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Investigation of slurry concentration effects on solid particle erosion rate for an impinging jet

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ABSTRACT

The slurry particle concentration effect on the erosion rate of tool components is a critical factor in the design and maintenance of industrial equipment. The relationship between slurry particle concentration and erosion rate was tested and evaluated at a jet impingement test facility using glass spheres impacting acrylonitrile butadiene styrene (ABS) coupons. Particle concentration ranged from 4.6% to 22.4% by weight, and three different nozzle standoff heights were used (H/D=3.0, 5.2, and 7.4). The results show the erosion rate is dependent on the slurry concentration and the test duration. Two distinct erosion profiles correlated with changes in erosion rate over the test duration. The transition between the erosion profiles and the change in erosion rate were dependent on the initial test geometry and slurry concentration.

1. Introduction

Wear caused by solid particle erosion has been a topic of interest for more than 60 years because of the potential for equipment damage and the associated repair/replacement costs during processing or transport of multiphase slurries in industrial equipment. Although the specific mechanisms of erosion are not consistently agreed upon, there is consensus about the influencing factors. The key influencing factors fall into four categories: impact properties, particle properties, impacted surface properties, and fluid properties. The dominant impact properties include the particle velocity and the impact angle of the particle. Particle properties include the particle size, shape, density, and hardness. Impacted surface properties typically focus on the mechanical properties of the surface being eroded, such as hardness, ductility, toughness, and yield strength. The fluid viscosity and density determine the particle trajectory at impact and as such can have significant influence on the global erosion rate and erosion pattern for a given test facility or tool system [1]

One area of relatively limited focus is the effect slurry particle concentration has on the erosion rate and resulting erosion profile. This area of focus is of interest for industrial applications where a wide range of slurry concentrations are found. For example, in the oil and gas industry, ceramic proppant is transported downhole during hydraulic fracturing operations and can often lead to significant erosive wear. The particle concentration typically ranges from 1% to 30% by volume in this application [2]. It becomes critical to understand the difference in tool erosion rate across the range of slurry concentrations when evaluating treating programs that require pumping extensive volumes of proppant at multiple concentrations.

Multiple studies have evaluated the relationship between particle concentration and erosion rate for particles transported by gas [3–5] and were limited to relatively low concentrations. They are not the area of focus for this work, this study focuses on applications transporting particles by a liquid and evaluates the high concentration effects. Table 1 shows a summary of previous work conducted using an impinging jet with a liquid-based slurry. Fig. 1 shows the key geometric properties of a typical jet impingement test facility.

The nozzle diameter, D average exit velocity, U particle diameter, d_p particle density, ρ_d and fluid viscosity, μ_f are used to calculate the Stokes number, St for each test. The characteristic time of the particle, τ_p is calculated for a spherical particle. Particles with low sphericity or high angularity such as natural sand or aluminum oxide will have a smaller characteristic time, resulting in a lower Stokes number than what is calculated [17].

$$St = \frac{\tau_p U}{D} \quad (1)$$

$$\tau_p = \frac{\rho_p {d_p}^2}{18\mu_f} \quad (2)$$

The particle entrainment influences the particle trajectories near the wall (Fig. 2). The high Stokes number case has minimal

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entrainment which causes the particles to impact the surface with the same trajectory at which they left the nozzle [7]. The impact angle, α is predominately at 90°, and the velocity distribution is dependent on the flow regime at the nozzle exit. The particle entrainment in the low Stokes number case changes the particle trajectory near the wall leading to particle impact angles of 90° at the centerline of the nozzle and going towards 0° moving radially outward.

The Stokes numbers for the presented studies typically fall between 1 and 40. This indicates the particles were predominately entrained by the fluid. Three of the previous works on erosion had low Stokes number; and thus, significant differences in the fluid entrainment. Mansouri et al. [8] used a high-viscosity fluid (carboxymethyl cellulose) resulting in a Stokes number less than one, which led to strong entrainment of the particles within the fluid. Li et al. [15] tested multiple slurry configurations ranging from St = .02 to 40. The highly entrained slurry was coal particles (d_p=24 μm, ρ_p= 1500 kg/m^3) in kerosene. Giourntas et al. [6] used significantly larger particles that increase the Stokes number such that the particle entrainment was lower. For comparison, a typical gas-based jet impingement test has a Stokes number of 7400 [7].

Table 1
Summary of liquid-based jet impingement erosion testing.

Author	*H* (mm)	*D* (mm)	*H*/*D*	*U* (m/s)	d_p (μm)	Vol%	*St*
Giourntas [6]	5	3	1.7	24	550	0.01	356
Mansouri [7]	12.7	7	1.8	14	300	0.4	27
Mansouri [8]	12.7	8	1.6	14	150	0.2	0.4, 5.8
Nguyen [9]	12.7	6.4	2.0	15–30	150	0.5	12–23
Sugiyama [10]	25	3	8.3	10	80	0.4	3.1
Wang [11]	9	4.8	1.9	14	300	1–3.2	39
Turenne [12]	N/A	4.8	N/A	17	250	0.4–8.6	33
Gnanavelu [13,14]	5	7	0.7	5, 7.5	250	0.4	6.6, 10
Li [15]	38.1	3.2	11.9	18–23	24, 150	N/A	.02–28
Mansouri [16]	12.7	7	1.8	14	300	0.4–6.4	1.3–27
Current work	19–47	6.4	3.0–7.4	29.9	150	2.1 – 11.4	15

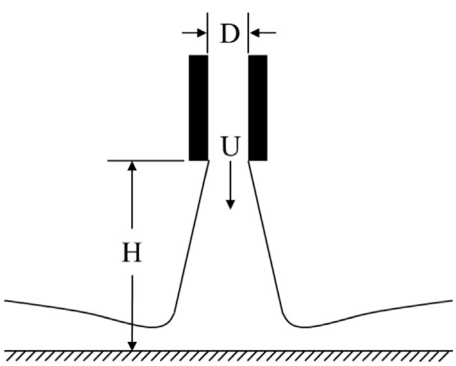

Fig. 1. Impinging jet configuration.

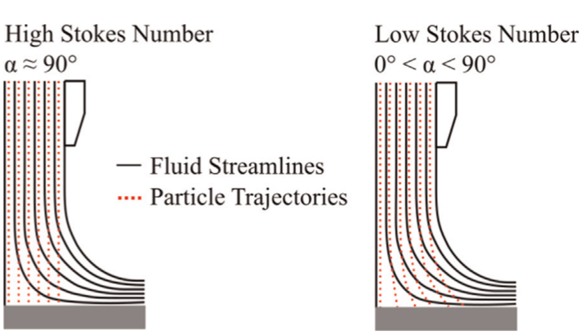

Fig. 2. Fluid streamlines and particle trajectories in an impinging jet flow for high and low Stokes number conditions.

1.1. Slurry concentration

Only three of the works reviewed evaluated the effect of slurry concentration on erosion. Turenne et al. [12] studied the influence of slurry concentration on erosion rate for sand transported by water against aluminum specimens. The tests were conducted using a normally impinging jet not submerged in the test fluid. Slurry concentrations of 1%, 5%, 10%, 15%, and 20% by weight were tested at a single flow rate resulting in an average nozzle velocity of 17 m/s. The results showed a mass-based erosion rate was inversely related to the volume fraction of the particles to the one-third power

$$ER = \frac{\Delta W}{M} = \frac{k}{\varphi^{0.33}} \tag{3}$$

where ΔW is the change in mass of the test coupon, M is the total mass of particles pumped during the test, φ is the volumetric ratio of the particles within the slurry, and k is a constant based on the test conditions. The inverse relationship was attributed to a screening effect of the particles near the already impacted surface that reduced the impact velocity of the particles coming from the impinging jet.

Wang et al. [11] conducted testing with a submerged jet of silica sand in water with a concentration ranging from 1 to 8% by weight. The nozzle height was 9 mm from the coupon, giving a standoff ratio H/D=1.88. The analysis showed the relationship of change in weight per unit time to the sand concentration was given by a power law:

$$\Delta W = k_2 C^{0.8}. \tag{4}$$

Review of the data shows the erosion rate can be given in the same form as Eq. 3 although the exponent is slightly different compared to results of Turenne et al.

$$ER = \frac{\Delta W}{M} = \frac{k}{\varphi^{0.19}} \tag{5}$$

Recent work by Mansouri et al. [16] evaluated the erosion rate of 316 SST for sand slurry concentrations ranging from 1 to 15% by weight. The results showed that the erosion rate decreased as the concentration increased when the fluid was 1 cP, but the results were more linear compared to the previously presented work. Additional testing was conducted with higher viscosity fluids (15 and 20 cP) and it was observed that the reduction in erosion rate relative to the slurry concentration was significantly reduced. It was proposed that this was due to the increased efficiency of higher viscosity fluid removing particles away from the coupon surface after impact.

The earliest study that considered slurry concentration was conducted by Li et al. [15] The results were inconsistent with the other studies presented and the gas-based investigations on slurry concentration. A coal and kerosene slurry was tested at 10, 20, and 30 wt%. The erosion rate increased as the slurry concentration increased. It is worth noting the Stokes number of this slurry (St = .02) was significantly lower than all other reviewed work and the nozzle standoff height (H/D = 12) was significantly higher in comparison. This suggests the flow field could develop in a manner inconsistent with other jet impingement test facilities. The second series of tests was conducted with an Al_2O_3 and water slurry at 10%, 20%, and 30% by weight. The results showed the