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An experimental and numerical analysis of erosion caused by sand pneumatically conveyed through a standard pipe elbow

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ABSTRACT

Erosion of surfaces is an on-going industrial problem wherever solid particles are conveyed. The literature reveals very limited data reported for elbow erosion. Almost all data that is available only relates to the elbow extrados, or else provides an overall mass loss of surface material with no information on erosion distribution. A detailed surface map of erosion depth in a standard elbow (90° bend, with bend radius to pipe diameter ratio equal to 1.5) is presented using measurements taken with a surface profiler. The full erosion data map is reported on a 40×20 point grid for erosion caused by the passage of 200 kg and 300 kg of sand through the elbow. The sand had a median diameter of 184 μm, and was conveyed by room temperature air travelling at 80 m s^{-1}.

Numerical modelling of the erosion distribution is then performed using the conventional Euler–Lagrange approach to erosion prediction. It is found that the use of this approach, in combination with a smooth wall assumption for particle–wall collisions, leads to inaccurate prediction of maximum erosion depth together with a characteristic "vee"-shaped erosion scar that is not present in the experimental data. By adopting a suitable rough wall collision model the erosion depth and distribution are much more accurately predicted. However, particle shape, surface profile development and surface roughness development are all factors that may also affect the erosion pattern.

The numerical modelling demonstrates the importance of accurately incorporating particle–wall collisions, as well as other more complex flow behaviour, into the simulation if a true prediction of the erosion distribution is to be captured.

1. Introduction

Pipe bends, or elbows, are ubiquitous in many engineering processes. The conveyance of particles through these bends causes erosive wear of wall material, leading to regular and costly replacement of components, or else component failure. In the oil and gas industry, the production of sand from wells travels at high pressures and high velocities through elbows at ground level, causing significant safety concerns. Similarly in the alumina industry, elbows in refineries must regularly be replaced to avoid high pressure spills of caustic slurry. These are just two countless industrial processes that rely on the integrity of pipes to carry particulate material safely and reliably.

A standard 90° elbow is shown in Fig. 1a. The pipe making up the elbow has a diameter equal to *D*, while the radius of the bend itself is denoted as *r*. The location of the smallest inner surface bend radius is called the intrados, and has radius equal to $r_{intrados}$. Similarly, the location of the largest inner surface bend radius is called the extrados, and has radius equal to $r_{extrados}$. The distance around the elbow is denoted as θ, and goes from $\theta = 0°$ at the inlet to $\theta = 90°$ at the outlet. These variables are defined in Fig. 1a.

Particle transport through elbows has been studied for decades. Some of the earliest work was performed by Bikbaev et al. [1], and involved the investigation of sand particles conveyed through 90° elbows using air as the carrier fluid. Although little information of the experimental setup is provided, it appears that a profile measurement device was used to determine the thickness of material along the extrados after passage of different quantities of sand through the bend. The change in profile position with time (presented in units of mm h^{-1}) around the elbow is shown, locating the point of maximum erosion to be between $\theta = 25°$ and 35°, depending on the bend radius used by Bikbaev et al. Also shown in the work is an image of the concentration distribution of particles as they pass through the elbow. Their image shows a focusing of sand particles in the region of highest wall erosion, and this focusing behaviour is of interest to the current work, as will be shown.

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Many researchers have performed subsequent experiments to provide data on the erosion distribution in a 90° elbow. Two experimental methods have primarily been employed. In some cases the mass of the elbow is measured before the experiment, and then at subsequent times after the commencement of the experiment [2–7]. This “mass loss” technique allows for the overall effect of erosion on the elbow to be quantified, but it does not give the distribution of mass loss around the elbow. The second technique is to measure the change in position of the inner surface of the elbow. The measurement is commonly performed using ultrasonic probes to determine the thickness of the pipe wall from its outer surface [2,4,8]. Alternatively, a profilometer measures the surface shape [3,5]. In the studies cited, the profile of the elbow extrados was measured, and therefore only gives a linear profile of the erosion variation. Only one paper was found that attempted to give more detailed surface erosion profile data, and that was the work conducted by Kesana et al. [9]. In their study, an array of 16 ultrasonic thickness measurement transducers was positioned at various locations on the outer surface of the elbow. The approximate locations are shown in Fig. 1b, with probes 2, 7, 10 and 15 measuring erosion at the extrados, while the remaining 12 probes measured erosion on either side of the extrados. While these measurements provided some detail of the erosion away from the extrados, they were inadequate for providing a detailed three-dimensional map of the erosion scar caused by particles passing through a pipe elbow.

While experimental measurements provide tangible data on the rate of erosion occurring during a specific erosion flow condition, it is often quicker and more efficient to use computational fluid dynamics (CFD) to investigate a wide variety of different flow conditions through elbows. However, the accuracy of the CFD simulation is strongly dependent on the erosion model incorporated into the numerical analysis. Many correlations and equations have been developed for predicting erosion rate under a variety of conditions, starting with the work of Finnie [10]. Indeed, some of the work numerically investigating erosion rate in elbows compares the erosion rate prediction of different models to understand their strengths [11]. However, of interest in this study is the prediction of the shape and depth of the erosion scar. Many studies were found in the literature that used different computational techniques to predict erosion in bends. Most commonly, researchers used standard Reynolds-averaged Navier–Stokes (RANS) solvers to predict Eulerian fluid flow through the elbow, followed by Lagrangian tracking of particles [3,9,11–17]: the so-called Euler–Lagrange approach. However, Dubey et al. [8] investigated the use of more complex techniques, including the dense discrete phase model available in the ANSYS-FLUENT suite of software, and also a coupled CFD–DEM (Discrete Element Model) approach. Most commonly, researchers predicted a “vee”-shaped erosion scar, as shown schematically in Fig. 2a. An elliptical region of high erosion is predicted to form on the inner surface of the pipe wall, and this region is centred on the extrados. Then two additional scars, less severe than the main one but nonetheless distinct, are also predicted, and these scars form a vee-shape downstream of the main scar. Also predicted, although less commonly, is a simple elliptical erosion scar without the vee-shape [8,16], as shown in Fig. 2b.

It is the authors' experience that vee-shaped erosion scars do not routinely occur in experiments. However, as both types of erosion scar (Fig. 2a and b) are centred on the extrados of the

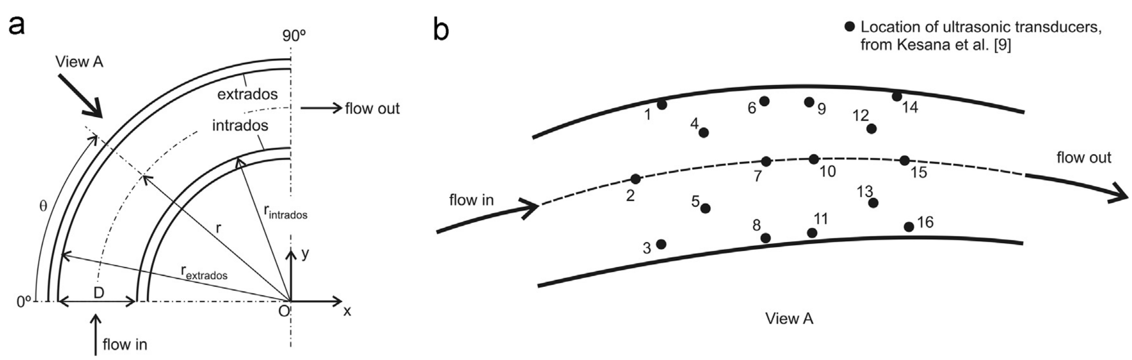

Fig. 1. (a) Standard pipe elbow, with dimensions defined; (b) view of external surface of elbow, showing locations of ultrasonic wall thickness transducers as used by Kesana et al. [9].

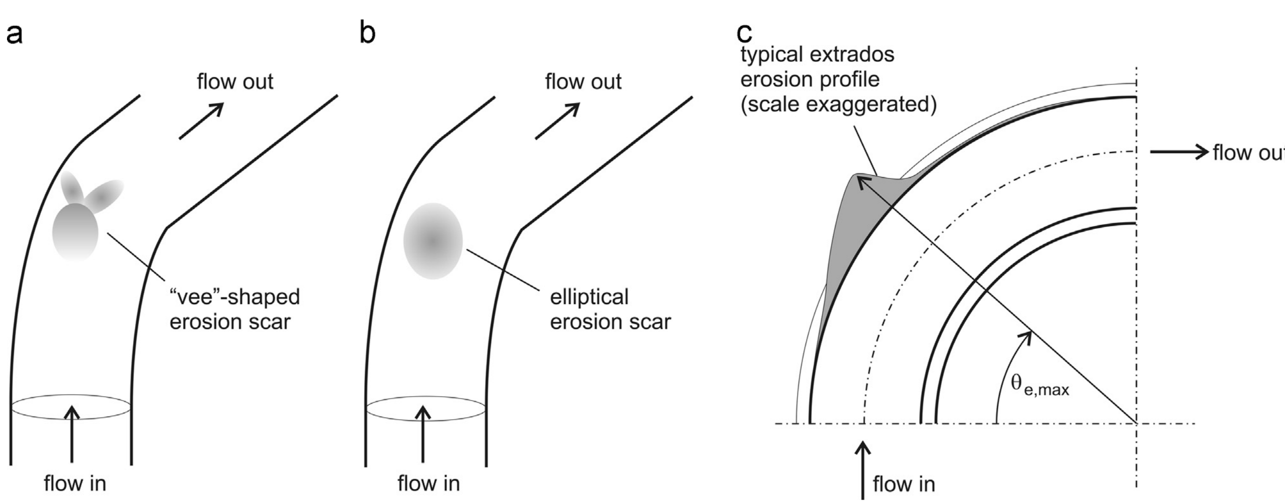

Fig. 2. (a) "Vee"-shaped erosion scar; (b) elliptical erosion scar; (c) typical erosion distribution measured on the elbow extrados.