Paper No.
6130

NACE INTERNATIONAL CORROSION 2015 CONFERENCE & EXPO

Investigating the Effect of Sand Concentration on Erosion Rate in Slurry Flows

Amir Mansouri, Marzieh Mahdavi, Siamack A. Shirazi, Brenton S. McLaury
The Erosion/Corrosion Research Center
Department of Mechanical Engineering
The University of Tulsa
800 S. Tucker Dr.
Tulsa, OK 74104
USA

ABSTRACT

Oil produced from offshore reservoirs may contain sand particles. Sand particles in slurry flows impact pipeline walls and cause erosion damage. Therefore, predicting the erosion rate is very crucial to the oil industry. In order to gain a better understanding of the effect of sand concentration on erosion ratio, a series of submerged impinging jet tests was conducted. Total erosion ratio was calculated by measuring the weight loss. It was found that for 1 cP fluid viscosity, the erosion ratio decreases as sand loading increases, whereas for 15 and 20 cP fluid viscosities, erosion ratio remains approximately constant. This observation can be ascribed to more sand particle rebounds near the surface at higher concentrations, which can form a protective cloud reducing the number of particle impacts on the target surface. This effect may become less important for fluid flows with higher viscosities. Also, Computational Fluid Dynamics (CFD) simulations were performed. It is found that unlike the conventional Eulerian – Lagrangian approach, Eulerian – Granular approach is capable of capturing the decrease in erosion ratio in higher sand loadings.

Key words: Sand erosion, Sand concentration, CFD, Slurry flow

INTRODUCTION

The surface degradation of industrial equipment due to continued solid particle impacts is a common problem in the oil and gas production industry. Because sand particles are usually produced along with oil in offshore reservoirs, erosion damage can result in many components such as the tube body of drill pipe, production tubing, subsea hardware, pipeline, control valves and elbows. This erosion damage can cause failures leading to costly maintenance and loss of production time. Therefore, there is a high demand for predicting the severity of erosion which can help in determining the service life of the equipment and optimizing the design. In the past, many companies relied on the American Petroleum Institute Recommended Practice 14E (API RP 14E), which suggested a velocity V_e [m/s] as the limiting production velocity to avoid erosion issues[1].

$$V_e = \frac{C}{\sqrt{\rho_m}} \quad (1)$$

Where C is an empirical constant [$kg^{0.5}/m^{0.5}/s$] and ρ_m [kg/m^3] is the fluid mixture density. Although Equation 1 is very simple and easy to use, the main disadvantage of this equation is that it does not account for many parameters playing key roles in the erosion phenomenon. Lack of incorporating the important factors can lead to unrealistic predictions by Equation 1.[2] Also, Arabnejad et al. studied erosion due to liquid impact and concluded that erosional velocities obtained from Equation 1 are very conservative.[3,4] It is generally accepted that many parameters such as sand particle impact speed and angle, sand size, sand sharpness, hardness of the sand and target material are important to erosion. An erosion ratio can be expressed to account for many of these parameters as shown in Equation 2. [5-9]

$$ER = k\ V_P^n\ f(\theta) \quad (2)$$

Where ER [kg/kg] is the erosion ratio defined as mass loss of target material divided by the amount of erosive particles impinging the surface. k is an empirical constant depending on the particle shape and hardness of sand particles and target material. V_P and θ are the local particle impact speed and angle, respectively. $f(\theta)$ is a dimensionless function showing the variation of erosion rate with changing the impact angle. This function is dependent on the hardness of the target material. The maximum erosion ratio occurs at low impingement angles for ductile materials, whereas for brittle materials, normal impingement angles cause maximum erosion.[10] Particle impact speed has the most significant effect on erosion ratio, and according to Equation 2 erosion ratio is proportional to V_P^n, where n is in the range of $2<n<3$.[11] In addition to all of the aforementioned factors, the effect of particle flux has been studied by researchers to understand whether erosion ratio changes with varying the particle flux or remains constant. In dry impact testing, it was observed that erosion ratio decreases as the particle flux increases.[12,13] This observation can be ascribed to rebounding particles which produce a protective barrier near the target surface. The influence of sand concentration on erosion ratio in slurry flows has also been investigated by Turenne et al.[14] They studied the erosion ratio of aluminum specimens under a slurry jet. In their apparatus, the slurry jet and specimen were not immersed in the fluid. They found that erosion rate decreases according to the power law of the sand concentration. The aim of this work is to study the effect of sand concentration on the erosion ratio in a submerged direct impinging jet test. The fluid viscosity was also varied from 1 to 20 cP to investigate the effect of sand concentration in viscous liquids. Furthermore, in this paper the erosion profile for slurry flows is discussed.

EXPERIMENTATION

Erosion tests were performed with a slurry test apparatus which is shown in Figure 1. A series of tests were conducted and erosion ratios of the stainless steel (SS316) samples were measured. The slurry jet was positioned so that the flow from the nozzle was normal to the sample surface. Sand particles with average sizes of 150 and 300 μm were used. Sand particles were added to liquid with viscosities of 1, 15 and 20 cP. The viscous liquid is prepared in a reservoir tank prior to experiments by mixing CMC (Carboxymethyl Cellulose) and water. CMC increases the viscosity of the liquid without a significant change in the density. Then, sand particles were mixed with the solution prepared for the desired viscosity in the reservoir tank. During the experiment, a slurry mixer was used to prevent the settling of sand particles and maintaining the homogeneity of the mixture. An air-powered diaphragm pump was used to maintain an average nozzle exit velocity of 14 m/s during the experiments. The prepared sand concentration measured by weight was varied from 1, 3, 6, 8, 10, 12, 14 to 15%, however it was found that the actual concentration at the nozzle exit was slightly different from the sand concentration in the reservoir tank. The sand concentration measured at the nozzle exit was used in the erosion ratio calculations. The total erosion ratio ER (kg/kg) is calculated by Equation 3.

$$ER(\frac{kg}{kg}) = \frac{W_1 - W_2}{M_{sand}\, t} \tag{3}$$

Where, W_1 (kg) and W_2 (kg) are the weight of the coupon before and after the erosion test, respectively. M_{sand} (kg/s) is the sand rate and t (s) represents the duration of the test. The inner diameter of the nozzle used in the test loop was 7 mm, and the distance between the nozzle and coupon was 12.7 mm for all tests.

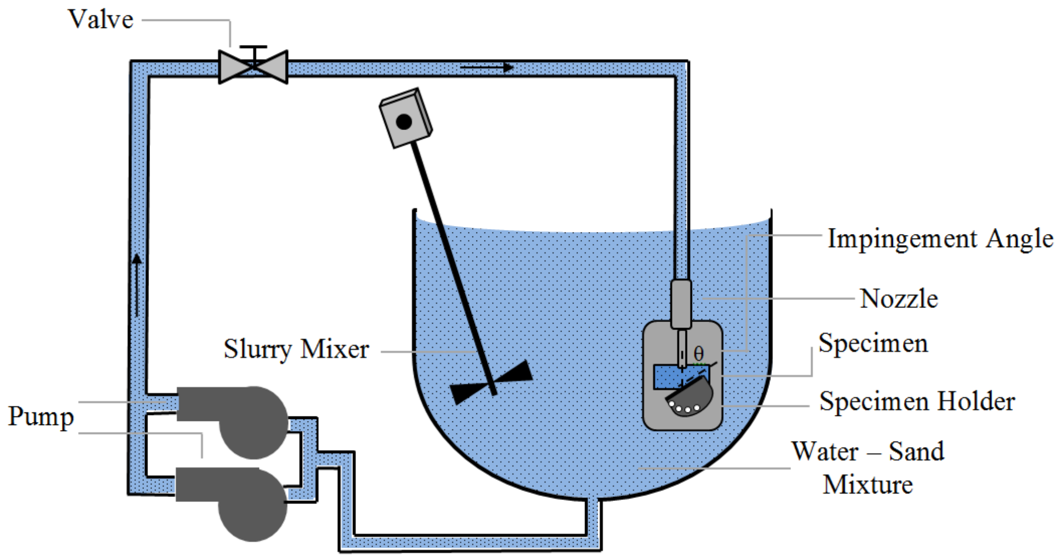

Figure 1: Schematic diagram of the slurry test facility

RESULTS AND DISCUSSION

In this section, experimental data and Computational Fluid Dynamics (CFD) results are presented to investigate the effect of sand concentration in slurry flows on erosion ratio. In order to ensure that the measured erosion does not change with time, the erosion test was interrupted every 15 minutes and the mass loss of the specimen was measured. The mass removed from the specimens versus the testing time for various sand concentrations are plotted in Figure 2. Mass loss is a linear function of testing time which shows that the erosion ratio does not change during the test. This figure also shows the more mass is removed for slurries with higher concentrations, since more particles are present to impinge the target surface. It is worthwhile mentioning that all the lines drawn in Figure 2 have a zero intercept which indicates no incubation period in erosion testing. The erosion profile created on the specimen was scanned by a 3D profilometer after the test. A cross-section of the erosion profile is shown in Figure 3. As illustrated in Figure 3, the slurry jet produces a *W* shape erosion pattern on the specimen at the normal incidence angle.[8] This *W* shape surface profile is produced due to the influence of fluid flow on sand particles in slurry flows. When the fluid flows toward the target surface, the velocity approaches zero at the center of the eroded area. The particle impact velocity significantly decreases in this region, and this leads to approximately no thickness loss near the stagnation point. Then, the fluid flow and consequently particle speed increase radially near the target surface, and this causes a highly eroded region which is also shown in Figure 3. As it is expected, in the slurry flow with 3% sand concentration, more erodent particles strike the specimen surface and cause higher thickness loss compared to 1% concentration flow. It was shown that higher sand loadings will increase the mass loss, but it is worthwhile investigating how adding more sand influences the erosion ratio (ratio of mass loss to mass of erodent particles). Figure 4 presents the effect of sand concentration on erosion ratio measured for 1 cP fluid viscosity and particle size of 300 μm. It is shown that with increasing the sand concentration erosion ratio decreases. Based on the plot shown in Figure 4, erosion ratio decreases 50% as sand concentration increases by 15%. This means that increasing the sand loading does not necessarily increase the effective particle impacts with the target surface. As mentioned by Levy[15], increasing the sand loading may lead to a *blanketing effect* which covers and protects the target surface. This effect reduces the number of efficient particle impacts.

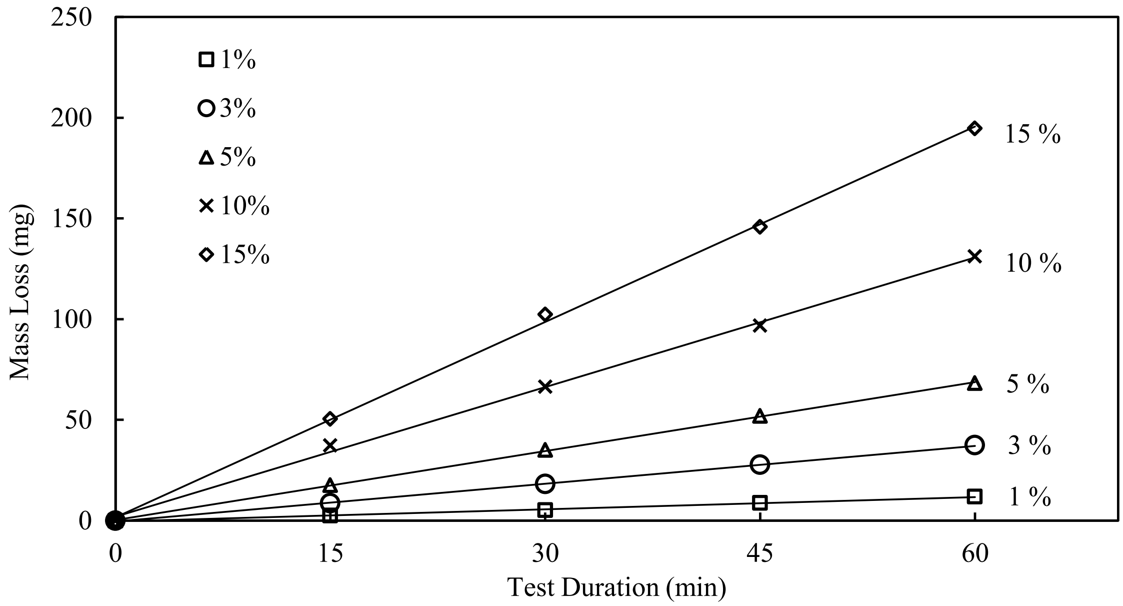

Figure 2: Mass loss of specimen vs. test duration time for various sand concentrations measured by weight (sand size= 150 μm)

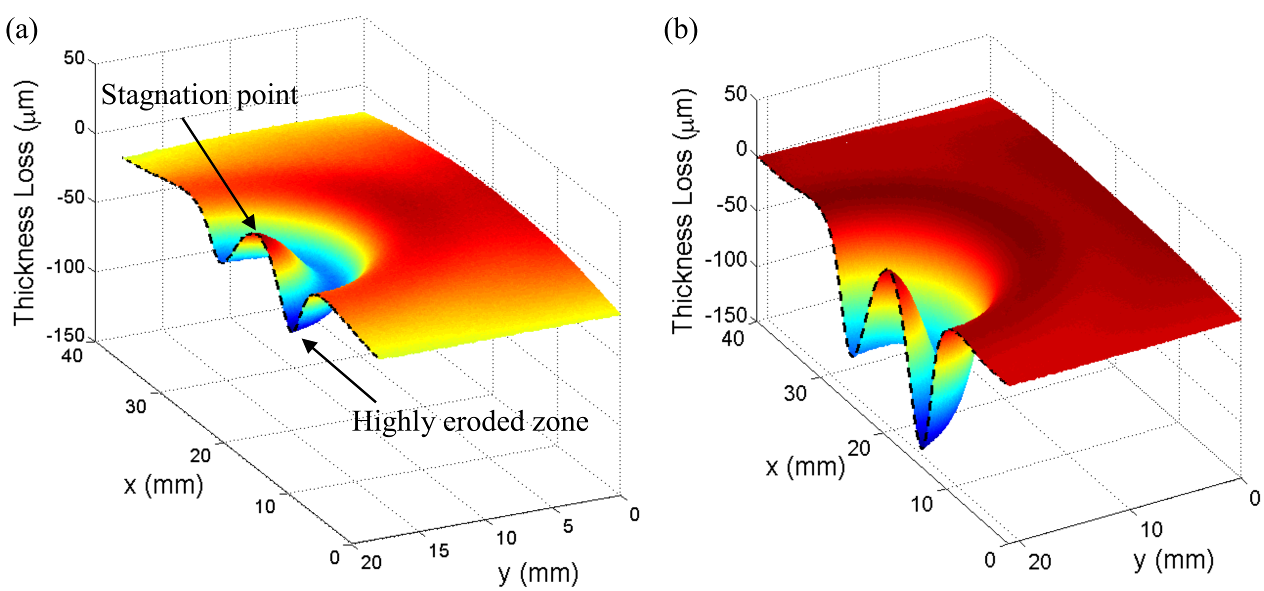

Figure 3: Cross section of the eroded surface under the slurry jet for sand size= 150 μm, nozzle average velocity 14 m/s and after 3 hours, a) sand mass concentration=1%, b) sand mass concentration=3%

The blanketing or particle rebounding effect is more powerful in dry testing as Anand et al.[12] observed a significant drop in erosion ratio with increasing the particle flux. But in slurry flows due to higher viscosity of the fluid, the solid particles are forced to follow the fluid streamlines and turn near the target surface and this hinders the formation of a protective cover. This fact is shown in Figure 5. In this figure, particle trajectories are simulated for sample particles via CFD simulation. It is observed that in slurry flows sand particles tend to impinge the surface and move away; whereas, in dry testing, sand particles bounce and interact with incoming particles reducing their speeds and reducing the erosion ratio.

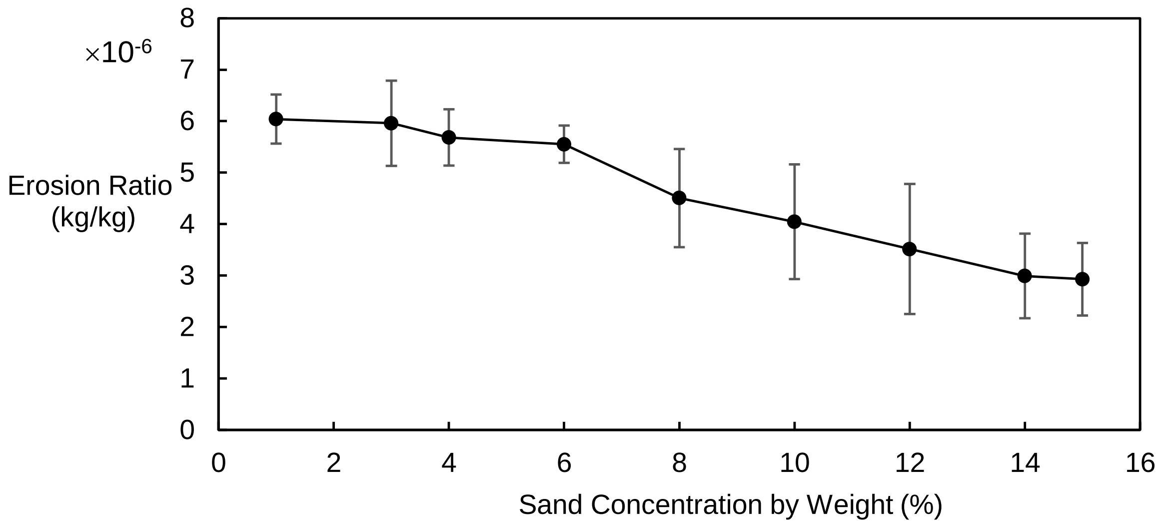

Figure 4: Erosion ratio vs. sand concentration for nozzle average velocity=14 m/s, fluid viscosity=1 cP, sand size= 300 µm

The influence of sand concentration on erosion ratio for fluid viscosities of 15 and 20 cP is shown in Figure 6. It is found that in viscous fluids erosion ratio remains approximately constant as sand concentration increases. The blanketing effect becomes less important for higher viscosity fluids perhaps due to the increase in fluid drag on particles and particles are being removed more efficiently from the eroded area.

CFD Simulation

In order to gain a better understanding of the effect of sand concentration on erosion damage, CFD simulations were performed for similar conditions as experimental tests were conducted. The computational mesh and boundary conditions are shown in Figure 8. 14 m/s is used at the inlet of the nozzle for the inlet boundary condition. A no-slip wall boundary condition is also imposed for the target surface and nozzle wall. The boundary condition at the outlet is a pressure outlet. The Shear-Stress Transport *SST k-ω* turbulence model is used to account for turbulence effects. In the simulations two approaches, *Eulerian - Lagrangian* and *Eulerian – Granular,* were employed. In the Eulerian - Lagrangian model, the fluid flow solution is obtained in an Eulerian way and then sand particles are tracked with a Lagrangian scheme. In this approach, a one-way coupling is employed, meaning that the carrier fluid affects the particle motion and the influence of particles on fluid flow is negligible. Therefore, this model is limited to dilute particulate flows. The Eulerian - Granular model takes into account the influence of sand particles on the carrier fluid and is more suitable for simulating high concentration flows. For calculating the erosion rate, the equation developed at the Erosion/Corrosion Research Center (E/CRC) was implemented. The erosion ratio is expressed in the following form,

$$ER(\frac{kg}{kg}) = C\,BH^{-0.59}\,F_s\,V_p^{2.41}\,f(\theta) \quad (4)$$

Where

$$BH = \frac{H_V + 0.1023}{0.0108} \tag{5}$$

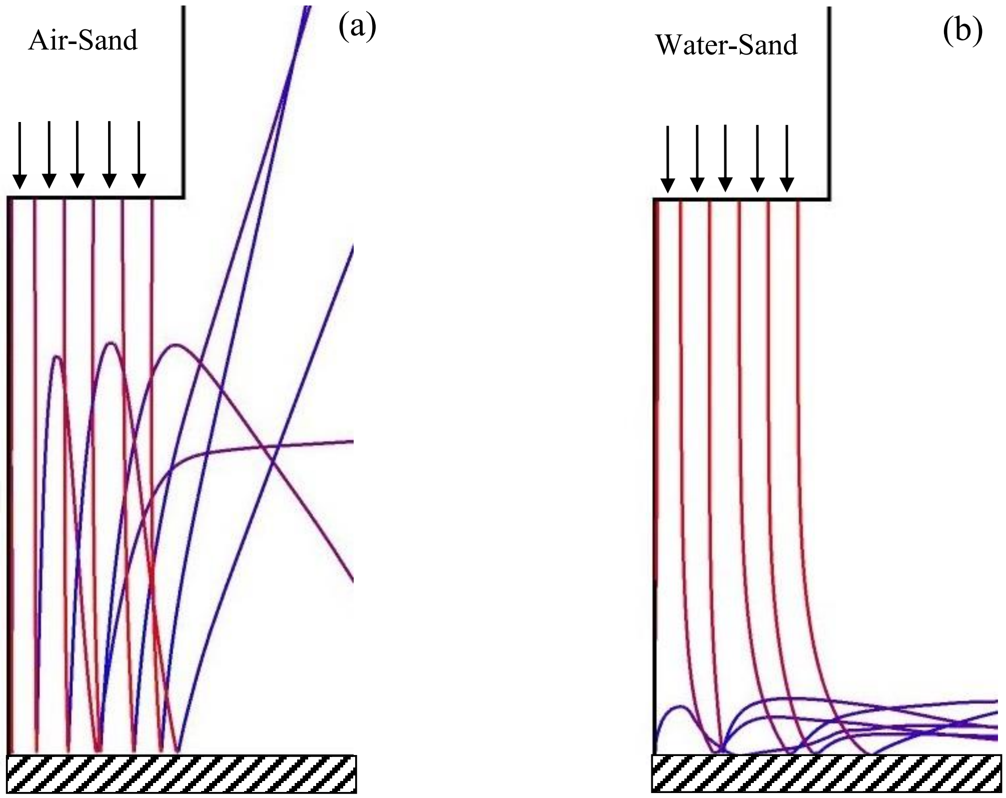

Figure 5: Particle trajectories obtained via CFD simulation for direct impingement testing a) air-sand flow b) water-sand flow

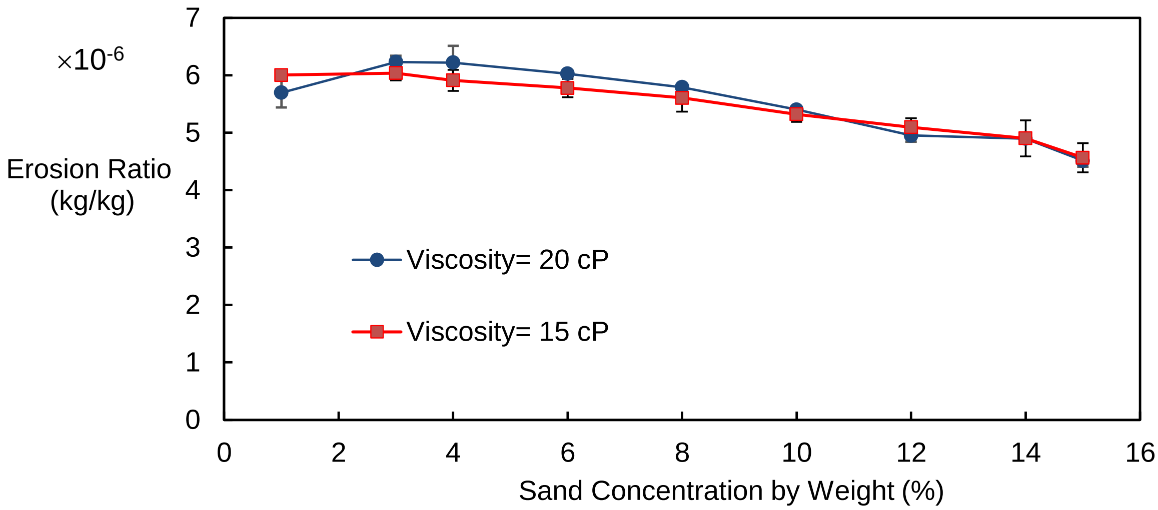

Figure 6: Erosion ratio vs. sand concentration for nozzle average velocity=14 m/s, fluid viscosity=15 cP and 20 cP, sand size= 300 µm

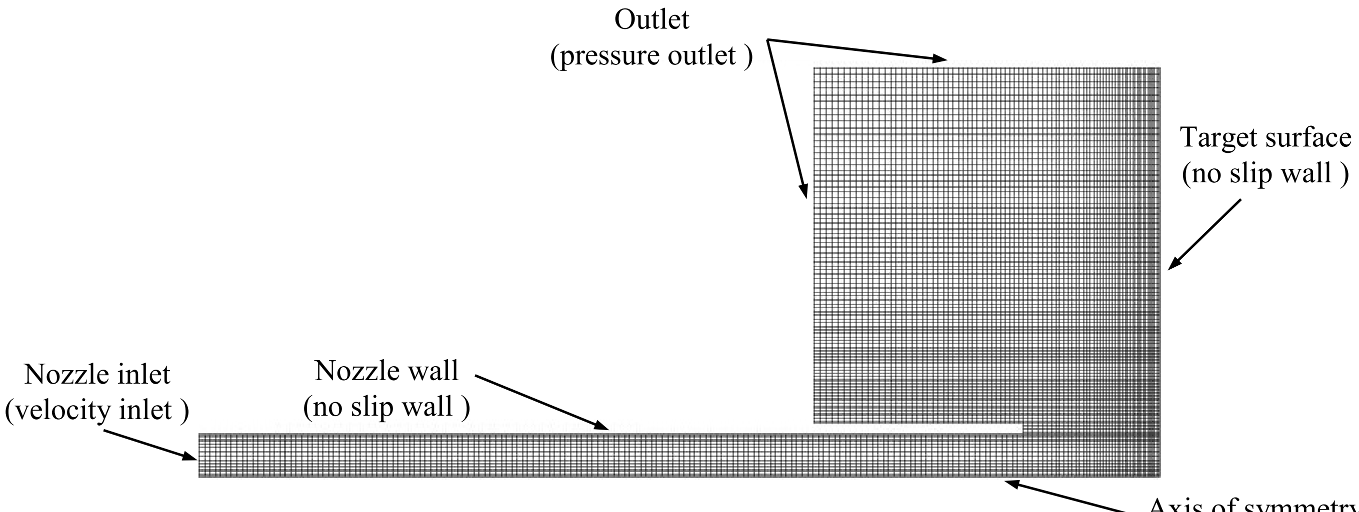

Figure 7: Mesh and boundary conditions

In Equations 4 and 5, *BH, HV*, *Fs*, V_P and *f(θ)* are the Brinell hardness, Vickers hardness of the target material, particle sharpness factor, particle impact velocity and impact angle function, respectively. The impact angle function can be written as:

$$f(\theta) = \frac{1}{f} . \sin(\theta)^{n1} \ . (1 + H_V^{n3} (1 - \sin(\theta))^{n2} \qquad (6)$$

The values for empirical constants used in Equations 4 – 6 are given in Table 1.

Table 1
Empirical constants in Equations 4-6 for Stainless Steel (SS316)

Constant	Value
C	4.49E-07
Hv (GPa)	1.83
F_S	1.0
f	1.714
n1	0.2
n2	0.85
n3	0.65

The comparison of the CFD predictions and erosion measurements for various mass concentrations is presented in Table 2. Both Eulerian - Lagrangian and Eulerian - Granular approaches under predict the experimental data. It should be noted that similar to experimental data CFD results predicted by the Eulerian – Granular model decrease as sand concentration increases. However, the Eulerian – Lagrangian approach does not sense the concentration variations. Figure 9 compares the normalized erosion ratio predicted by CFD with the experimental data. This figure indicates that the Eulerian –

Granular approach follows the trend of experimental data while the Eulerian – Lagrangian model results do not change at various concentrations.

Table 2
Comparison of erosion ratio measurements with CFD predictions (sand size=300 µm, nozzle exit velocity= 14 m/s, fluid viscosity= 1 cP)

Mass Concentration %	Experimental Data kg/kg	CFD (Eulerian - Granular) kg/kg	CFD (Eulerian - Lagrangian) kg/kg
1	6.04E-06	3.07E-06	3.16E-06
6	5.55E-06	1.54E-06	3.16E-06
10	4.05E-06	1.31E-06	3.16E-06
15	2.93E-06	1.19E-06	3.16E-06

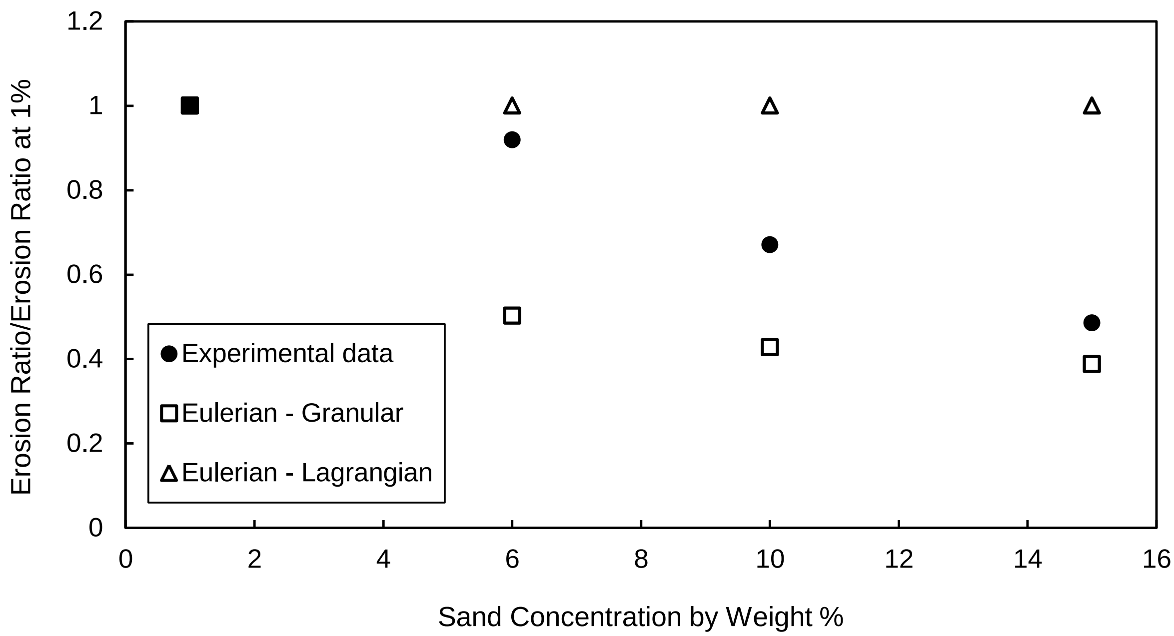

Figure 8: Normalized erosion ratio vs. sand concentration

CONCLUSIONS

The effect of sand concentration on erosion ratio is studied experimentally and numerically. A series of tests for submerged direct impinging jet at various sand concentrations was conducted, and mass loss of the flat specimen was measured. It was found that for 1 cP fluid viscosity, the erosion ratio decreases as sand loading increases; whereas for 15 and 20 cP fluid viscosities, erosion ratio remains approximately constant. In order to obtain more knowledge of the effect of sand concentration on erosion ratio, CFD simulations were performed for similar conditions as the experimental tests carried out. CFD simulation results under predict the experimental data. Also, it was found that the Eulerian –

Granular model is more suited for flows with high particle fractions than the Eulerian – Lagrangian model.

ACKNOWLEDGEMENTS

The authors would like to thank Ed Bowers of The University of Tulsa for his invaluable technical expertise. The authors wish to acknowledge financial support of many oil and gas production and service companies that have supported E/CRC research for many years.

REFERENCES

1. API RP 14E, "Recommended Practice for Design and Installation of offshore Production Platform Piping Systems," (Washington, DC: API, 1990)

2. S. A. Shirazi, B. S. McLaury, J. R. Shadley, and E. F. Rybicki, "Generalization of the API RP 14E Guideline for Erosive Services," *Journal of Petroleum Technology* 47, 8 (1995): p. 693-698.

3. H. Arabnejad, S. A. Shirazi, B. S. McLaury, and J. R. Shadley, "A Guideline to Calculate Erosional Velocity due to Liquid Droplets for Oil and Gas Industry." SPE Annual Technical Conference and Exhibition, (Amsterdam, Netherlands, 2014).

4. H. Arabnejad, S. A. Shirazi, B. S. McLaury, and J. R. Shadley, "Calculation of Erosional Velocity Due to Liquid Droplets with Application to Oil and Gas Industry Production" SPE Annual Technical Conference and Exhibition, (New Orleans, Louisiana, 2013).

5. I. Finnie, "Erosion of Surfaces by Solid Particles," *Wear* 3, 2 (1960): p. 87-103.

6. B. S. McLaury, S. A. Shirazi, J. R. Shadley, and E. F. Rybicki, "Modeling Erosion in Chokes," *ASME-Fluids Engineering* 236, 1 (1996): p.773-782.

7. Y. I. Oka, K. Okamura, and T. Yoshida, "Practical Estimation of Erosion Damage Caused by Solid Particle Impact: Part 1: Effects of Impact Parameters on a Predictive Equation," *Wear* 259, 1 (2005): p. 95-101.

8. A. Mansouri, S. A. Shirazi, and B. S. McLaury, "Experimental and Numerical Investigation of the Effect of Viscosity and Particle Size on the Erosion Damage Caused by Solid Particles," ASME 2014 4th Joint US-European Fluids Engineering Division Summer Meeting and 12th International Conference on Nanochannels, Microchannels, and Minichannels, paper no. 21613 (Chicago, IL: ASME, 2014).

9. M. Parsi, K. Najmi, F. Najafifard, Shokrollah Hassani, B. S. McLaury, and S. A. Shirazi, "A comprehensive review of solid particle erosion modeling for oil and gas wells and pipelines applications, " Journal of Natural Gas Science and Engineering 21 (2014): p.850-873.

10. I. Finnie, J. Wolak and Y. Kabil, "Erosion of metals by Solid Particles," *Journal of Materials* 2, 3 (1967): p. 682-700.

11. Y. Zhang, E. P. Reuterfors, B. S. McLaury, S. A. Shirazi, and E. F. Rybicki, "Comparison of Computed and Measured Particle Velocities and Erosion in Water and Air Flows," *Wear* 263, 1 (2007): p.330-338.

12. K. Anand, S. K. Hovis, H. Conrad, and R. O. Scattergood, "Flux Effects in Solid Particle Erosion," *Wear* 118, 2 (1987): p.243-257.

13. H. Uuemois, and I. Kleis, "A Critical Analysis of Erosion Problems Which Have Been Little Studied," *Wear* 31, 2 (1975): p.359-371.

14. S. Turenne, M. Fiset, and J. Masounave, "The Effect of Sand Concentration on the Erosion of Materials by a Slurry Jet," *Wear* 133, 1 (1989): p.95-106.

15. A. V. Levy, and Y. Paul, "Erosion of Steels in Liquid Slurries." *Wear* 98, 8 (1984): p.163-182.