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Experimental and computational study of erosion in elbows due to sand particles in air flow

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Severe equipment degradation in production piping can occur for gas–solid flows. Advances in modeling and solid particle erosion simulations are gained through matching computer generated predictions to real-world experimental results. This paper presents a comprehensive approach in modeling and computational study to determine erosion in elbows due to sand particles entrained in air. Firstly, utilizing a particle image velocimetry (PIV) technique, the slip velocity between the gas and sand particles in a direct impact geometry has been measured. Secondly, an erosion equation has been generated based on PIV results and erosion testing of stainless steel in air. Thirdly, erosion patterns are measured in a 76.2 mm ID standard elbow for air-sand flows using a state-of-the-art non-invasive Ultrasonic Technology (UT) device. The metal loss is measured at 16 different locations in the elbow using dual element ultrasonic transducers. Erosion experiments in the vertical to horizontal elbow are performed with gas velocities ranging from 11 m/s to 27 m/s at nearly atmospheric pressure. Two different sand sizes (150 and 300 μm sand) were used for performing tests. The shapes of the sand are also different with the 300 μm sand being sharper than the 150 μm sand. Finally, the new erosion equation has been implemented into a commercially available Computational Fluid Dynamics (CFD) code to predict erosion ratios in elbows for a variety of flow conditions and particle sizes. The predicted CFD erosion magnitudes are compared with present and previous UT erosion data in elbows. The comparisons show that CFD predictions are within a factor of two of present and previous UT single-phase erosion data. Four correlations for erosion from literature are also studied and validated in simulations. The correlation developed and validated in this work can be used to predict the bend lifetime for particular operating conditions.

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1. Introduction

Any industrial process involving the transport of solid particles entrained in a fluid phase can be subject to erosion damage. Erosion has been long recognized as a potential source of problems in pneumatic and hydraulic transport systems [1–3] and oil and gas production systems [4,5]. Equipment erosion caused by produced sand has long been a major operating problem in many areas, both in terms of cost of equipment replacement and in terms of the risk of pollution and/or fire caused by flowline or equipment cutouts. For example, a number of dangerous elbow failures occurred in the North Sea on production platforms and drilling units between 1993 and 2001 [6]. To make a well financially healthy, flow rates must be high in order to justify the huge amounts of resources that must be utilized to find and produce oil and gas. Higher throughput is preferred because of the advantage of having higher production rates and lower liquid holdups. The operation managers, on the other hand, must run a safe and low maintenance operation and often they desire lower, more manageable flow rates. These two desires conflict and in order to satisfy the owners the operators must work with velocities not of their choosing. The challenge to the design engineers is to find the optimum pipeline dimension that offers the highest throughput while keeping the fluid velocity below the safe operating limit.

To optimize the design of process equipment and the piping system, it is important to identify the location and magnitude of the maximum erosion rate for single-phase flows in elbows. Additionally, gas and sand experiments allow the qualification of measurement devices to determine sand erosion [7]. Medium and high gas velocity flows with low sand concentrations are expected to remove material from inner walls in a symmetric pattern. Data captured during many gas and sand experiments demonstrate maximum measured erosion patterns and the location of the maximum erosion rate.

Computational Fluid Dynamics (CFD) based erosion modeling has many advantages making it a powerful tool to predict erosion damage. Unlike many simplified erosion models, CFD-based erosion modeling can be applied to any complex components and can provide great

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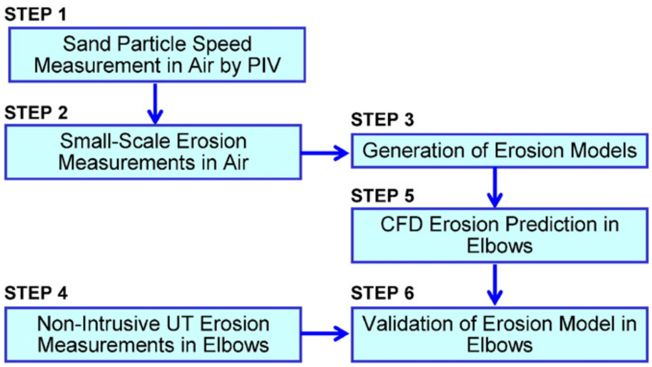

Fig. 1. Process of generating and validating erosion models.

help in developing a simple, timely procedure to predict detailed patterns of erosion.

The primary goal of this work is to improve and validate CFD-based erosion modeling predictions. The tasks and steps in the present work are shown in Fig. 1. In order to accomplish the goal, several steps have been accomplished. (1) Utilizing a particle image velocimetry (PIV) technique, the slip velocity between the gas and sand particles has been determined in a direct impact geometry. (2) Erosion data were collected for stainless steel 316 target material in air for the same flow geometry. (3) An erosion equation was generated to represent these conditions. (4) Erosion data for the same stainless steel material were collected for the same particle type in a 76.2 mm ID standard elbow using non-invasive ultrasonic transducers. (5) The new erosion equation has been implemented into a commercially available CFD code to predict erosion ratios in elbows for a variety of flow conditions and particle sizes. (6) The predicted CFD erosion magnitudes in elbows are compared with present and previous erosion data, and with four empirical correlations, proposed by Oka et al. [8], Zhang et al. [9], Det Norske Veritas (DNV) [10] and Neilson and Gilchrist [11]. These empirical models are widely used in the literature for erosion calculations.

The present work also focuses on low sand concentration (less than 2% by weight) and small sizes, which are representative of the situations encountered in oil and gas productions systems. Therefore, interactions between particles are not considered.

2. Background

2.1. Erosion ratio equations

A wide variety of erosion equations or models has been developed by many investigators [5,12]. There is no universal erosion equation for all materials to predict erosion rate as erosion is dependent on many factors. Meng and Ludema [12] concluded that there are four primary mechanisms for which solid particle erosion occurs: cutting wear and plastic deformation, cyclic fatigue, brittle fracture and melting of the materials. Besides variation of solid particle erosion mechanisms, many investigators have found that particle speed at impact and incoming angle of the impacting particles should be used to determine erosion characteristics [13]. In order to develop an impact angle dependence function, erosion tests are usually conducted with particles entrained in gas flow impacting a target wall, since the impact speed and angles are similar to the values in the flow stream. Therefore, a deeper understanding of erosion is obtained by performing small-scale experiments on metallic coupons. By performing these experiments, erosion equations are developed, which are implemented into CFD codes for predicting erosion for a variety of cases.

Finnie [14] developed the one of the earliest erosion equations erosion equations for predicting the erosion rate. Finnie [14] suggested his equation in the form of Eq. (1) and since then several erosion equations in this form were developed.

$$ER = K\ \ F_S V_P^n f(\theta), \tag{1}$$

where ER is the erosion ratio that is defined as the amount of mass lost by the wall material due to particle impacts divided by the mass of impacting particles, K is a wall material dependent constant, F_S is the particle shape coefficient that has values equal to or less than unity for sharp, semi-round and fully-round sand, V_P is the particle impingement velocity, n is an empirical constant. A range of values between 2 and 3 is recommended in the literature for the constant n. Based on previous experimental tests conducted at the E/CRC, the value of 2.41 is used as the speed exponent in the present investigation. $f(\theta)$ is an empirical function for incorporating the particle impingement angle.

Ahlert [15] and McLaury [16] at the Erosion/Corrosion Research Center (E/CRC) at the University of Tulsa performed a series of erosion tests to determine the empirical constants in Eq. (1). Ahlert [14] studied carbon steel and McLaury [16] studied aluminum. Recently, Okita [17] utilized a small-scale experimental facility to study erosion in a direct impingement geometry using glass beads in air. Erosion models were developed based on air testing for aluminum and stainless steel using LDV (Laser Doppler Velocimeter) technique for particle velocity measurements. For aluminum, erosion models were generated for two types of sand: Oklahoma #1 and California 60. These newly developed equations were used to predict erosion rates in CFD. Later, Mansouri et al. [18] performed a series of dry impingement jet tests for normal and oblique configurations. Utilizing a particle image velocimetry (PIV) technique, they determined the slip velocity between the gas and sand particles.

2.2. Experimental work in elbows in air-sand flows

There is not a large amount of published data on erosion problems in the field. Therefore, it becomes necessary to design and build experimental facilities to understand erosion phenomena under controlled conditions and develop and improve erosion prediction models. The experimental approach requires using a flow geometry of interest (such as pipe, elbow, or tee) or a representative elbow specimen to conduct the erosion tests under specific flow conditions. The erosion rate (wall thickness loss per unit time, mm/year) and/or erosion ratio (wall thickness loss per unit sand throughput, mm/kg) are then calculated from the mass loss or thickness loss data, geometry, flow and test conditions. This experimental erosion data can be used to validate erosion models.

The erosion of bends conveying a gas–solid mixture has been investigated by many researchers. Earlier experimental studies were carried out by Bikbiaev et al. [1–2]. They found that the erosion rate increases as the inlet gas velocity and curvature ratio increase. Tolle and Greenwood [19] studied the flow of gas/sand mixtures in tubulars for gas velocities of up to 30 m/s. Both high and low sand concentrations in air were used at different velocities in 50.8 mm standard elbows. Bourgoyne [20] studied experimentally the effect of flow velocity, liquid content, and sand concentration in standard elbows. Chen et al. [21] performed experimental erosion tests as well as numerical simulations in an elbow and a plugged tee with 25.4 mm diameter. Results showed that particle rebound model plays an important role in determining the motion of particles. Mazumder et al. [22] investigated the location and magnitude of maximum erosion in single-phase flows in a 25.4 mm elbow using aluminum and stainless steel specimens at different fluid velocities. The maximum erosion ratio at 34.1 m/s for 150 μm sand particles was measured at 55° from the inlet of the elbow.

Evans et al. [23] carried out an erosion study in high velocity gas systems at high pressure (6.89 MPa) in 101.6 mm long-radius elbows. Intrusive Electrical Resistance (ER) Probes were installed where the centerline of the elbow inlet intersects with the elbow surface. Similarly, extensive empirical information has been gathered at The Tulsa

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