Effects of Viscosity, Particle Size and Shape on Erosion Measurements and Predictions

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Outline

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Introduction

• Oil and gas removed from reservoirs generally contain impurities like sand particles of varying size that are often sharp which can cause erosion.
• In order to predict erosion, it is important to derive an erosion equation.
• Erosion equations are developed based on material, particle properties as well as impact conditions.
Introduction

- We normally develop erosion equations based on gas testing.
- These equations are then used in SPPS and CFD to predict erosion for both gas and liquids.
- We need to investigate if this assumption is valid for liquid dominated flows.
Motivation

- Okita (2010) conducted experiments with sand particles in a direct impingement geometry both with gas and liquid jets in liquid.

- Erosion equations obtained from gas testing were implemented in CFD to calculate erosion in liquids.
Erosion Ratio vs. Viscosity – Exp. Data and CFD (300 µm Sand) Liquid Velocity = 10 m/s, (Okita, 2010)
Erosion Ratio vs. Viscosity – Exp. Data and CFD (150 µm Sand) Liquid Velocity = 10 m/s (Okita, 2010)
Objective

• In CFD calculations, we assume particles are spherical and use models for tracking spherical particles.

• In the present work, experiments are conducted with spherical particles in gas and liquid and results will be compared with CFD calculations.
Objective

• Study effects of particle size, shape and liquid viscosity on erosion predictions.

California 60 (300 µm)  Oklahoma #1 (150 µm)  Silica Flour (20 µm)

350 µm Glass Beads  150 µm Glass Beads  50 µm Glass Beads
Summary of Present Work

- Improve Particle Tracking
  - Measure Particle Velocity with LDV
  - Erosion Testing in Gas
  - Erosion Equations

- CFD Predictions in Liquid with Different Viscosities
  - Erosion Exp. in Liquids
  - Compare CFD Results with Exp. Data
  - Agree
  - Yes
  - Improved CFD and SPPS

- No

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Erosion Ratio Equations

\[ ER \left( \frac{kg}{kg} \right) = K \times (H_v)^{k1} \times \left( \frac{V}{V'} \right)^{k2} \times \left( \frac{D}{D'} \right)^{k3} \times \rho \times F(\theta) \]

- Function of particle impact angle
- Empirical constant
- Material Vicker’s hardness (Gpa)
- Particle impact velocity
- Particle diameter
- Target density

E/CRC Equation

\[ ER \left( \frac{kg}{kg} \right) = K \times F_s \times V_p^{2.41} \times F(\theta) \]

- Function of particle impact angle
- Empirical constant
- Particle impact velocity
- Particle sharpness factor
- Mass Loss of Material
- Mass of Sand Throughput

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Laser Doppler Velocimetry (LDV) Setup

1. Laser
2. Color Burst
3. Fiber Optic Probe
4. Local Measurements
5. Signal Processing
6. Computer Displays Velocity Histograms
LDV Measurement Locations (Gas Flow)

Erosion Testing Target

Nozzle

8 mm

12.7 mm

r = 0 mm

r = 1 mm

r = 2 mm

r = 3 mm
Particle Velocity (LDV) vs. Gas Velocity (Pitot Tube) 
(50 μm Glass Beads)
Particle Velocity (LDV) vs. Gas Velocity (Pitot Tube)

- No Slip

- Fluid Velocity

- Pitot Tube

- Particle Velocity

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Experimental Facility – Gas Testing

\[ V_p = 24, 42 \text{ m/s} \]
\[ \theta = 15, 30, 45, 60, 90 \text{ deg} \]

Particle Type = 50, 150 and 350 µm Glass Beads
Measured Erosion Results in Air (Al 6061-T6) 
Direct Impact Test Sample Results 
(50 μm Glass Beads, \( V_p = 24 \text{ m/s} \))

![Graph showing cumulative mass loss vs. particle throughput for different angles (45°, 60°, 30°, 15°, 90°). The graph plots particle throughput in grams on the x-axis and cumulative mass loss in grams on the y-axis. The graph includes data points for each angle and a note: \( V_p = 24 \text{ m/s}, \theta = 30° \).]
Measured Erosion Results in Air (Al 6061-T6)
Direct Impact Test Sample Results
(50 μm Glass Beads, $V_p = 24$ m/s)

Erosion Ratio

$y = 4.4556 \times 10^{-6}x - 2.9900 \times 10^{-3}$
$R^2 = 9.9155 \times 10^{-1}$

$y = 3.6349 \times 10^{-6}x - 2.0667 \times 10^{-3}$
$R^2 = 9.9990 \times 10^{-1}$

$y = 6.5370 \times 10^{-7}x - 1.1744 \times 10^{-3}$
$R^2 = 9.9549 \times 10^{-1}$

$y = 6.3492 \times 10^{-7}x - 2.0714 \times 10^{-3}$
$R^2 = 9.9657 \times 10^{-1}$
Measured Erosion Results in Air (Al 6061-T6) (50 µm, 150 µm & 350 µm Glass Beads)

Erosion Ratio (g/g) vs. Impact Angle θ (degrees)

- For 50 µm, Vp = 42 m/s, θ = 15°
- For 50 µm, Vp = 24 m/s
- For 150 µm, Vp = 42 m/s, θ = 60°
Measured Erosion Results and Angle Functions in Air
(50 μm Glass Beads)

\[ F(\theta) = A \cdot \sin^2 \theta \cdot [1 + \text{Hv}^2 \cdot (1 - \sin \theta)]^{n2} \]

- \( V_p = 42 \text{ m/s} \)
- \( V_p = 24 \text{ m/s} \)

Impact Angle \( \theta \) (degrees)
Measured Erosion Results and Models in Air (50 μm Glass Beads)

Erosion Ratio (g/g) vs. Impact Angle θ (degrees)

E.R (g/g) = K * Fl * Vp^2.41 * F(θ)

Vp=42 m/s, Vg=71 m/s Trial 1 (exp)  
Vp=42 m/s, Vg=71 m/s Trial 2 (exp)  
Vp=42 m/s, E/CRC Eq.  
Vp=24 m/s, Vg=41 m/s Trial 1 (exp)  
Vp=24 m/s, Vg=41 m/s Trial 2 (exp)  
Vp=24 m/s, E/CRC Eq.
Measured Erosion Results and Models in Air (150 μm Glass Beads)

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Measured Erosion Results and Models in Air (350 μm Glass Beads)

Erosion Ratio (g/g)

Impact Angle $\theta$ (degrees)

$E.R \left( \frac{g}{g} \right) = K \times F_s \times V_p^{2.41} \times F(\theta)$

- $V_p=42$ m/s, $V_p=136$ m/s Trial 1 (exp)
- $V_p=42$ m/s, $V_p=136$ m/s Trial 2 (exp)
- $V_p=24$ m/s, $V_g=77$ m/s Trial 1 (exp)
- $V_p=24$ m/s, $V_g=77$ m/s Trial 2 (exp)

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Experimental Setup – Liquid Testing

Liquid Viscosity $\mu = 1, 10, 30$ cP
Particle type = 50, 150, 350 µm Glass Beads
Erosion Ratio vs. Viscosity – Exp. Data (Al 6061-T6)
Liquid Velocity = 10 m/s, Glass Beads Vs. Sand

Viscosity (cP)

Erosion Ratio (kg/kg)

- 300 μm Sand $F_s = 1.0$ (Okita (2010))
- 350 μm GB $F_s = 0.2$
Erosion Ratio vs. Viscosity – Exp. Data (Al 6061-T6)  
Liquid Velocity = 10 m/s, Glass Beads Vs. Sand

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Viscosity (cP)

Erosion Ratio (kg/kg)

1.00E-07
1.00E-06
1.00E-05

0 5 10 15 20 25 30 35

150 μm Sand
$F_s = 0.5$
(Okita (2010))

150 μm GB
$F_s = 0.2$

$X 3$

Erosion Ratio ($\times 3$)

$100 \mu m$

$12.7 \text{ mm}$

Oklahoma City 200x
Erosion Ratio vs. Viscosity – Exp. Data (Al 6061-T6) Liquid Velocity = 10 m/s, Glass Beads Vs. Sand

Erosion Ratio (kg/kg)

Viscosity (cP)

20 μm Sand
(Okita (2010))

50 μm GB
$F_s = 0.2$

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Erosion Ratio vs. Viscosity
(Glass Beads)
(90% Confidence Interval)
Sensitivity Study of CFD

• Effect of grid size on erosion rate predictions has been studied. It was observed that grid size has small effect on erosion predictions for small particles.

• Predicted erosion rates from 2D mesh and 3D mesh were compared. Both the meshes yield similar results.

• Effect of turbulence models was also studied. It was observed that selection of turbulence model affects CFD predictions.
CFD Erosion Predictions – Simulation Design Input

Number of Cells = 6875

25.4 mm Pressure Outlet

Target (Wall)

25.4 mm Nozzle

Target Wall

12.7 mm Nozzle Exit (Velocity Inlet)

38.1 mm Nozzle (Wall)

Nozzle Exit (Velocity Inlet)

Center Line (Axis of Symmetry)
CFD Erosion Predictions – Simulation Design Input

Velocity Vectors Colored By Velocity Magnitude (m/s)

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CFD Erosion Predictions - Simulation Design Input – Shorter Target Wall vs. Extended Target Wall (150 µm Glass Beads)
Predicted Erosion Rates vs. Measured Erosion Rates (350 µm Glass Beads)

Viscosity (cP)

Erosion Ratio (m³/kg)

- Experimental Data
- CFD Predictions (15000 Cells)
Predicted Erosion Rates vs. Measured Erosion Rates (150 µm Glass Beads)

Erosion Ratio (m³/kg)

Viscosity (cP)

- Experimental Data
- CFD Predictions (15000 Cells)

X 8

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Predicted Erosion Rates vs. Measured Erosion Rates (50 µm Glass Beads)

![Erosion Ratio vs. Viscosity Graph]

- **Erosion Ratio (m³/kg)**
  - 1.00E-10
  - 1.00E-11
  - 1.00E-12

- **Viscosity (cP)**
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35

**Graph Details**
- Black dots represent **Experimental Data**.
- Red diamonds represent **CFD Predictions (15000 Cells)**

**Inset Image**: 0 mm 12.7 mm

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CFD Predictions - 50 µm Glass Beads

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CFD Predictions – Sand (300 µm) vs. Glass Beads (350 µm)

- **Erosion Ratio (m³/kg)**

- **Viscosity (cP)**

- **CFD Predictions (300 um Sand)**
- **CFD Predictions (350 um GB)**

- **Fs = 1.0**
- **Fs = 0.2**

- **Okita (2010)**

- **X 8**
- **X 5**

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CFD Predictions – Sand (150 µm) vs. Glass Beads (150 µm)

![Graph showing CFD Predictions for Sand and Glass Beads at different viscosities and erosion ratios.]

- **Erosion Ratio (m³/kg)**
- **Viscosity (cP)**

- **F_s = 0.5**
  - Okita (2010)
- **F_s = 0.2**
  - 150 µm GB
  - 150 µm Sand

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CFD Predictions – Sand (20 µm) vs. Glass Beads (50 µm)

- CFD Predictions (20 um Sand)
- CFD Predictions (50 um GB)

Okita (2010)

F_s = 1.0

F_s = 0.5

Erosion Ratio (m^3/kg)

Viscosity (cP)

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Conclusions from Erosion Measurements

• **Air**
  – Particle size does not affect erosion ratio significantly as long as the particles have same impact speeds.

• **Viscous Liquid**
  – Particle size influences erosion ratio in magnitude and trend for 1 to 30 cP liquids.
  – Viscosity significantly effects erosion ratio for smaller particles.
  – For the range of viscosities considered in the existing test facility and flow geometry, it can be concluded that viscosity does not have much influence on erosion ratio of larger particles.
Conclusions from CFD Predictions

• Grid size has small effect on erosion predictions for larger particles.
• 2D mesh and 3D mesh yield similar erosion rates.
• Selection of turbulence model affects CFD predictions.
• CFD significantly under predicts measured erosion rates for 350 and 150 µm particles.
• For 50 µm particles, CFD over predicts measurements and the trend of predictions do not match that of measurements.
• CFD predictions follow a similar trend for both glass beads and sand particles.
Future Work

• Use other turbulence models, near wall treatments and compare.

• Include particle size distributions in CFD simulations.

• User Defined Functions may be modified to control number of impacts according to experimental results.

• Use a 3D profilometer to measure the thickness loss of the coupon due to erosion.
Future Work –
High Velocity Submerged Liquid Testing Facility

- This facility will provide similar flow profiles for the viscosities examined.
Thank you
CFD -
Effect of Grid Size on Erosion Rate Predictions

Number of Cells = 15000

Number of Cells = 24720
CFD - Effect of Grid Size on Erosion Rate Predictions (350 µm Glass Beads)

Erosion Ratio (m$^3$/kg)

Viscosity (cP)

- Regular Mesh
- Finer Mesh

0 5 10 15 20 25 30 35

0 mm 12.7 mm
CFD -
Effect of Grid Size on Erosion Rate Predictions
(150 µm Glass Beads)

Erosion Ratio (m³/kg)

Viscosity (cP)

Regular Mesh
Finer Mesh
CFD -
Effect of Grid Size on Erosion Rate Predictions
(50 µm Glass Beads)

Viscosity (cP)

Erosion Ratio (m³/kg)

Regular Mesh
Finer Mesh

0 5 10 15 20 25 30 35

3.00E-10
3.00E-11
3.00E-12

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CFD -
Effect of Grid Size on Erosion Rate Predictions
(50 µm Glass Beads, 1 cP)
CFD -
2D Mesh vs. 3D Mesh
150 µm Glass Beads, 1 cP

Number of Cells = 491620
Pressure Outlet
Nozzle (Wall)
Nozzle Exit (Velocity Inlet)
Target (Wall)
CFD -
2D Mesh vs. 3D Mesh
150 µm Glass Beads, 1 cP

Predicted Erosion Rate (m³/kg)

Viscosity (cP)

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CFD Predictions -
Effect of Turbulence Models
(150 µm Glass Beads)
CFD Predictions – Turbulence Model Analysis (150 µm Glass Beads)

10 cP

No. of Impacts (-)

Radial Locations (m)

RSM

k-epsilon

low Re

Avg. Impact Speed (m/s)

Radial Locations (m)

30 cP

No. of Impacts (-)

Radial Locations (m)

RSM

k-epsilon

low Re

Avg. Impact Speed (m/s)

Radial Locations (m)

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