped that is observed in the common scenario is also diffused out. The key observation is the reduction of the maximum erosion by 35% at the peak. The observation shows the effectiveness of the swirling flows in accommodating the solid particles in facing the abrupt change in the flow direction. The swirl allows “more time” for the particles to adapt to the flows changes. This is evidenced in the shift of the particle trajectories from a concentrated stream to a diffused stream, as depicted in the particle trajectories plot in Figure 4(b). Increasing the swirl to 20 degree further amplifies the effect of the swirling but only marginal improvement on the erosion reduction. The erosion peak is shifted further downstream, and a further reduction of 8% is achieved in the maximum erosion.

A significant shift in the flow dynamic occurs when the swirl is increased to thirty degree. At this condition, the swirl is sufficiently strong to transform the characteristics of the particle trajectories from a converging streamline into rotating flows. As a result, the erosion peak is eliminated and, instead, the erosions are diffused out over the entire pipe, with characteristics of a swirling flow. This effectively

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Figure 3. Erosion rate prediction along the centerline of the pipe bend for different mesh and the comparison against experimental result.
reduces the maximum erosion by a hefty margin of 82%. The maximum erosion reduction is summarized in Figure 5.
Figure 4. Erosion contour on the pipe (top), flow streamline (middle), and particle trajectories (bottom) for 10°, 20° and 30° swirling flows.

Figure 5. Maximum erosion rate as a function of swirling degree.

5. Conclusion
This study presents a numerical investigation on the erosion reduction on the elbow-type bend using the mean of swirling inlet. The study shows that a significant 35% reduction in the maximum erosion is achieved when a mere 10 degree swirl is imposed on the flows. When the swirl is increased to 30 degree, the particle trajectories are completely transformed into a rotating flows that sees a significant 82% reduction is achieved in the maximum erosion. The study highlights the effectiveness and potential of the swirling flows as a mechanism to reduce erosion. Further study will investigate more diversified boundary conditions to ascertain the applications of the swirling in greater range of scenarios.

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