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Numerical analysis of mitigating elbow erosion with a rib

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ABSTRACT

Particle erosion is an ongoing problem in many engineering fields. In this work, a trapezoidal rib installed at different positions on the extrados of a 90° elbow is investigated numerically with the intent of mitigating the erosion. The CFD-DPM Eulerian-Lagrangian approach is employed to evaluate the anti-erosion effect. The computational model is validated by comparing the predicted CFD erosion magnitudes to the present and previous experimental data for a standard elbow. An ellipse erosion zone with a vee-shaped scar is formed on the extrados due to the first and second particle impacts. The rib placed in front of the first impingement can partly protect the elbow from the direct impacts. As a sacrificial element, the rib itself becomes more prone to erosion. A reduction of elbow erosion peak up to 31.4% can be achieved by placing the rib at $\theta = 25°$. However, the erosion resistance is reduced as the rib moves backward. As the flow velocity increases, the sacrificial speed of the rib is accelerated while the anti-erosion effect is weakened. The larger the particle mass loading, the severer the elbow erosion. Taking the sacrificial speed of the rib and the anti-erosion effect into account, placing the rib at $\theta = 25°$ is a good choice for such measure.

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1. Introduction

In oil and gas industry, sand is frequently produced along with production fluids [1]. When the particle-laden fluids flow through pipelines, parts such as elbows, for instance, are particularly prone to wear due to the impingement of sand particles against the surface [2,3]. The erosive wear is more challenging in gas pipelines because of the higher flow velocities. Therefore, protecting elbows from particle erosion is essential to prolong the lifetime and minimize unnecessary expenses [4]. However, flow erosion is a complex process determined by a number of factors such as flow velocity, particle concentration, impact angle and target surface properties [5].

Finnie [6] discussed the mechanism of particle erosion on ductile and brittle materials. For the ductile materials and particles impinging at low angles [7], cutting wear dominates the erosion, while deformation wear becomes the predominate one for the brittle materials and particles impinging at high angles [8,9]. The two mechanisms usually act together to produce wear scars [10]. Extensive efforts have been dedicated to predicting the erosion magnitude of a standard elbow both experimentally and numerically. The majority of experiments were carried out in air-sand flow loops with one or more testing elbows installed in the pipelines [11–13]. The weight losses of the testing elbows or the specimens cut from the elbows were measured to analyze the erosion rate [14,15]. Unfortunately, only the maximum erosion rate or the linear erosion profile along the extrados was obtained in many tests [16]. Until recently, ultrasonic, particle image velocimetry and surface scanning techniques have been employed in tests to describe the erosion distribution in more detail [17–20]. However, it is still challenging for experimental studies to figure out the three-dimensional erosion distribution considering all the related factors.

It is more efficient to investigate the particle erosion in a broad range of flow conditions by means of computational fluids dynamics (CFD). The CFD-based erosion calculation consists of three steps: modeling the flow field, tracking particles in the flow domain, and calculating the erosion rate based on the particle impact information [21,22]. The CFD-DPM (computational fluids dynamics-discrete phase model) and CFD-DEM (computational fluids dynamics-discrete element method) approaches have been developed and widely used to calculate the particle-laden flow. The interaction among particles is neglected in the CFD-DPM approach so that it is only suitable for dilute flow, while the CFD-DEM approach has an advantage in solving high-concentration granular flow [2]. Since gas wells are usually equipped with sand screens now, the sand-laden gas flow in natural gas pipelines belongs to dilute flow. Thus the CFD-DPM approach is employed in the present work. Furthermore, by applying particle-wall rebound models in the CFD-DPM approach, numerical results consisted well with experimental results in many reported literatures [23–26].

In the past decades, several methods have been proposed to reduce elbow erosion. Developing new high performance alloys and coatings is a traditional method to improve the erosion resistance of the elbow itself. However, this method not only increases the cost, but also raises the difficulty in the manufacture. From the perspective of gas-solid two-phase flow, some geometric modifications have been designed to

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control the flow or change the flow direction with the purpose of reducing erosion. Duarte et al. [27] investigated a method to mitigate erosion by adding a vortex chamber to the extrados of a standard elbow. A deflection region is created downstream of the chamber entrance, resulting in a more effective cushioning effect. Santos et al. [28] reported the insertion of a twisted tape upstream of a bend could attenuate the direct collisions against the same spot in the bend wall because of the swirl imparted by the tape. Recently, Duarte and Souza [29] proposed a novel pipe wall design to mitigate elbow erosion by twisting a pipe wall along the flow streamwise direction upstream of the elbow. Such configuration can also generate a swirling flow, preventing particles from focusing on a single point at the elbow wall. Notwithstanding, these alternative structures will also be worn by the particle collisions. Once the vortex-chamber elbow or twisted pipe is damaged, it needs to be replaced as a whole, increasing the time and cost of replacement. Compared to the significant geometric modifications, adding ribs to the inner wall of a bend is a simpler anti-erosion method. Moreover, only the ribs need to be replaced instead of replacing the whole elbow, significantly saving the expenditure. Song et al. [30] conducted both experimental and computational investigations to demonstrate the erosion-reduction effect of this method. Yao et al. [31] observed in their experiments that setting ribs on the wall of a bend could enhance the bend erosion protection ability. Fan et al. [32–34] examined the effect of rib shape on particle erosion. It was observed that the isosceles triangle ribs have the best anti-erosion efficiency among the three considered shapes. However, the bend concerned in their studies is a square-section one.

The main objective of current study is to examine the anti-erosion effect of a rib installed on the extrados of a standard elbow. The CFD-DPM approach coupled with a particle-wall rebound model and an erosion model was adopted to predict the erosion performance of a ribbed elbow. The effects of gas velocity, particle concentration and the installation position of the rib are discussed.

2. Problem description

As shown in Fig. 1, a 90° horizontal-horizontal elbow with a diameter of 70 mm and a curvature ratio of $R/D = 1.5$ is considered in simulations. The elbow is made of carbon steel with density of 7800 kg/m^3, Young's modulus of 2×10^{11} GPa and Poisson's ratio of 0.3. A trapezoidal rib made of the same material is installed on the extrados of the elbow. The height and axial angle of the rib are 5 mm and 5°, respectively. The annular angle of the rib is 180° so that it covers half of the elbow along the annular direction. The location of the rib (θ) is defined by the distance from the elbow inlet to the frontage of the rib. Twelve

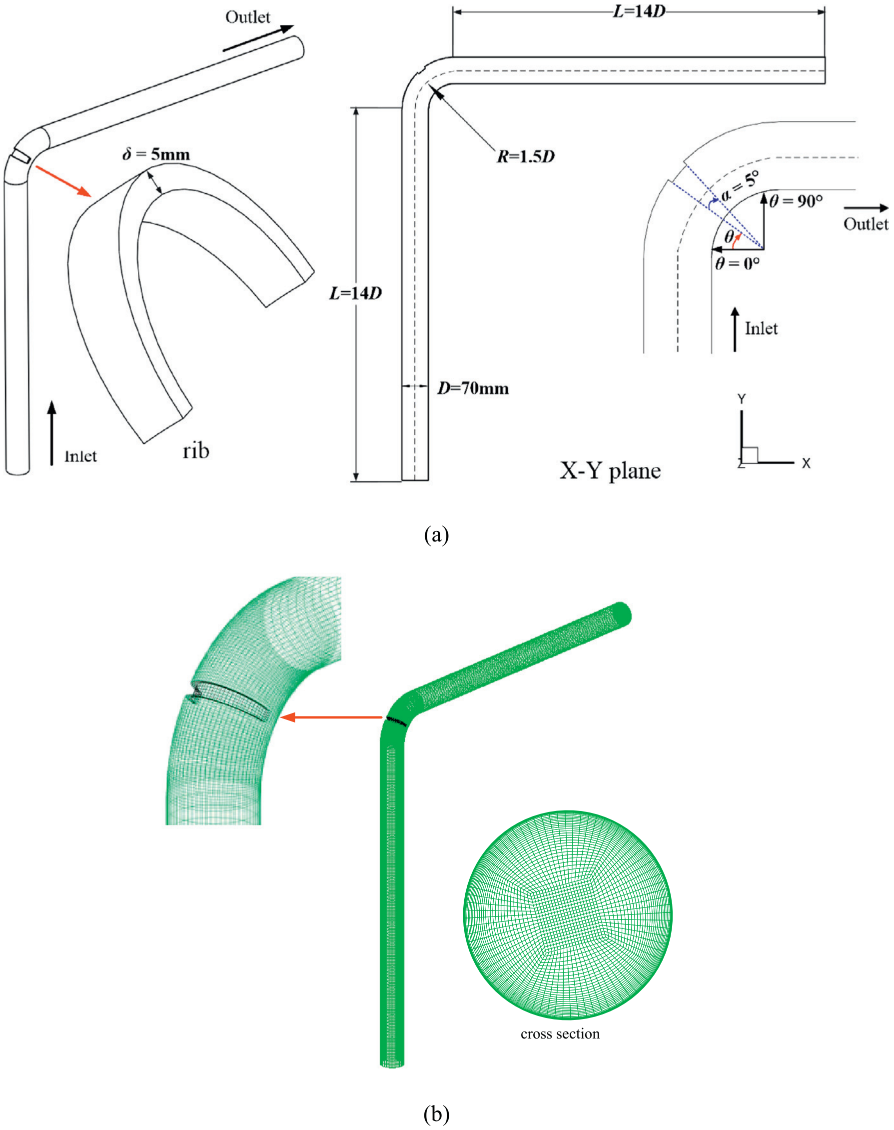

Fig. 1. Schematic of the geometry and computational mesh: (a) computational domain; (b) computational mesh.

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