Erosion of water-based fracturing fluid containing particles in a sudden contraction of horizontal pipe

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Abstract. A lab experiment was carried out to study the effects of pipe flow rate, particle concentration and pipe inner diameter ratio on proppant erosion of the reducing wall in hydraulic fracturing. The results show that the erosion rate and erosion distribution are different not only in radial direction but also in circumferential direction of the sample. The upper part of sample always has a minimum erosion rate and erosion area. Besides, the erosion rate of reducing wall is most affected by fluid flow velocity, and the erosion area is most sensitive to the change in the diameter ratio. Meanwhile, the erosion rate of reducing wall in crosslinked fracturing fluid is mainly determined by the fluid flowing state due to the high viscosity of the liquid. In general, the increase in flow velocity and diameter ratio not only cause the expansion of erosion-affected flow region in sudden contraction section, but also lead to more particles impact the wall.

1. Introduction
During hydraulic fracturing, proppants constantly impact the pipe wall and the inner surface of pipe sheet (that connects the two pipes), which causes material loss of the reducing wall, especially in the pipe at wellhead or in the central tube of the downhome tool. Excessive material loss may lead to tube thread tripping, frequent failure and loss of valuable production time in oil or gas well.

Experiment on particle erosion has been studied from many aspects, such as mixed media flows, particle sizes and contents, mechanical properties of the metal surface [1] and corrosive characteristics. And erosion tests of special structure, such as sudden contraction, have been studied extensively by scientists. Malta et al. [2] investigated erosion – corrosion behavior in sudden pipe constrictions and found that the erosion rate suddenly increases in pipe constriction section. Wong et al. [3] obtained material loss information in air-suspended sands flowing through aluminum pipe annular cavity. Lin et al. [4] also analyzed the effects of cavity height on cavity erosion under gas – solid flow. Their results showed that micro-erosion occurs on the top area of aft wall, and the height difference between cavity walls markedly affects the maximum erosion rate.

Different pipe flow velocities, particle concentrations and diameter ratios can cause the difference in fracturing fluid flow properties and particle erosion state on the reducing wall. Therefore, a laboratory experimental was used to study the difference in the erosion rate and area of reducing wall by changing fluid flow velocity, particle concentration, and pipe diameter ratio. Meanwhile, the
erosion pattern of reducing wall under different flow conditions was discussed. Finally, the wall erosion rate under large fracturing displacement fracturing was predicted by erosion-velocity functional model.

2. Experimental method

2.1. Pipe flow system
In this work, erosion damage was studied in a flow loop with a sudden contraction test cell. A schematic of the flow loop and an image of the test system are shown in Figure 1. The experimental loop mainly comprised a liquid storage tank, a screw pump, a magnetic flow meter (8712HR, Rosemount. Co., America), and an erosion test section.

The test section consisted of a sudden contraction and two straight pipes (Figure 2(a)). The large-diameter pipe (D=50 mm) was connected to a small-diameter pipe (d=35 mm), and both pipes were made of acrylics. Two annular samples (super 13Cr tubing steel) were fixed by four screws on the reducing wall. The outer diameter of the sample was 50mm and the inner diameters were 35mm, 30mm and 25mm, respectively (i.e., d/D=γ=0.7, γ=0.6 and γ=0.5) (Figure 2(b)). The sample surface profiles were verified by H1200WIDE confocal scanning laser microscopy (Laertes. Co., Ltd., Japan).

![Figure 1. Schematic diagram and actual picture of experimental set-up:](image)

(1)electrical control cabinet; (2)liquid storage tank containing electric heater (2m³); (3)screw pump; (4)(6)cut off valve; (5)flow meter; (7)computer; (8)high-speed camera; (9)test section; (10)pressure transducer.

2.2. Experimental set-up

2.2.1 Solution: The base fluid used in this test added 0.4 wt% hydroxypropyl guar gum as the thickener and 0.4 wt% inorganic boron as the cross-linking agent. Before the experiment, the viscosities of base fluid and cross linked fluid were 27.42 mPa·s and 537.68 mPa·s, respectively. The viscosity of cross linked fluid at the end of the experiment was still higher than 150 mPa·s. Fracturing circular ceramists with a density of 1870 kg/m³ and an average diameter of 0.6 mm were used as the erosion abrasive. Mass concentrations of the particles in suspension were 50 kg/m³, 100kg/m³ and 150 kg/m³ (i.e., w=50 kg/m³, w=100kg/m³ and w=150 kg/m³).
2.2.2 Fluid flow temperature and velocities: The liquid temperature was set to a fixed value of 50°C with positive and negative fluctuations of 3°C to simulate the actual pipe flow temperature. In order to avoid excessive temperature rise and to ensure adequate erosion time, the inlet flow velocities in this experiment were 1.5 m/s, 2 m/s, 2.5 m/s, 3 m/s, and 3.5 m/s.

2.2.3 The operating principle: Firstly, the liquid was set and heated to a predetermined temperature with stirring, followed by mixing the fluid and particles in the tank. Secondly, the mixture was stirred by the screw pump for 5 min in the bypass pipe. Finally, the cut-off valve was opened when the flow reached stability, and related data, including particle motion image, flow pressure, and temperature, were recorded. In order to prevent the particles from completely settling in the lower part of the pipe, each erosion test was limited to 1 h.

3. Results

3.1. Erosion characteristics of reducing wall
As shown in Figure 3, the deepest erosion area is close to the inner edge of the sample, and Erosion area 1 has the minimum erosion depth. If we define the serious erosion area as an area where erosion depth is greater than 10% of maximum erosion depth, it will find that the serious erosion surface underwent multiple overlapping impacts with formation of craters, platelets, and extruding lips. And many scars caused by particle impingement were independently distributed on the outer circumference surface of sample. Although only 25% ~ 40% of total erosion areas are serious erosion areas, the surface of these areas are seriously damaged due to constant plastic deformation and cutting process acting by particle impacts. Therefore, the damage rate and width of each serious erosion area were measured as the important parameters.
3.2. Erosion rates of reducing wall

Figure 4(a) (b) (c) show the maximum erosion rates of each serious erosion area under different flow velocities, particle concentrations and diameter ratios. Except that the erosion rate increases with the increasing liquid flow velocity, the change of erosion rate with the particle concentration and diameter ratio is as follows:

3.2.1 Effect of particle concentration: When the particle concentration increases from 50 kg/m$^3$ to 100 kg/m$^3$, the growth of erosion rate is in the range of 23% ~ 31% (Figure 4(a)). And this growth is reduced to 18% with concentration of 150 kg/m$^3$. The difference in erosion rate among different areas is large when $w<100$ kg/m$^3$, and small at high particle concentration.

3.2.2 Effect of pipe diameter ratio: The smaller the diameter ratio, the greater the liquid flow velocity in the downstream tube, which may result in a greater particle impact velocity on the reducing wall. The growth of erosion rate varies in a wide range of 14% ~ 36% at flow velocity of 1.5 m/s ~ 2.5 m/s between $\gamma=0.7$ and $\gamma=0.6$ (Figure 4(a) and (b)), and this variation range decreases as the flow rate increases. When the diameter ratio is reduced to 0.5 (Figure 4(c)), the growth of erosion rate is less than 10% comparing to $\gamma=0.6$.

3.3. The widths of erosion area

As shown in Figure 4(d) (e) (f), the significant factor affecting the erosion area is the diameter ratio, followed by the concentration of particles. The widths of Erosion area 2 and 3 are similar and are much larger than the width of Erosion area 1. When the particle concentration increased by 50 kg/m$^3$, the growth of each width is almost less than 5% (Figure 4(d)), which indicates that the change in particle concentration has little effect on the erosion area. However, when the downstream pipe diameter is reduced, the width of erosion area increases significantly. Erosion width almost increased by 40% when diameter ratio is reduced from 0.7 to 0.6, which is maintained at a diameter ratio of 0.5.
Figure 4. Erosion rates and widths of reducing wall.

4. Discussion
In the process of changing the flow direction in the sudden contraction section, if the particles are out of the fluid control, they will directly impact on the wall due to inertia. In this case, the erosion area is mainly affected by inter-particle collisions and partial turbulence of liquid. And this erosion pattern can be called Particle Dominated Erosion. If the particles have good following properties, the erosion
area and rate will change with the erosion-affected flow region. This erosion is called as Flow Dominated Erosion.

The characterization of particle following property mainly depends on the value of Stokes number, which can be expressed as $St = \frac{\rho_p d_p u}{18 \mu D}$ [5]. When $St > 1$, the fluid has little effect on motion of the particles. For $St < 1$, particles follow fluid streamlines closely. When $St = 1$, the erosion map of the reducing wall with different pipe inner diameters is shown in Figure 5. The area above each curve indicates the Flow Dominated Erosion, and the area under each curve represents Particle Dominated Erosion. Consequently, the particle erosion at the reducing wall in cross linked fracturing fluid (Figure 6(a)) is mainly determined by the flowing state due to the high viscosity of the liquid. And the erosion pattern in flow-back fluid (i.e., gel out fluid) can be treated as Particle Dominated Erosion (Figure 6(b)). Therefore, the flow velocity in the fracturing fluid injection process plays a crucial role for the reducing wall erosion.

![Figure 5](image1.png)

**Figure 5.** The erosion map of the reducing wall with different pipe inner diameters when $St=1$.

![Figure 6](image2.png)

(a) Cross linked fracturing fluid; (b) gel out fluid.  
**Figure 6.** Particle distribution in different fluids:

5. Conclusion
The conclusions derived from the present study can be summarized as follows:

(1) Both of the erosion widths and the erosion depths of each erosion area increase with increasing flow velocity, and the deepest erosion area is close to the inner edge of the sample. The width and the depth of Erosion area 1 are smaller than that of other erosion areas in each flow velocity.

(2) Erosion rate of reducing wall is most affected by fluid flow velocity, followed by particle concentration and diameter ratio. By contrast, the width of erosion area is most sensitive to the change in
the diameter ratio, then the particle concentration and flow velocity. The difference in erosion rate between Erosion area 1 and other areas is obvious at the low flow velocity than the high flow velocity. And the growth rate of erosion is slowing down with the increase of particle concentration and the decrease of diameter ratio.

(3) The particle erosion in different fluids can be divided into two erosion patterns based on particle following property. And the erosion rate of reducing wall in cross linked fracturing fluid is mainly determined by the flowing state due to the high viscosity of the liquid.

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