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Study on erosion wear of fracturing pipeline under the action of multiphase flow in oil & gas industry

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ABSTRACT

During hydraulic fracturing operations, pipelines are especially prone to particle erosion caused by high-rate pumping fracturing fluid. Previous studies likely ignore the stress state of equipment during the erosion wear process. In this study, fracturing pipeline erosion was evaluated under the action of multiphase flow through both experimental study and computational fluid dynamics (CFD) simulation. Firstly, a new erosion wear test rig which can apply tensile stress on erosion samples was developed to indicate the failure mechanism and main parameters of erosion influence factor. The results indicate the erosion wear was greatly influenced by different states of stress. Secondly, according to the experimental results and fluid dynamic theory, the flow mode and erosion simulation model were established. The flow characteristic of particles in fracturing pipe can be described as comprehensive effects of centrifugal force, turbulent diffusion, main stream and secondary flow carrying effect. Based on the CFD simulation, the erosion distribution of pipes was also obtained. Finally, the correlation of erosion wear results from CFD simulation, experimental study, and field situation was validated in this study.

1. Introduction

The solid particles carried by liquid phases, which move through pipelines at a certain angle and velocity, impact the material surface and create wear scars; this phenomenon is called the “multiphase flow erosion wear” or the “slurry erosion wear”. As one of the primary mechanisms of material degradation, slurry erosion wear occurs frequently in the natural resource industry (Zhang et al., 2015a,b). Once erosion damage grows severe, equipment failure, economic loss and even serious accidents can result (Nieto and Zhang, 2013; Zhang et al., 2015a,b).

Hydraulic fracturing technology is an effective means to improving oil and gas production. The proppant in fracturing fluid is typically comprised of silica sand and ceramsite, both of which feature high strength and highly rigid solid particles. During hydraulic fracturing operation, as proppant-containing fracturing fluid moves through pipelines at high flow rates, slurry erosion wear is a common cause of failure in the related facilities. Accurately measuring this type of material erosion due is necessary to predict the life of equipment under different operating conditions (Futakawa et al., 2014; Haines et al., 2005; Dular and Petkovšek, 2015).

Because existing methods for inspecting the wall thickness of pipelines are expensive, there is considerable (and urgent) necessity for an accurate model for predicting pipeline erosion rates under working conditions (Vieira et al., 2014; Zhao et al., 2011). Lin et al. (2015) studied effect of gas-solid two-phase flow velocity on elbow erosion to develop an erosion prediction model which combines the theoretical and Lagrange discrete phase erosion models and accounts for the effects of multiphase velocity and gas pressure. Chong et al. (2015) studied the effects of erosion on two sizes of circular cavities and the regular and irregular weld bead-configurations commonly encountered on pipeline surfaces.

Combining physical experiments and computational fluid dynamics simulation is a novel approach to studying the erosive effect of surface imperfections in pipelines. Nguyen et al. (2014) studied the effects of impact angle and testing time on erosion in stainless steel at high flow velocities; by observing surface microstructures, they identified different erosion mechanisms associated with different impact angles. Parsi et al. (2015) applied ultrasonic measurement to sand particle erosion in gas-dominant multiphase churn flows in vertical pipelines, and identified the erosion patterns in vertical churn flows and the effects of different parameters on

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maximum erosion rates accordingly. Shah and Jain (2008) investigated the effects of erosion in reel tubing to find that as particle migration increases, erosion grows more severe with linear gel compared to viscous gels or cross-linked fluids. The same research team identified three main erosion mechanisms in coiled tubing: Direct impact, random impingement of particles, and friction damage from a sliding bed of solid particles (Shah and Jain, 2008). Parsi et al. (2014) described the key factors influencing erosion, reviewed available erosion equations, and discussed several useful empirical and mechanistic models for erosion prediction − including computational fluid dynamics (CFD) − in pipelines.

We drew a few main conclusions based on our review of the literature:

- The mechanism of slurry erosion is more complex than that of air-solid erosive wear, and the current research on erosion mechanism of liquid-solid phase flow is insufficient compared to that on air-solid phase flow.
- The existing models on erosion mechanism of multiphase flow and predicting methods are likewise insufficient due to differences in working conditions and pipeline materials leading to significant differences in erosion wear characteristics. The literature to date is concerned only with specific working conditions or certain structured pipelines, and there is a general lack of information regarding the influence of proppant in the fluid in fracturing pipes.
- Slurry erosion researchers so far have only taken into account the conventional impact factors, and neglected the impact of the pipeline stress state on erosion wear. It is necessary to further explore the destructive effect of fluid-solid interactions on pipeline materials.

We focused on the above issues in the present study in effort to remedy the knowledge gaps in the literature, and to establish a useful method of predicting the residual life of pipelines and pipeline equipment.

(1) A new erosion wear test rig is developed to apply tensile stress on erosion samples.
(2) Based on the experimental study, the failure mechanism and main influence factor such as impact angles, impact velocity, and the high-stress state effects on the erosion are researched.
(3) A new erosion calculation model is established by using of the experimental results.
(4) According to the erosion calculation model and fluid dynamic theory, the characteristics of multiphase flow and erosion wear distribution of entire pipelines can be obtained via CFD simulation.

A technical roadmap and summary of this study are shown in Fig. 1.

2. Erosion experiment

2.1. Experimental test rig

A full-size substance specimen testing rig has advantages in terms of researching erosion wear, because it can be used to simulate actual working conditions under a very realistic approximation. In a typical laboratory, however, it is very difficult to build a full-scale erosion testing rig with suitably high internal pressure. It is difficult and dangerous to implement high pressure on the inner wall of the rig, and involves complex processing techniques and expensive material to construct high-pressure pipe joints and/or various sizes of structures.

A sketch of the elbow's extrados subjected to fluid erosion is shown as Fig. 2. When the solid particles impact the sample surfaces, the force they exert can be decomposed in two parts at two directions: perpendicular and parallel to the sample surface. The circumferential stress (which is always shown as tensile) in both straight and elbow pipelines is considerably larger than the radial axial stress due to the effects of high internal pressure. Accordingly, this paper developed a novel jet−pattern erosive wear testing rig in which local circumferential stress on the inner wall can be simulated by applying stress to sliced samples, and the effects of other erosion influence factors (e.g., flow rate, proppant grain size, sand concentration, and erosion time) on high-pressure pipeline material can be accurately measured.

Erosion tests were conducted using a recirculating, impinging jet rig. The erosion test equipment included a multiphase flow mixing system, pipeline transport system, hydraulic pressure loading system, integrated control system, slurry jet device, and erosion chamber. A schematic model of the test rig is shown in Fig. 3.

2.2. Test conditions

Artificial ceramic proppant (diameter 40−50 mesh) served as the solid particle in the sample fracturing fluid, and water as the liquid phase. Ceramsite proppant is commonly utilized in hydraulic fracturing technology; its main ingredient is bauxite. After breaking apart and grinding the ceramsite sand, mixing it with various annexing agents, and sintering it, the material shows considerable advantages including high rigidity, resistance to temperature, pressure, and erosion, high intensity, and favorable sphericity and flow conductivity properties.

Erosion test samples were taken from fracturing pipes comprised of 42CrMo steel ($\sigma_s = 1000$ Mpa, $\sigma_b = 1200$ Mpa). The experimental conditions were: flow velocity of 5 m/s-20 m/s, impact angle from 15° to 90°, slurry concentration of 126 kg/m^3, and erosion test time of 1 h.

The mass loss method was adopted to gather material erosion information and study material erosion behavior. Material erosion rate $\boldsymbol{\varepsilon}$ based on mass loss was calculated as follows:

$$\varepsilon = \frac{Difference\ before\ and\ after\ material\ erosion\ (mg)}{Sand\ blast\ mass\ (\mathrm{g})} \tag{1}$$

Fig. 4 shows a comparison of proppant particles before and after the 1-h test, where the diameter changed relatively little; in effect, the test conditions were stable.

2.3. Experimental results

2.3.1. Effect of impact angles on erosion

The scar profiles of impact wear for 42CrMo specimens at different impact angles are shown as Fig. 5. After 1 h of testing, the wear patterns of the specimens varied dramatically− the scars were longer and shallower at smaller impact angles, and deeper and more circular (i.e., crater-like) at larger angles.

Erosion wear mechanisms likewise varied substantially at different impact angles (Fig. 6). The impact force of particles on the material surface involves both a horizontal component and vertical component; both components affect the material erosion features synergistically. When the impact angle was small (15°−30°), the horizontal component of the impact force was large and predominant, cutting traces through material surface such as sand waves. When the impact angle ranged from 45° to 60°, the horizontal component of the impact force decreased while the vertical