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An experimental study of slurry erosion involving tensile stress for pressure pipe manifold

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ABSTRACT

During fracturing, high pressure pipe manifold can be easily damaged under the coupling effect of the internal high pressure and erosion. In order to reveal the damage mechanism, a new apparatus which can provide an axis tensile force for specimen has been developed and built to perform the tests. Based on the macroscopic and SEM analyses, it is demonstrated that the erosion at any orientation angle increases with the tensile stress and the maximum value occurs at 30°. Furthermore, the width and depth of scratches will also increase with the tensile stress at any impact angle.

1. Introduction

Fracture in low and ultra-low permeability formations is a very effective method to generate a flow rate that achieves both the well unloading (stable production) and the economic payback. Recently, with the unceasing reduction of oil reserves, oil exploration continually becomes more difficult, the hydraulic fracturing equipment with large displacement, high-horsepower and high pressure have been adopted [1]. The high pressure pipe manifold is not only working under the high internal pressure, but also suffering the erosion from hydraulic fracturing with entrained the solid particles. Beneath these coupling working conditions, the pipelines could be easily damaged or reduced its service life and performance, such as pipe elbows, tube constrictions, and other structures which alter flow direction or velocity are susceptible to this type of erosion [2–5].

Erosion is a complex process that is affected by numerous factors and small or subtle changes in operational conditions can significantly affect the damage it causes [5]. In general, the factors which influence erosive wear in an inert environment might be roughly classified into three categories: fluid flow conditions (angle of impingement, particle velocity, particle concentration in the fluid, etc.), particle properties (size, shape, hardness, etc.), surface properties (stress as a function of strain, strain-rate, temperature, toughness, stress level and residual stress, etc.) [6]. Each parameter has its own influence on the erosive wear behavior of materials.

Up to now, researchers and engineers have taken unremitting efforts to study on the erosive wear problem in pipes and have developed many erosion prediction models. In theory, it includes Micro-cutting theory [7,8], platelet theory [9,10], micro-cutting and deformation theory [11], based on the dependent variable model [12], etc. Among them, Micro-cutting theory, platelet theory and wear deformation theory are affected the most. Generally, micro-cutting theory applies to explain the case of the cutting erosion at the low impact angle of the rigid particles. Platelet theory is mainly focused on the high impact angle, while the erosion theory is targeting to the deformation history and the variation of the energy during the erosion procedure. The advantage of the Hutchings model is to evaluate the erosion behavior of the material by using the critical strain, but it is still not mature enough, further investigation is needed. Zhang, et al. [13] discussed the effects of the slurry velocity, bend orientation and angle of elbow on the puncture location by using a numerical simulation. McLaury, et al. [14] developed a mechanistic model to predict erosion in straight pipes based on random impingement. In another study, Keating and Nesic [15] and Chen et al. [16] applied the CFD approach to investigate the erosion-corrosion problems in U-bends, elbows and plugged tees. Wood and Jones [17] researched the distribution of erosion rates and the erosion mechanisms that occurred over wetted surfaces within pilot-scale pipe systems handling water-sand mixtures. In addition, Hanley et al. [18] presented a macro-scale model of the breakage of particles at a 90° bend during dilute phase pneumatic transport. Njobuenwu and Fairweather [19] used a computational fluid dynamic model coupled to a Lagrangian particle tracking routine

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and a number of erosion models to predict the solid particle erosion in four different 90° square cross-section bends. Gandhi et al. [20–23] studied extensively the effects of various solid concentrations, particle sizes, impact angle and velocities on the material erosive wear rate by using a slurry pot tester.

Surprisingly, there is a dearth of research on the configuration related to the study of erosive wear of pipe and more specifically predicting models for the erosion rate under high internal pressure. The objective of this paper is to study the high internal pressure's influence on the erosive wear rate for the high pressure pipe manifold.

2. Experimental set-up

Based on the analysis to the working conditions of the hydraulic fracturing, the high pressure pipe manifold would be subjected to the internal high pressure during the process of fracturing, and the stress concentration in the longitudinal and circumferential direction would be generated. Moreover, the circumferential tensile stresses would be significant larger than the longitudinal in the stagnation zone [24,25]. At present, there are various of erosion test equipment for studying erosive wear under different influencing factors, such as pot tester [26], coriolis slurry tester [27,28], high temperature erosion apparatus [29], slurry jet test apparatus [30], etc., but none of them can simulate the influence of the stress on the erosive wear rate, because full scale erosive wear testing device which can simulate the situation of hydraulic fracturing is not easy to build in the laboratory.

So a new type of erosion experimental apparatus was designed and built, which can exert the adjustable axial tensile force on the erosion specimen during the erosion process. The schematic diagram is shown in Fig. 1. The apparatus consists of a mixer motor, a larger slurry cylindrical tank (approximately 110 L), impact test mechanism, a slurry pump, a hydraulic bolt tensioning jack, computer acquisition system, magnetic flow meter, etc. A mixer motor has a long steel shaft with a propeller attached to it at the tank bottom, the solid particle can be kept in a suspended state inside the slurry tank by propeller rotation. The impact test mechanism is a bowl with two specimen holders and a slurry water jet nozzle. One of the sample holders has a mechanical device which can provide angular position adjustment. The impact sample orient angle can be adjusted between 0°and 90° with the incoming slurry jet direction. The other holder connects to a tension sensor which is used for measuring the axial tension of the specimen. The hydraulic bolt tensioning jack is attached to the tension sensor it can provide an axial tensile force for the specimen. The slurry jet nozzle is perpendicular to the sample in place, and the distance between nozzle and sample is adjustable on a scale of 0–50 mm.

During the test, the slurry is pumped into the impact test mechanism from the slurry tank through the flow loop. The tensile stress on the specimen is generated by adjusting the pressure from the air-driven hydraulic pump. The major experimental parameters, containing the mixing speed, flow rate and tensile stress magnitude are measured and monitored by computerized system.

3. Materials and range of parameters

The material adopted in the tests was 30CrMo steel taken from high-pressure pipe manifolds. Its chemical composition and some of its physical characteristics are given in Tables 1 and 2. The samples were machined according to the geometry shown in Fig. 2. Before conducting the experiments, each specimen was polished with emery paper to make the identical initial conditions for each test nearly the same. A new kind of precoated sand with a spherical shape sieved to a nominal size range of 450–650 μm was used as an erodent, as seen in Fig. 3 [31].

In order to evaluate the erosive wear behavior of the 30CrMo steel under the stress state, some special experiments were conducted. The inner diameter of the selected alumina ceramic nozzle in these tests was 6 mm and the outlet portion contained a 77 mm long straight cylindrical passage to minimize the diverging effect of the slurry. The distance between the nozzle outlet and the specimen was about 20 mm. The tensile stress used for the tests were approximately 0 MPa, 300 MPa and 500 MPa. For each stress level, experiments were conducted at the nozzle exit velocity of 30 ± 2 m/s with $10 \pm 0.5\%$ solid concentrations (by weight) and the test period was 1 h. The impact angles used for the tests were 15°,30°,45°,60°and 90°. These angles were selected to evaluate and ascertain the material erosion behavior at different impact angles. The laboratory temperature was between 25 °C and 30 °C. The range of the pH value of the slurry using by pH conductivity before and after the experiment is 7.12–7.46. Hence, this is to avoid remarkably corrosion of the specimen during the tests [32].

Table 1
Chemical composition of the materials used in erosive wear tests.

Material	Composition, wt%					
	C	Si	Mn	Cr	Mo	Ni
30CrMo						
Min	0.26	0.17	0.40	0.80	0.15	
Max	0.34	0.37	0.70	1.10	0.25	0.03

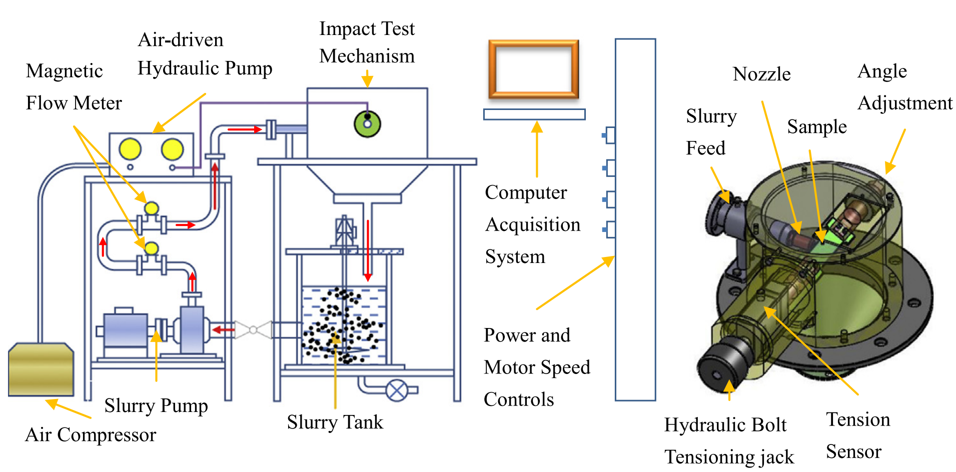

Fig. 1. Schematic diagram of the erosive wear testing system.