Effect of Particle Flow Rates on Erosion Ratio in Particle Impingement Experiments

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Abstract. Erosion caused by solid particles could not be neglected in oil and gas transportation industry, especially in gathering gas pipelines. Particles with small size may also erode the inner wall of pipelines after cumulative impacting and even lead to the leakage. Normally, a lot of solid particles are carried in the gathering gas before filtering. Additionally, corrosion productions may fall off the wall as the gas flowing. Researches on erosion of pipeline caused by solid particles are important for predicting the remaining wall thickness, which can be a guide for pipeline inspection and safety protection. However, effect of particle flow rates on erosion ratio is normally omitted in studies on erosion ratio calculations. It was observed that particle flow rates have a great influence on the mass loss of specimens in the impingement experiments of this work. According to groups of Particle Tracking Velocimetry (PTV) results obtained under various conditions, the particle velocity decreased when the particle flow rate was larger under the same experimental condition and the mass loss of the specimen became lower. Relations between particle velocity and particle flow rate under different experimental conditions were calculated according to the PTV results. Further, relations between erosion ratio and particle flow rate were purposed in this work. It is better to consider effect of particle flow rate while calculating solid particle erosion of pipelines in industry.

1. Introduction
Failures of pipelines and facilities caused by particle erosion are normal in the oil and gas industry. Serious erosion may even lead to leakage accidents or hidden danger for the society and companies [1, 2]. Even through the gathering gas is filtered to omit particles, some particles with small sizes are still there carried by the natural gas. In addition, corrosion productions may also fall off the inner wall as the gas flowing. Erosion occurs under impacting of these small particles. It is well known that particle velocity, size and impact angle have major contributions to erosion [1, 3, 4]. Levy and Sapate investigated the effects of particle shape, hardness and angle on erosion for a range of size of particles [5, 6] to propose simple relations between them. Kumar used a high speed impingement experimental rig to obtain erosion behaviors on two different kinds of coating under 90° [7]. Ballout and Lindsley used rotating devices to investigate the velocity exponent in erosion calculations [8, 9]. Currently, effect of particle size distributions in solid-gas and solid-liquid two-phase flow were discussed based on comparing experimental results by Zamani and Nguyen separately in their works [10, 11]. In researches about simulations, Wong investigated the erosion on pipes with small diameter by simulating [12]. Arabnejad and Mansouri proposed a better calculation method on erosion ratio calculation [13, 14] in their papers. However, little researches mentioned effect of particle flow rate on
erosion and particle flow rate is rarely considered in particle impingement experiments. Actually, particle flow rate has a great influence on erosion ratio. In this work, effect of particle flow rates on erosion for gas-solid two phase flow were discussed. In order to make the experimental results more comparable, particle flow rate should be well controlled while studying the effect of particle parameters (such as size and shape) on erosion ratio [15].

2. Effect of Particle Flow Rates on Impingement Experimental Results

An experimental rig was designed to investigate relations between the erosion ratio and particle parameters. In order to obtain better comparable experimental results, experiments mentioned in this paper are similar to those finished before in Erosion Corrosion Research Center (E/CRC) [15]. The connection of test rig is shown as Fig. 1. Particles and compressed gas came together from two different tubes and mixed in the nozzle. The specimen was fixed on the holder and the impact angle was controlled by the holder. The distance between the nozzle exit center and the specimen surface was 1.27 cm. The 316 stainless steel (SS316) specimens were used in these experiments and have dimensions of 75×50×1.5mm. Air and silica sands were used in the impingement experiments.

![Figure 1. Connection of test rig](image1)

![Figure 2. Method of erosion ratio calculation](image2)

The gas pressure near the specimen surface was measured before each group of impingement experiment to calculate the gas velocity. The erodent specimen should be swiped to omit possible broken particles which are attached on the surface. The material loss were calculated by measuring the weight of the specimen before and after particle impacting. Erosion ratio (ER) was defined as Fig. 2 to describe the impingement experimental results. The vertical axis represents the cumulative material loss (g) and the horizontal axis is the sand throughput (g) in experiments. The experimental results can be calculated according to equation 1.

$$ER = \frac{m_{\text{loss}}}{m_{\text{particle}}}$$  

Where, $ER$ is the erosion ratio, $m_{\text{loss}}$ is the mass loss during the impingement experiment, $m_{\text{particle}}$ is the mass of erodent particles used in experiments.

Groups of experiments under different particle flow rates and incidence angles were design in this work. Parameters are shown in Tab. 1, the particle size is 150 μm and the throughput of erodent particles for each group is 300 g.

| Parameter            | Value      |
|----------------------|------------|
| Particle size        | 150 μm     |
| Throughput           | 300 g      |
| Gas velocity         | 94 m/s     |
| Impact angle         | 15°, 90°   |
| Particle flow rate   | 0.53 g/s, 2.83 g/s |
When the particle flow rate is high, more particles come out from the nozzle, so they are more likely to impact other particles while moving to reduce the particle erosion. On the other side, more particles will impact the specimen surface at the same time. Thus, it is hard to predict erosion ratio under various particle flow rates without analyzing the impingement experimental results.

Experimental results under different particle flow rates (0.53 g/s and 2.83 g/s) and different impact angels (15° and 90°) were compared in Fig. 3. According to Fig. 3, the cumulative material loss of specimens are larger when the particle flow rate is lower under those two impact angles. Thus, erosion ratio is higher when the particle flow rate is lower when using the particle throughputs are the same in impingement experiments. It is necessary to obtain more experiments results under various conditions for further investigation on relation between erosion and particle flow rate.

![Figure 3. Comparison of erosion test results](image)

3. Effect of Particle Flow Rates on Particle Velocity

PTV was used to measure and calculate particle velocity in this work. Particle velocities were caught by PTV with two different sand flow rates to study effect of particle flow rate on particle velocity. PTV system includes a double-pulsed laser, a CCD camera, a synchronizer and a processor [16]. The schematics of PTV is shown in Fig. 4. The gas velocity (1.27 cm away from the nozzle exit) and particle flow rate were measured before every group of experiments.

![Figure 4. Schematics of particle image velocimetry](image)

Particles caught by PTV are shown in Fig. 5(a). Different velocities of particles near the plane 1.27 cm away from the nozzle exit were calculated by the two contiguous images obtained from the CCD camera. The count of particle with various velocities are shown in Fig. X (b). The vertical and horizontal axis represent the count of particles and particle velocities caught through PTV separately.
Relations between particle velocity and gas velocity were obtained by PTV. In these tests, the particle size is 150 μm and the particle flow rates are 0.53 g/s and 2.83 g/s separately. Particle velocities of these two kinds of particles in front of the nozzle are shown in Fig. 6 under different gas velocities. The vertical axis is the particle velocity (m/s) and the horizontal axis shows the gas velocity (m/s). It is observed that solid particles are more likely to be accelerated by the flowing gas when the particle flow rate is low. So particles have a higher velocity than those under high particle flow rate even when the gas velocities are the same, and they may cause more erosion on specimen surfaces.

In order to obtain better comparable experiment results, particle flow rate should be well controlled during impingement experiments for investigating effect of particle parameters on erosion. A vibratory feeder was designed in E/CRC [15] to control the particle flow rate in impingement experiments, which can control most small sand drop rates required in experiments. As shown in Fig. 7, particles are put in the particle inlet and go out from the outlet through the transparent tube. The particle drop rates are controlled by setting the frequency of the vibrator at the end of the device. The particle flow rates were test before every groups of experiments to keep them constant.
Four different particle flow rates (such as 0.53 g/s, 1.02 g/s, 1.52 g/s and 2.83 g/s) were set in the impingement experiments to investigate effect of particle flow rates on erosion. As shown in Tab. 2, relations between the particle velocity and gas velocity for particles with various particle sizes has been calculated by E/CRC [17].

**Table 2. Relation between the particle velocity and gas velocity**

| Particle diameter | Relation between $V_p$ and $V_g$   |
|-------------------|-----------------------------------|
| 75 μm             | $V_p=0.415V_g$                    |
| 150 μm            | $V_p=0.3063V_g$                   |
| 300 μm            | $V_p=0.3171V_g$                   |
| 600 μm            | $V_p=0.01709V_g$                  |

According to Tab. 2, the relation between the particle velocity and gas velocity is simply accord with equation 2.

$$V_p = C_{p/g} V_g$$

(2)

Where, $C_{p/g}$ is the relative coefficient between particle velocity and gas velocity. Based on Tab. 2, sands with the size of 75 μm have a better motion performance. Normally, smaller particles have better motion performance with flow in gas-solid two-phase flow while flowing, so the relative coefficient is bigger for smaller particles. However, because of the densities of particles are not constant, changing of particle velocities are similar when the sand sizes are 150 μm and 300 μm.

It was found that the relative coefficient is not constant for different particle flow rates, even when the particle size are the same. Relative coefficients for sands with various sizes were calculated according to the PTV test results while the range of the gas velocities is from 66 m/s to 115 m/s. Relations between particle velocity and gas velocity of different particles under various particle flow rates (FR) are shown in Tab. 3, Tab. 4, Tab. 5 and Tab. 6. It is obvious that the relative coefficient is bigger for smaller particles and the relative coefficients are not constant for each particle size. Because the particle interaction, volume fraction and acceleration changes when the particle flow rates are different. Thus, the particle flow rates should be well controlled in particle impingement experiments to obtain more comparable experimental results.
Table 3. Relation between particle velocity and gas velocity (FR=0.53 g/s)

| Particle diameter | Relation between $V_p$ and $V_g$ |
|-------------------|----------------------------------|
| 75 μm             | $V_p = 0.5267V_g$                |
| 150 μm            | $V_p = 0.3612V_g$                |
| 300 μm            | $V_p = 0.2959V_g$                |
| 600 μm            | $V_p = 0.2633V_g$                |

Table 4. Relation between particle velocity and gas velocity (FR=1.02 g/s)

| Particle diameter | Relation between $V_p$ and $V_g$ |
|-------------------|----------------------------------|
| 75 μm             | $V_p = 0.4581V_g$                |
| 150 μm            | $V_p = 0.3421V_g$                |
| 300 μm            | $V_p = 0.2816V_g$                |
| 600 μm            | $V_p = 0.2448V_g$                |

Table 5. Relation between particle velocity and gas velocity (FR=1.52 g/s)

| Particle diameter | Relation between $V_p$ and $V_g$ |
|-------------------|----------------------------------|
| 75 μm             | $V_p = 0.4403V_g$                |
| 150 μm            | $V_p = 0.3151V_g$                |
| 300 μm            | $V_p = 0.2379V_g$                |
| 600 μm            | $V_p = 0.2198V_g$                |

Table 6. Relation between particle velocity and gas velocity (FR=2.83 g/s)

| Particle diameter | Relation between $V_p$ and $V_g$ |
|-------------------|----------------------------------|
| 75 μm             | $V_p = 0.4372V_g$                |
| 150 μm            | $V_p = 0.3054V_g$                |
| 300 μm            | $V_p = 0.2131V_g$                |
| 600 μm            | $V_p = 0.2047V_g$                |

4. Effect of Particle Flow Rates on Erosion Ratio

Because the particle diameter is bigger, the flow rate of 600 μm sands is unsteady when it is low. So particle erosion experiments are compared only for particles with the size of 75 μm, 150 μm and 300 μm. In order to investigate the effect of particle flow rates on erosion, the particle velocities are controlled at about 24 m/s for all different particles. Relations between the particle velocity and gas velocity of these three kinds of particles are obtained by PTV tests, so the gas velocities can be calculated for different experimental conditions. The throughput of sands are 300 g for each particle impingement experiments under different conditions and the average values of mass loss on specimens were measured and calculated. The experimental results are shown in Fig. 8, where the vertical axis is the erosion ratio (g/g) calculated by equation 1 and the horizontal axis represents particle flow rate (g/s).
According to Fig. 7, interactions between particles are more obvious when the particle flow rates are higher, so the particle erosion ratio decreases as the particle flow rate increases and the relation is complicated. The influence of particle flow rate on erosion is stronger when the impact angle is 90°, because the collisions between particles and the specimen surface are mainly in the normal direction when the impact angle tending to 90° and the rebound particles are easy to collide with each other [18-20]. And when the particle flow rate increases, the collision probability between particles increases obviously, which affects the erosion ratio on specimens. Additionally, the erosion ratio distresses faster as the particle flow rate increases for smaller particle, since the relative coefficients for smaller particles are bigger.

5. Effect of Particle Flow Rates in Erosion Ratio Calculations
Particle interactions are usually ignored in particle erosion calculations, however, particle flow rate have a great influence on particle collisions and even erosion ratio in such impingement experiments mentioned in this paper. So it is better to take particle flow rates into consideration when calculating
particle erosion ratio in solid-gas two-phase flow. According to Fig. 7, relation between erosion ratio and particle flow rate conform to the equation 3.

$$ER \propto aQ_p^b$$

(3)

In order to improve the particle erosion calculating method, the experimental results are combined with the erosion calculating equation shown as equation 4 [21, 22].

$$ER = \frac{m_p c(d_p) f(\alpha) \nu^{b(u)}}{A_{face}}$$

(4)

Where $ER$ is the erosion ratio of the material, $m_p$ is the particle mass, $c(d_p)$ is a function of the particle diameter $d_p$, $f(\alpha)$ is a function of the impact angle $\alpha$, $\nu^{b(u)}$ is a factor about velocity. Varying the formation of functions of particle mass and diameter as follows.

$$ER = \frac{f(\alpha) \nu^{b(u)} f(Q_p) D_1^a f_2^a(\alpha)}{A_{face} f_2^a(\alpha)}$$

(5)

Where $Q_p$ is the particle flow rate and $f(Q_p) = aQ_p^b$. The factor $a$ and $b$ for different particles can be confirmed by experimental results. More experimental investigations about effect of particle sizes, shapes and flow rate on erosion ratio under well controlled particle flow rates are necessary to better modify the erosion calculation method. The area of the nozzle exit, accelerate distance and accelerated factor should also be taken into consideration in further researches to propose a better equation.

6. Summary and Conclusions

Effect of particle flow rates on erosion were discussed based on the impingement experimental results for particles with different sizes of 75 μm, 150 μm, 300 μm and 600 μm. The conclusions are summarized as follows.

1. According to the test results, particles with lower flow rates caused more erosion on the surface of the target material when the particle diameter, gas velocity and particle throughput are the same under the experimental condition mentioned in this paper. Based on PTV test, particles are more likely to be accelerated by the gas when the particle flow rate is lower.

2. Because of the effect of particle flow rates on particle velocity, it should be well controlled during impingement experiments. Relation between the changing particle velocity and particle flow rates for four different sizes were obtained based on PTV test results.

3. The erosion ratio is affected by the particle flow rate. If the interaction between particles is neglected in simulations, the relative coefficient of particle flow rate should be taken into consideration while calculating erosion ratio.

4. The area of the nozzle exit, accelerate distance and accelerated factor should also be taken into consideration in further researches to propose a better equation.

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8. References

[1] Arabnejad H, Mansouri A, Shirazi S A et al., Development of mechanistic erosion equation for solid particles, Wear, 332-333 (2015) 1044–1050.

[2] Paris M, Najmi K, Najafifard F et al., 2014. A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications. Journal of Natural Gas Science and Engineering, 21, 850-873.
[3] Bellman R, Levy A, Erosion mechanism in ductile metals, Wear, 70 (1981) 1-28.
[4] Srinivasan S, Scattergood R. O, Effect of erodent hardness on erosion of brittle materials. Wear, 128 (2) (1988) 139-152.
[5] Sapate S. G, RamaRao A V, Effect of Erodent Particle Hardness on Velocity Exponent in Erosion of Steels and Cast Irons, Materials and Manufacturing Processes, 18 (2003) 783-802.
[6] Levy A, Chik P, The effects of erodent composition and shape on the erosion of steel, Wear 89 (1983) 151-162.
[7] Kumar R K, Kamaraj M, Seetharamu S, Effect of Spray Particle Velocity on Cavitation Erosion Resistance Characteristics of HVOF and HVA Processed 86WC-10Co4Cr Hydro Turbine Coatings, Journal of Thermal Spray Technology, (2016) 1059-9630.
[8] Ballout Y A, Mathis J A, Talia J E, Effect of particle tangential velocity on erosion ripple formation, Wear, 184 (1995) 17-21.
[9] Lindsley B A, Marder A R, The effect of velocity on the solid particle erosion rate of alloys, Wear, 225-229 (1999) 510-516.
[10] Zamani S, Mahmoodabadi M, Effect of particle-size distribution on wind erosion rate and soil erodibility, Archives of Agronomy and Soil Science, 59 (2013) 1743-1753.
[11] Nguyen V B, Nguyen Q B, Zhang Y W, Effect of particle size on erosion characteristics, Wear, 348-349 (2016) 126-137.
[12] Wong C Y, Boujanger J, Short G, Modelling the effect of particle size distribution in multiphase flows with computational fluid dynamics and physical erosion experiments, Advanced Materials Research, 891-892 (2014) 1615-1620.
[13] Arabnejad H, Mansouri A, Shirazi S A et al., Evaluation of Solid Particle Erosion Equations and Models for Oil and Gas Industry Applications, in: Proceedings of the SPE Annual Technical Conference and Exhibition, Houston, 2015.
[14] Mansouri A, Arabnejad H, Shirazi S A et al., A combined CFD/experimental methodology for erosion prediction, Wear, 332-333 (2015) 1090-1097.
[15] Lin N, Arabnejad H, Shirazi S A et al. Experimental Study of Particle Size, Shape and Particle Flow Rate on Erosion of Stainless Steel, Powder Technology, 226 (2018) 70-79.
[16] Arabnejad H, Development of erosion equations for solid particle and liquid droplet impact, PhD Thesis, The University of Tulsa, 2015.
[17] Li Q, Erosion prediction in contractions and expansions based on computational fluid dynamics (CFD), Master Thesis, The University of Tulsa, 2015.
[18] Oka Y I, Okamura K, Yoshida T, Practical estimation of erosion damage caused by solid particle impact: Part 1: effects of impact parameters on a predictive equation, Wear, 259 (1) (2005) 95-101.
[19] Tilly G, A two stage mechanism of ductile erosion. Wear, 23 (1) (1973) 87-96.
[20] Sheldon G, Similarities and differences in the erosion behavior of materials, Journal of Fluid Engineering, 92 (3) (2015) 619-626.
[21] Lee B E, Tu J Y, On numerical modeling of particle-wall impaction in relation to erosion prediction in relation to erosion prediction: Eulerian versus lagrangian method. Wear, 2002, 252: 178-188.
[22] Edwards J K, Mclaury B S, Shirazi S A, Evaluation of alternative pipe bend fittings in erosive service. In ASME 2000 Fluids Eng. Division Sumer Meet., Boston, pp. 959-966.