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Invited Review

A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications

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ABSTRACT

Sand is commonly produced along with production fluids (oil and gas), and this is a major problem for the oil and gas industry. Sand production is a concern, since it can bring about a variety of problems. Amid them, three problems stand out above all: pressure drop, pipe blockage, and erosion. The latter is a complex mechanical process in which material is removed from the pipeline due to repeated sand particle impacts. As a result, the pipeline can be eroded. Eroded pipelines may cause pipe failures which can result in financial losses and environmental issues. Therefore, it is important to know what parameters govern the erosion phenomenon and how it can be modeled. The present work describes key factors influencing erosion and reviews available erosion equations. Furthermore, empirical and mechanistic models for erosion prediction in pipelines are discussed. These models are used by oil and gas companies to limit the maximum production flow rates and avoid excessive erosion damage. Computational fluid dynamics (CFD) based erosion modeling as a comprehensive method for erosion studying is explained as well. Finally, possible limitations and gaps in knowledge concerning erosion are indicated. The current work can be used by oil and gas companies as a comprehensive review of erosion challenges and remedies. Of course, further studies must be undertaken in order to expand the knowledge of erosion and find applicable models for erosion damage prediction and prevention.

1. Introduction

Production of sand from oil and gas wells happens very often. Sand production can cause severe financial and environmental difficulties. Production of sand can result in erosion, blockage of pipelines, under sand deposit corrosion, disposal and other complications. An approach to deal with sand can be eliminating sand using sand screens and gravel packs. However, there are many technical and financial problems to eliminate or control sand production especially at downhole conditions. For example, sand screens cannot prevent smaller particles (less than 50 μm, keeping in mind that this value varies with screen dimensions) from being entrained with the produced fluids. These small particles can pass through sand screens or block a portion of the screen causing higher velocities in other sections resulting in erosion. This process makes the screen openings larger allowing larger particles to pass, erode the sand screen and cause failure. One of the important results of sand production is sand erosion. Sand erosion can cause failure of equipment, leaks in pipelines resulting in environmental disasters and potential injury to personnel. Therefore, predicting solid particle erosion rate is a helpful tool in designing and selecting equipment to prevent failures.

Predicting solid particle erosion in gases and liquids is a challenging task. Despite all the resources that have been spent to investigate and study erosion, the solid particle erosion mechanism is still not fully understood. A variety of models and approaches have been proposed by researchers. Usually, erosion prediction models are divided into three categories: empirical, mechanistic and CFD-based. Since erosion is complicated, most proposed erosion prediction models are a combination of all these categories.

The main objective of this paper is to provide a comprehensive review of literature concerning solid particle erosion modeling. The paper is structured as follows. Section 2 discusses important parameters for the prediction of solid particle erosion. Section 3 is divided into different subsections. It begins with an overview of available erosion equations in the literature. Then, various empirical and mechanistic erosion prediction models are surveyed.

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Finally, CFD-based erosion modeling is discussed. In Section 4, an evaluation of some of the surveyed models is presented. The next section suggests some areas for further work.

2. Mechanism of solid particle erosion

When a particle impacts a surface, it scars the surface. Shapes of these scars depend on many parameters including surface material, particle size, and impact angle. Researchers studied these scars to explain the mechanism of erosion and generally agree that the mechanism of erosion changes based on the ductility of the surface. Finnie (1958) proposed a micro-geometry model for ductile materials. He suggested that erosion in ductile materials is the result of micro-cutting. When a particle impacts a surface at a low impact angle, it creates a crater. Other particle impacts make the crater larger and also pile up material around the crater. The piled up material is eventually removed by continued particle impacts. The micro-geometry model under predicts erosion magnitude from the particles which impact the surface at higher angles compared to experimental data. Later, Finnie (1960) modified the model to address this weakness. Based on the erosion micro-geometry model, work hardening of the metal surface should decrease the erosion rate. However, Levy (1995) showed that initial erosion is lower than erosion from previously eroded surfaces. Bellman and Levy (1981) proposed a macroscopic erosion mechanism. They suggested that particles hitting the surface create shallow craters and platelet-like pieces. These platelets are easy to separate from the surface by subsequent particle impact (Fig. 1). During the formation of platelets, adiabatic shear heating on the surface and work-hardening under the surface occur. The occurrence of these two processes helps platelet formation which explains the higher erosion rate for the steady-state condition compared to the initial erosion rate.

Other solid particle erosion mechanisms for ductile materials are suggested by researchers and can be found in literature (Chase et al., 1992; Hutchings, 1980; Andrews, 1981; Jahanmir, 1980).

Unlike the solid particle erosion mechanism for ductile materials, there is wide acceptance of the erosion mechanism for brittle material. It has been suggested that in brittle material, erosion is due to crack formation (Srinivasan and Scattergood, 1988; Sundararajan 1991, Kleis and Kulu, 2008). When a particle hits a brittle surface, it creates lateral and radial cracks. Other impacts cause these cracks to grow. These cracks divide the surface into smaller pieces which can be removed by other particles impacting the surface (Fig. 2).

2.1. Important parameters in predicting solid particle erosion

Many parameters have been found that influence erosion. Based on these parameters, researchers have proposed different erosion ratio equations which relate particle characteristics (shape, size, material, density, hardness, etc.), particle impingement information and target wall material characteristics to the mass loss of the wall. The following discussion describes some of the important parameters that influence erosion. Before erosion data is considered it should be noted that erosion data is reported differently by various investigators. For example, erosion rates are normally mass loss of materials or thickness loss of materials as a function of time such as kg/hr or mils per year or mm per year. Some authors report erosion data in the units of mass loss, volume loss or thickness loss per mass of impacting particles such as g/g or mils/lb (in/1000 lb), etc. The latter will be referred to as “erosion ratio” in this manuscript.

2.1.1. Particle properties

Particles properties such as size, density, hardness, and shape have significant influence on solid particle erosion. To have a better understanding of the influence of particle properties on erosion, the effect of each particle property on erosion needs to be investigated separately.

2.1.1.1. Particle shape. It has been observed that particle shape has a significant effect on the magnitude of erosion. Salik et al. (1981) showed that it can change the erosion magnitude by an order of magnitude. Levy and Chik (1983) observed the same behavior and reported that the sharpness of particles has a huge influence on the magnitude of erosion. They employed two different particle shapes, sharp angular particles and spherical particles. The erosion results from angular particles were four times larger compared to erosion results from round particles. It also has been reported that the impact angle that results in maximum erosion depends on particle shape and varies based on particle angularity (Hutchings et al., 1976). A particle shape factor is introduced in most of the erosion ratio equations proposed by researchers, since the shape of the particle has a pronounced influence on erosion magnitude.

2.1.1.2. Particle size. Particle size is another important particle property which influences erosion magnitude because larger particles have larger kinetic energies even if they strike a target with the same velocity as the smaller particles. Some erosion data is reported as a function of particle size (Tilly, 1973) as shown in Fig. 3. This figure indicates that the *erosion ratio* (mass of eroded materials/mass of impacting particles) is nearly independent of particle sizes when the particles are larger than approximately 100 μm.

Gandhi and Borse (2002) investigated the effect of sand size on cast iron erosion behavior for two different impact angles of 30° and 75°. The carrier fluid velocity was 3.62 m/s and sand concentration was 20 wt% (Fig. 4). They observed a linear relation between sand size and erosion rate. This behavior was reported by other researchers as well (Elkholy, 1983; Clark, 1991). These results are influenced by the fact that impact velocity of particles is not constant and changes with particle size when particles are entrained in liquid streams.

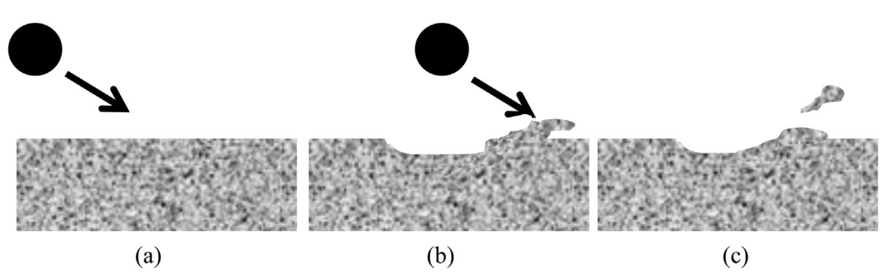

Fig. 1. Schematic of erosion procedure in ductile material (a): before the impact, (b): crater formation and piling material at one side of the crater, (c): separation of material from the surface.