Erosion Prediction for Low-Liquid Loading and Annular Flows

Ronald Vieira
PhD Student

Erosion/Corrosion Research Center
Department of Mechanical Engineering
The University of Tulsa

November 8, 2012
Outline of Presentation

- Introduction
- Goals and Objectives
- Previous Studies
- Sand Erosion Measurements in Elbows
- Model Development
  - Low-Liquid Loading and Annular Flow Characteristics in Straight Pipes
  - SPPS Validation
  - New Modeling Improvements Plans
- Summary and Conclusion
- Future Work and Deliverables
Introduction

- Low-liquid loading and annular gas-liquid flow conditions are commonly encountered in gas transportation pipelines.
- They may also occur in other production facilities as gas/condensate production systems.
- Experience gained from production of hydrocarbons has shown that severe degradation of production equipment may occur as a result of erosion.
Introduction

- Sand erosion in multiphase flows with entrained sand is a complex phenomenon.
- There are many issues that remain unanswered.
- Severity of erosion depends on a multitude of factors such as fluid properties, flow rate, sand size and rate, material type, geometry as well as many others.
Introduction

- However, trying to isolate the effect of one of these factors and making the findings applicable to a wide range of conditions is challenging.

- One factor that affects the severity of erosion that has not been addressed directly in literature but has been observed experimentally is the pipe orientation, horizontal or vertical.
Introduction

- Semi-mechanistic erosion prediction procedure (SPPS) was previously created by E/CRC.
- SPPS extension for multiphase flows was developed based on limited data for 25.4 mm (1”) and 50.8 mm (2”) pipe diameters.
- SPPS 4.1 results for annular flow conditions in 76.2 mm (3”) and 101.6 mm (4”) pipe diameters underpredicted erosion data significantly.
Introduction

- Problems were identified in earlier multiphase flows models that lead to inaccuracies in erosion predictions.

- Experimental work on two-phase vertical upward flow has shown that pipe diameter has an effect on many flow structure parameters in annular flows such as film thickness and entrainment rate.

- Thus, it becomes necessary to carefully evaluate multiphase flow models that are incorporated in SPPS.
Goals

- Main goal is to improve current model predictions under low-liquid loading and annular gas-liquid flow.

- Expand our current sand erosion database in pipelines for gas dominant multiphase flows.
Objectives

- Examining accuracy of various multiphase flow models for annular flow and low liquid loading conditions,

- Collecting experimental data that will be obtained at E/CRC for low liquid loading and annular flow using Ultrasonic Transducers and ER Probes in 76.2 mm (3”) and 101.6 mm (4”) elbows,

- Examining paint erosion patterns and thickness loss profiles in a 76.2 mm CPVC test cell to study how flow orientation can affect erosion results.
Objectives

- Use new erosion ratio models for different oilfield materials,
- Use new empirical data that will be gathered at E/CRC for low liquid loading and annular flow conditions to validate current model improvements,
- Study the effect of pipe orientation, vertical and horizontal, on the severity of erosion.
Model Development Approach
Erosion in Low-Liquid Loading and Annular Flows

Low-Liquid Loading and Annular Flow Characteristics
(Entrainment Fraction and Liquid Film Calculations)

Impacting Sand Rate and Particle Velocities Estimation

Sand Distribution Measurements

Particle Tracking in the Gas Core and Liquid Film
Particle Impact Velocities Calculation

Erosion Ratio Equations

Erosion Calculation in Elbows

Model Validation
(Model Agree with Data?)

Yes

Sand Production Pipe Saver (SPPS)

No

Improvements

Feedback

Erosion/Corrosion Research Center
Previous and Related Studies on Erosion for Low-Liquid Loading and Annular Flows
Background
Previous Models

- Salama (1998) extended a single-phase model to account for multiphase flow by using mixture properties.


- Mazumder (2005) presented a model for annular flow in vertical pipes that was based on previous E/CRC models.

- McLaury et al. (2006) refined the annular flow erosion model by accounting for 2-D particle tracking through the annular film.
Background
Previous Experimental Work on Gas Dominant Flows

Extensive empirical information has been gathered at TUSMP to examine sensitivity of ER probes in multiphase flows:

- Antezena (2004) examined sensitivity of ER probes in 25.4 mm (1") pipes and plug tees.

- Pyboyina (2006) conducted experiments in 2 different orientations, vertical and horizontal for 50.8 mm (2") pipes.

- Nuguri (2007) carried out experiments to find the effect of low-liquid rates on ER probes for gas dominant flows for 50.8 mm (2") and 76.2 mm (3") pipe diameters.

- Fan (2010) examined ER probes for 76.2 mm (3") and 101.6 mm (4") pipes under low liquid loading.
Background
Previous Experimental Work on Gas Dominant Flows

- In these experiments, the ER probe was placed flush with the outer wall at the midpoint of the bend in an elbow.

- Although these experiments provide valuable information for erosivity, these ER probe data were collected in a short period of time and repeatability of erosion data needs to be examined.
Sand Erosion Measurements in Elbows
Sand Erosion Measurements in Low-Liquid Loading and Annular Flows

- Low-Liquid Loading and Annular Flow Characteristics
  (Entrainment Fraction and Liquid Film Calculations)
- Impacting Sand Rate and Particle Velocities Estimation
- Sand Distribution Measurements
- Particle Tracking in the Gas Core and Liquid Film
  Particle Impact Velocities Calculation
- Erosion Ratio Equations
- Erosion Calculation in Elbows
- Model Validation
  (Model Agree with Data?)
- Erosion Testing in Elbows
- Improvements
  Feedback
  No
  Yes
  Sand Production Pipe Saver (SPPS)
Sand Erosion Measurements
Electrical Resistance Probes

- Erosion Testing in Elbows
  - Intrusive Electrical Resistance (ER) Probes
  - Current Transducer Configuration
  - New Configuration
  - Paint Erosion Tests
  - Metal Loss Measurements
- Non-Intrusive Ultrasonic Transducers
- CPVC Test Cell

Erosion/Corrosion Research Center
Previous ER Probe Erosion Measurements
Vertical Annular Flow in 50.8 mm (2”) Elbows

$V_{SG} = 30 \text{ m/s}$, Water 1 cP Viscosity, 1% concentration by weight, 300μm Sand Size

- ER Probe Data

Data from Nuguri (2006)
Effect of Liquid Velocity on ER Probe Erosion Measurements
Vertical Annular Flow in 76.2 mm (3’’) Elbows

\[ V_{SG} = 27 \text{ m/s}, \text{ Water 1 cP Viscosity, 1 \% concentration by weight, 300\mu m Sand Size} \]
Effect of Liquid Velocity on ER Probe Erosion Measurements
Vertical Low-Liquid Loading in 76.2 mm (3”) Elbows

\[ V_{SG} = 15 \text{ m/s}, \text{ Water 1 cP Viscosity, 1 \% concentration by weight, 300}\mu\text{m Sand Size} \]
Effect of Liquid Velocity on ER Probe Erosion Measurements
Churn-Annular Flow in 76.2 mm (3”) Elbows

1 % concentration by weight, 300μm Sand Size

- Water 1 cP
- Water/CMC Mix 10 cP

Erosion Rate, mm/yr

<table>
<thead>
<tr>
<th>$V_{SL}$</th>
<th>0.19</th>
<th>0.13</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{SG}$</td>
<td>21</td>
<td>27</td>
</tr>
</tbody>
</table>

Superficial Velocities, m/s
Effect of Particle Size on ER Probe Erosion Measurements
Vertical Annular Flow in 76.2 mm (3”) Elbows

$V_{SL} = 0.04 \text{ m/s, Water 1 cP Viscosity, 1 \% concentration by weight}$

![Graph showing the effect of particle size on erosion ratio vs. superficial gas velocity. The graph compares the erosion rates of 150 micron and 300 micron particles.](image)

Erosion/Corrosion Research Center
Effect of Pipe Diameter on ER Probe Erosion Measurements
Annular Flow in 101.6 mm (4") Elbows – High Gas Velocity

$V_{SG} = 30 \text{ m/s}$, $V_{SL} = 0.2 \text{ m/s}$, water 1 cP, 1 % concentration by weight, 300μm

Erosion Rate Measured:
- Vertical = 14 mm/yr (550 mils/yr)
- Horizontal = 9 mm/yr (350 mils/yr)
Sand Erosion Measurements
Ultrasonic Erosion Monitoring (UT)

- Erosion Testing in Elbows
- Intrusive Electrical Resistance (ER) Probes
- Non-Intrusive Ultrasonic Transducers
  - CPVC Test Cell
  - Current Transducer Configuration
    - New Configuration
    - Paint Erosion Tests
    - Metal Loss Measurements
- Metal Loss Measurements
Non-invasive technique for measuring erosion based on ultrasonic measurements was used to collect erosion data for multiphase flows under annular conditions.
UT Erosion Measurements
Ultrasonic Erosion Monitoring (UT)

Flow Pattern Maps for Annular and Low-Liquid Conditions in 76.2 mm (3”) Pipes

Erosion/Corrosion Research Center
## UT Erosion Measurements

### Ultrasonic Erosion Monitoring (UT)

- **Erosion Results for Vertical Flow**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>26-Jun-12</td>
<td>INTERMITTENT-ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.5</td>
<td>1</td>
<td>18532</td>
<td>471</td>
<td>7.17E-04</td>
</tr>
<tr>
<td>13-Jul-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.2</td>
<td>1</td>
<td>26264</td>
<td>667</td>
<td>2.54E-03</td>
</tr>
<tr>
<td>23-Jul-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.04</td>
<td>1</td>
<td>5723</td>
<td>145</td>
<td>2.50E-03</td>
</tr>
<tr>
<td>6-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.02</td>
<td>1</td>
<td>2167</td>
<td>55</td>
<td>1.91E-03</td>
</tr>
<tr>
<td>12-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.02</td>
<td>1</td>
<td>2235</td>
<td>57</td>
<td>1.97E-03</td>
</tr>
<tr>
<td>31-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.01</td>
<td>1</td>
<td>1203</td>
<td>31</td>
<td>2.12E-03</td>
</tr>
<tr>
<td>10-Sep-12</td>
<td>ANNULAR-MIST</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.003</td>
<td>1</td>
<td>413</td>
<td>10</td>
<td>2.40E-03</td>
</tr>
<tr>
<td>1-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>41</td>
<td>0.04</td>
<td>1</td>
<td>4093</td>
<td>104</td>
<td>1.79E-03</td>
</tr>
<tr>
<td>29-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>41</td>
<td>0.02</td>
<td>1</td>
<td>1665</td>
<td>42</td>
<td>1.46E-03</td>
</tr>
<tr>
<td>3-Sep-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>41</td>
<td>0.01</td>
<td>1</td>
<td>831</td>
<td>21</td>
<td>1.46E-03</td>
</tr>
<tr>
<td>8-Sep-12</td>
<td>ANNULAR-MIST</td>
<td>1</td>
<td>300</td>
<td>41</td>
<td>0.005</td>
<td>1</td>
<td>460</td>
<td>12</td>
<td>1.78E-03</td>
</tr>
<tr>
<td>26-Aug-11</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>35</td>
<td>0.1</td>
<td>1</td>
<td>5929</td>
<td>151</td>
<td>1.19E-03</td>
</tr>
<tr>
<td>26-Oct-11</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>36</td>
<td>0.1</td>
<td>1</td>
<td>4128</td>
<td>105</td>
<td>7.99E-04</td>
</tr>
<tr>
<td>29-May-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>150</td>
<td>36</td>
<td>0.1</td>
<td>1</td>
<td>1305</td>
<td>33</td>
<td>2.53E-04</td>
</tr>
<tr>
<td>29-Jun-12</td>
<td>CHURN-ANNULAR</td>
<td>1</td>
<td>300</td>
<td>27</td>
<td>0.09</td>
<td>1</td>
<td>7500</td>
<td>191</td>
<td>1.56E-03</td>
</tr>
<tr>
<td>19-Sep-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>27</td>
<td>0.02</td>
<td>1</td>
<td>636</td>
<td>16</td>
<td>6.15E-04</td>
</tr>
<tr>
<td>14-Sep-12</td>
<td>LOW-LIQUID LOADING</td>
<td>1</td>
<td>300</td>
<td>15</td>
<td>0.02</td>
<td>1</td>
<td>313</td>
<td>8</td>
<td>3.03E-04</td>
</tr>
</tbody>
</table>
UT Erosion Measurements
Vertical Annular Flow in 76.2 mm (3”) Elbows

Superficial Gas Velocity = 49 m/s
Superficial Liquid Velocity = 0.2 m/s

Water Viscosity = 1 cP
Sand Size = 300 μm
Sand Conc. = 1 % concentration by weight

Experiment Time = 45 min

Maximum Erosion Measured:
667 mm/yr (26,000 mils/yr)
Location = 42°

Erosion in mm/yr
UT Erosion Measurements

Percent of Maximum Erosion Average and 95% Confidence Interval

Superficial Gas Velocity = 49-15 m/s
Superficial Liquid Velocity = 0.5-0.003 m/s

Vertical Orientation

17 Gas-Liquid-Sand Conditions

Observed Flow Patterns: Intermittent-Annular, Annular, Annular-Mist and Low-Liquid Loading

Water Viscosity = 1 cP
Sand Size = 300 μm and 150 μm
Sand Conc. = 1 % concentration by weight

Units in %
Effect of Gas Velocity on UT Erosion Measurements
Vertical Annular and Low-Liquid Conditions in 76.2 mm (3") Pipes

$V_{SL} = 0.02 \text{ m/s}$, Water 1 cP Viscosity, 1 % concentration by weight

Max. UT Erosion Measured

Erosion Ratio, mm/kg

Superficial Gas Velocity, m/s

Erosion/Corrosion Research Center

31
Effect of Liquid Velocity on UT Erosion Measurements
Vertical Annular Flow in 76.2 mm (3”) Elbows

$V_{SG} = 41$ and $49 \text{ m/s}$, Water 1 cP Viscosity, 1 % concentration by weight

Erosion Ratio, mm/kg

Superficial Liquid Velocity, m/s

Erosion/Corrosion Research Center
Comparison of UT Erosion Measurements
Vertical Annular Flow in 76.2 mm (3”) Elbows

\[ V_{SG} = 49 \text{ m/s}, \quad V_{SL} = 0.02 \text{ m/s}, \quad \text{Water 1 cP Viscosity, 1 % concentration by weight} \]

![Graph showing erosion ratios at different transducer locations.](image)

Erosion/Corrosion Research Center
# UT Erosion Measurements

## Ultrasonic Erosion Monitoring (UT)

- Erosion Results for Horizontal Flow

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16-Apr-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.5</td>
<td>1</td>
<td>3242</td>
<td>82</td>
</tr>
<tr>
<td>16-Jul-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.2</td>
<td>1</td>
<td>3171</td>
<td>81</td>
</tr>
<tr>
<td>25-Jul-11</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.04</td>
<td>1</td>
<td>3517</td>
<td>89</td>
</tr>
<tr>
<td>8-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.02</td>
<td>1</td>
<td>1883</td>
<td>48</td>
</tr>
<tr>
<td>1-Sep-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.01</td>
<td>1</td>
<td>1224</td>
<td>31</td>
</tr>
<tr>
<td>12-Sep-12</td>
<td>ANNULAR-MIST</td>
<td>1</td>
<td>300</td>
<td>49</td>
<td>0.004</td>
<td>1</td>
<td>576</td>
<td>15</td>
</tr>
<tr>
<td>2-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>40</td>
<td>0.04</td>
<td>1</td>
<td>1338</td>
<td>34</td>
</tr>
<tr>
<td>14-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>40</td>
<td>0.02</td>
<td>1</td>
<td>1212</td>
<td>31</td>
</tr>
<tr>
<td>25-Aug-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>40</td>
<td>0.02</td>
<td>1</td>
<td>1152</td>
<td>29</td>
</tr>
<tr>
<td>5-Sep-12</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>40</td>
<td>0.01</td>
<td>1</td>
<td>754</td>
<td>19</td>
</tr>
<tr>
<td>16-Jul-11</td>
<td>ANNULAR</td>
<td>1</td>
<td>300</td>
<td>35</td>
<td>0.1</td>
<td>1</td>
<td>643</td>
<td>16</td>
</tr>
</tbody>
</table>

Erosion/Corrosion Research Center

34
UT Erosion Measurements
Horizontal Annular Flow in 76.2 mm (3”) Elbows

$V_{SG} = 49 \text{ m/s}, V_{SL} = 0.04 \text{ m/s}$, water 1 cP, 1 % concentration by weight, 300μm
Experiment Time = 90 min. Erosion in mm/yr

Maximum Erosion Measured:
89 mm/yr (3,500 mils/yr)
Location = 42°
UT Erosion Measurements
Percent of Maximum Erosion Average and 95% Confidence Interval

$V_{SG} = 49-35 \text{ m/s, } V_{SL} = 0.5-0.004 \text{ m/s, Water 1 cP, 1% concentration by weight, 300}\mu\text{m.}$


Units in %
Effect of Liquid Velocity on UT Erosion Measurements
Horizontal Annular and Low-Liquid Loading in 76.2 mm (3") Elbows

Water 1 cP Viscosity, 1 % concentration by weight

Erosion Ratio, mm/kg

Superficial Liquid Velocity, m/s

Erosion/Corrosion Research Center
Comparison of UT Erosion Measurements
Horizontal Annular Flow in 76.2 mm (3") Elbows

$V_{SG} = 40 \text{ m/s}, \ V_{SL} = 0.02 \text{ m/s}, \ \text{Water 1 cP Viscosity, 1 \% concentration by weight}$
Sand Erosion Measurements
CPVC Test Cell

- Erosion Testing in Elbows
  - Intrusive Electrical Resistance (ER) Probes
  - Non-Intrusive Ultrasonic Transducers
  - CPVC Test Cell
    - Current Transducer Configuration
    - New Configuration
    - Paint Erosion Tests
    - Metal Loss Measurements

Erosion/Corrosion Research Center
Sand Erosion Measurements
CPVC Test Cell

CPVC TEST CELL (76.2 mm Dia)
Sand Erosion Measurements
Paint Erosion Tests – Vertical Annular Flow

Superficial Gas Velocity = 49 m/s
Superficial Liquid Velocity = 0.2 m/s

Water Viscosity = 1 cP
Sand Size = 300μm
Sand Conc. = 1 % concentration by weight

Experiment Time = 10 min
Sand Erosion Measurements
Thickness Loss Profile in Aluminum Specimen

$V_{SG} = 49 \text{ m/s}, V_{SL} = 0.2 \text{ m/s}$, water 1 cP, 1 % concentration by weight, 300 μm
Experiment Time = 10 min.

![Thickness Loss Profile of Elbow Specimen](image)

- Max. Thickness Loss at 45°
Sand Erosion Measurements
Paint Erosion Tests – Horizontal Annular Flow

$V_{SG} = 49 \text{ m/s}, \quad V_{SL} = 0.2 \text{ m/s}, \quad$ water $1 \text{ cP}, \quad 1 \% \text{ concentration by weight}, \quad 300\mu\text{m}$

Experiment Time $= 30 \text{ min.}$
Sand Erosion Measurements
Effect of Flow Orientation on Erosion Ratios in Specimen

$V_{SG} = 49 \text{ m/s}, V_{SL} = 0.2 \text{ m/s}, \text{ water } 1 \text{ cP, } 1\% \text{ concentration by weight, } 300 \mu\text{m}$
Sand Erosion Measurements
Effect of Flow Orientation – Comparison between UT and Specimen

\[ V_{SG} = 49 \text{ m/s}, \quad V_{SL} = 0.2 \text{ m/s}, \quad \text{water} \ 1 \text{ cP, 1 \% concentration by weight, 300\mu m} \]
Model Development
Sand Erosion in Multiphase Flows
Mechanistic Models For Gas-Liquid Annular Flows

Particles travel in the core and in the liquid film and contribute to erosion.

The key to the model is to predict a representative particle impacting velocity and then apply an erosion equation:

\[ ER = K F_S F_P f(\theta)V_p^n \]  

(1)

Every term in Eq. (1) is empirically based with the exception of the particle impact velocity.

Particle tracking routines are used to find the velocity.
Sand Erosion in Multiphase Flows
Mechanistic Models For Gas-Liquid Annular Flows

- Particle in Gas Core
- Particle in Liquid Film
- Impact Velocity
- Erosion

- Superficial Gas Velocity
- Superficial Liquid Velocity
- Internal Diameter
- Film Thickness
- Entrainment Fraction

Erosion/Corrosion Research Center
Low-Liquid Loading and Annular Flow Characteristics
Modeling and Experimental Work

- Low-Liquid Loading and Annular Flow Characteristics
  (Entrainment Fraction and Liquid Film Calculations)
- Impacting Sand Rate and Particle Velocities Estimation
- Particle Tracking in the Gas Core and Liquid Film
- Particle Impact Velocities Calculation
- Erosion Ratio Equations
- Erosion Calculation in Elbows
- Model Validation
  (Model Agree with Data?)
- Yes
  Sand Production Pipe Saver (SPPS)
- No
  Improvements

Erosion/Corrosion Research Center
Expression for entrainment fraction, $E$, used in the current prediction model was presented by Zhang (2003) based on an original expression by Oliemans (1986).

\[
\frac{E}{1-E} = 0.003 \text{We}_{SG}^{1.8} \text{Fr}_{SG}^{-0.92} \text{Re}_{SG}^{-1.24} \text{Re}_{SL}^{0.7} \left( \frac{\rho_L}{\rho_G} \right)^{0.38} \left( \frac{\mu_L}{\mu_G} \right)^{0.97}
\]

where $\rho$ is the density and $\mu$ is the viscosity. The subscripts L and G represent the liquid and gas, respectively. $\text{Re}_{SG}$, $\text{Fr}_{SG}$, $\text{We}_{SG}$ and $\text{Re}_{SL}$ are dimensionless parameters given by:

\[
\text{Re}_{SG} = \frac{\rho_G V_{SG} D}{\mu_G} \quad \text{Fr}_{SG} = \frac{V_{SG}}{\sqrt{gD}} \quad \text{We}_{SG} = \frac{\rho_G V_{SG}^2 D}{\sigma} \quad \text{Re}_{SL} = \frac{\rho_L V_{SL} D}{\mu_L}
\]
Low-Liquid Loading and Annular Flow Characteristics
Validation of Entrainment Fraction Calculations

76.2 mm (3”) Pipe Diameter, Air-Water Flow  
Data from Magrini (2009)

Erosion/Corrosion Research Center
Published models for predicting film thickness are applied to experimental results in the present study for the purpose of validation.


\[
f_I = f_G \left( 1 + 13.8 We_G^{0.2} Re_G^{-0.6} \left( h_F^+ - 200 \sqrt{\frac{\rho_G}{\rho_L}} \right) \right)
\]

\[
We_G = \frac{\rho_G v_c^2 D}{\sigma} \quad Re_G = \frac{\rho_G v_c D}{\mu_G} \quad h_F^+ = \frac{\rho_G \delta v_c^*}{\mu_G} \quad v_c^* = \frac{\tau_I}{\rho_G}
\]
Low-Liquid Loading and Annular Flow Characteristics
Validation of Film Thickness Calculations

76.2 mm Pipe Diameter, Air-Water Flow

Data from Magrini (2009)

Erosion/Corrosion Research Center
Validation of SPPS
(Summary)
Recently, E/CRC developed new erosion equations for oilfield materials including Stainless Steel 316 and Inconel 625 based on direct impingement test results in air.

A modified version of the angle function suggested by Oka was used with parameters which are chosen to fit the experimental data.

\[
F(\theta) = A \times \sin(\theta)^n \times \left(1 + Hv^n \left(1 - \sin(\theta)\right)\right)^n
\]  

(4)

Erosion equation developed by Zhang at the E/CRC. 2.41 is used as an exponent for the particle velocity.

\[
ER\left(\frac{kg}{kg}\right) = K \times F_s \times V_p^{2.41} \times F(\theta) \quad \text{where} \quad K = C \times BH^{-0.59} \quad \text{for carbon steels.}
\]
Model Development
SPPS Annular Model Predictions using Current ER Equation

\[ V_{SG} = 49-15 \text{ m/s}, \quad V_{SL} = 0.2-0.01 \text{ m/s}, \quad \text{Water 1 cP and 10 cp, 1 \% concentration by weight, 76.2 mm (3") Elbows, Particle Sizes = 300 \mu m and 150 \mu m} \]
Model Development
SPPS Annular Model Predictions using Current ER Equation

$V_{SG} = 49-15 \text{ m/s}, V_{SL} = 0.2-0.003 \text{ m/s}$, Water 1 cP, 1 % concentration by weight, 76.2 mm (3") Elbows, Particle Sizes = 300μm and 150μm

Predicted Erosion Ratio, mm/kg

Experimental Data, mm/kg
New Modeling Improvements Plans
Modeling and Experimental Work

- Experimental Investigation of Liquid and Gas Phase Velocities
- Use of Wire-Mesh Sensor Technology in Gas-Liquid Flows
- Velocity in Mist Flows
- Film Thickness Estimation in Elbows
- Analysis of Film Thinning and Breakdown at 45° in Vertical Flows
- Development of a New Erosion Ratio Equation for Wet Surfaces

Erosion/Corrosion Research Center 58
Wire-mesh sensor comprises two sets of wires (electrodes) stretched over the cross-section of a pipe forming a grid of electrodes.

- Each of the measured signals reflects the composition of the flow within its associated sub-region, so each crossing point acts as local phase indicator.
- Hence, the set of data obtained from the sensor directly represents the phase distribution over the cross-section.

Instrumentation and data extraction software developed by Helmholtz-Zentrum Dresden-Rossendorf (HZDR-Germany)
New Modeling Improvements Plans

Void Fraction Measurements Using Wire Mesh Sensors

- Experimental Conditions in Horizontal Annular-Stratified Flows

<table>
<thead>
<tr>
<th>Upstream Section</th>
<th>VSG [m/s]</th>
<th>VSL [m/s]</th>
<th>Viscosity [cP]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 - 33.5</td>
<td>0.20 - 0.03</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9.1 - 33.5</td>
<td>0.20 - 0.03</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>9.1 - 33.5</td>
<td>0.20 - 0.03</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Downstream Section</th>
<th>VSG [m/s]</th>
<th>VSL [m/s]</th>
<th>Viscosity [cP]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 - 41.8</td>
<td>0.21 - 0.03</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9.1 - 41.8</td>
<td>0.21 - 0.03</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>9.1 - 41.8</td>
<td>0.21 - 0.03</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>
New Modeling Improvements Plans
Void Fraction Time-Series in Horizontal Annular Flow

\[ V_{SG} = 33.5 \text{ m/s, } V_{SL} = 0.2 \text{ m/s, water 1 cP} \]
New Modeling Improvements Plans
Film Thickness Estimation in Bends – Vertical Annular Flow

- Abdulkadir (2011) carried out experimental investigations in a large diameter pipe of 127 mm attached to a vertical 180° return bend r/D=3.0 using air-water as the model fluids.

- The objective was to measure, film fraction and local liquid film distributions in the annular flow regimes at different locations using conductance ring probes and electrical conductance techniques.
New Modeling Improvements Plans

Film Thickness Estimation in Bends – Film Breakdown at 45°

\[ V_{SG} \approx 15.5 \text{ m/s, 127 mm Pipe Diameter, Air-Water Vertical Annular Flow} \]

Data from Abdulkadir (2011)

---

Erosion/Corrosion Research Center
Summary and Conclusions

- Significant differences have been observed for erosion in horizontal and vertical flows.
- For annular flow conditions, vertical flow was more erosive than horizontal flow. For low-liquid loading conditions erosion magnitudes were similar.
- For certain conditions, higher erosion has been observed at a higher liquid velocity. One possible reason is that higher sand entrainment exists in the gas core region at higher liquid rates.
Summary and Conclusions

- Mechanistic model available for predicting erosion in multiphase flow was developed using data for 25.4 mm (1”) and 50.8 mm (2”) elbows.
- New data has been collected for 76.2 mm (3”) and 101.6 mm (4”) elbow diameters for both vertical and horizontal flows.
- Existing model needs to be refined further by comparing with new erosion test results in vertical and horizontal flow.
- Updated annular flow erosion model is available in SPPS 4.3
Future Work – UT Measurements
Second Configuration – New Stainless Steel Elbow

- A new 76.2 mm Stainless Steel bend has been instrumented.

- More transducers have been placed on the downstream section of the elbow.

- Transducer #3 (T3) has been placed exactly at 45° on the outer section of the bend.
Future Work
Measurements in Gas and Mist-Annular Flows

- Continue analyzing void fraction and velocity data for annular flows before and after the bend using Wire Mesh Sensors for horizontal annular flow.

- Conduct new experiments using Wire Mesh Sensor for vertical orientation and collect void fraction and velocity data before and after the bend for low-liquid, annular and churn-annular conditions.

- Continue collecting erosion data for annular flows in 76.2 mm (3”) and 101.6 mm (4”) pipes using ER Probes in Pipe Vertical and Horizontal Flows.

- Estimate measurement and modeling uncertainty to improve the reliability of model predictions.
Future Work
Anticipated Deliverables of this Project

- Deliverable: Modeling to improve SPPS 1-D for Annular flow (vertical)
  Completion Date: May 2011-November 2011 (SPPS 4.2) (Done).

- Deliverable: Experimental Database for LLL and Annular Flow
  (Location of max. erosion for larger diameter pipes and sand sampling)
  Completion Date: November 2012. (Done)

  Validation with New Data
  Anticipated Completion Date: May 2013.

- Deliverable: Modeling of Horizontal vs. Vertical (LLL and Annular)
  Anticipated Completion Date: May 2013.

- Deliverable: Improved SPPS for LLL and Annular flows in Horizontal and Vertical Pipes
  Anticipated Completion Date: November 2013.
End of Presentation

THANKS