## Tulsa University Artificial Lift Projects
### 62nd Advisory Board Meeting Agenda
### October 27th & 28th, 2016
### Allen Chapman Student Center – 440 South Gary Ave
### The University of Tulsa, Tulsa, OK

**Thursday, October 27th, 2016**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4:00pm</td>
<td>Facilities Tour with Refreshments in Alpine House</td>
<td>TU North Campus</td>
</tr>
<tr>
<td>5:30pm</td>
<td>Reception Dinner at a local restaurant.</td>
<td>ROKA 16th &amp; Utica</td>
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</tbody>
</table>

**Friday, October 28th, 2016**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30am</td>
<td>Registration and Breakfast</td>
<td>Allen Chapman Student Union, Alcove</td>
</tr>
<tr>
<td></td>
<td>Progress Report Meeting</td>
<td>Allen Chapman Student Union, Chouteau C</td>
</tr>
<tr>
<td>9:00</td>
<td>Welcome and TUALP Research Overview</td>
<td>Holden Zhang</td>
</tr>
<tr>
<td>9:30</td>
<td>Experiments and Modeling of ESP Performance under Gassy Flow Conditions</td>
<td>Jianjun Zhu</td>
</tr>
<tr>
<td>10:15</td>
<td>Problem Diagnosis and Data Analytics Review for Well Surveillance</td>
<td>Rachna Nanda Kumar</td>
</tr>
<tr>
<td>10:30</td>
<td>Coffee Break</td>
<td></td>
</tr>
<tr>
<td>10:45</td>
<td>Experimental Study of Viscosity Effect and Oil/Water Flow in ESP</td>
<td>Hattan Banjar</td>
</tr>
<tr>
<td>11:15</td>
<td>Unified Transient Model for Gas-Oil-Water Flow in Pipe</td>
<td>Fahad Al-Mudairis</td>
</tr>
<tr>
<td>12:00pm</td>
<td>Lunch</td>
<td>Allen Chapman Student Union, Alcove</td>
</tr>
<tr>
<td>1:00</td>
<td>ESP Gas-Liquid Flow Pattern Prediction with CFD Simulation and Experimental Validations</td>
<td>Jianjun Zhu</td>
</tr>
<tr>
<td>1:30</td>
<td>ESP Sand Erosion Literature Review and Test Flow Loop Design</td>
<td>Haiwen Zhu</td>
</tr>
<tr>
<td>2:00</td>
<td>Viscosity Effect on ESP Performance – Testing Flow Loop Design</td>
<td>Jiecheng Zhang</td>
</tr>
<tr>
<td>2:30</td>
<td>Questionnaire and Project Discussions</td>
<td>Holden Zhang</td>
</tr>
<tr>
<td>3:00pm</td>
<td>Adjourn</td>
<td></td>
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</table>
Tulsa University Artificial Lift Projects

Welcome to the TUALP 62nd ABM

Holden Zhang
McDougall School of Petroleum Engineering
The University of Tulsa

• TUALP 62nd Advisory Board Meeting
• Handout
  ➢ All presentations on thumb drive
  ➢ Will be posted on TUALP website after ABM for download by members who cannot attend (www.tualp.utulsa.edu)
Our Team

- Holden Zhang
  - Director
- Bryan Sams
  - Project Engineer
- Donna Trankley
  - Project Assistant

Our Team...

- Dr. Junqi Wang
  - Visiting professor from Xi’an Petroleum University
- Mr. Alberto Martinez
  - Visiting researcher from IMP
- Dr. Ruben Cuamatzi
  - Visiting researcher from IMP
Our Team...

- Jianjun Zhu
  - PhD candidate
- Hattan Banjar
  - PhD candidate
  - Sponsored by Saudi Aramco

Our Team...

- Fahad Al-Mudairis
  - PhD candidate
  - Sponsored by Kuwait University
- Haiwen Zhu
  - PhD candidate, TA
Our Team…

- Jiecheng Zhang
  - MSc student
- Yuchen Ji
  - MSc student
- Rachna Nanda Kumar
  - Undergraduate

2016 TUALP Members

- Baker Hughes
- eLynx Tech
- GE
- IMP
- KOC
- Pemex
- Petrobras
- Petroleum Experts
- Schlumberger
- Statoil
Welcome New Members

- **eLynx Tech**
  - A leading provider of web-based SCADA monitoring, and field automation services for the oil and gas industry

- **IMP, Mexican Petroleum Institute**
  - A leading research petroleum institute in Mexico
  - Close relationship with Pemex

A Separate Project with IMP

- **Technology Development/Training on ESP Performance under High Oil Viscosity, Oil/Water Emulsions and Sand Production Conditions**
  - IMP engineers participate in ESP experiments and modeling
  - Two year funding about $534K
Dr. Zhang on Sabbatical in 2017

- No classes and services, focusing on research
- More deliverables
- Visiting members and potential companies
- Explore new research topics

62nd Advisory Board Meeting
Oct 28, 2016

Agenda

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
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<tbody>
<tr>
<td>9:00am</td>
<td>Welcome</td>
<td>Holden Zhang</td>
</tr>
<tr>
<td>9:10</td>
<td>TUALP Researches and Outlook</td>
<td>Holden Zhang</td>
</tr>
<tr>
<td>9:30</td>
<td>Experiments and Modeling of ESP Performance under Gassy Conditions</td>
<td>Jianjun Zhu</td>
</tr>
<tr>
<td>10:15</td>
<td>Review of Problem Diagnosis and Data Analytics for Well Surveillance</td>
<td>Rachna Nanda Kumar</td>
</tr>
<tr>
<td>10:30</td>
<td>Coffee Break</td>
<td></td>
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<tr>
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<td>Experimental Study of Viscosity Effect and Oil/Water Flow in ESPs</td>
<td>Hattan Banjar</td>
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<tr>
<td>11:15</td>
<td>Unified Transient Model for Gas-Oil-Water Flow in Wells and Pipelines</td>
<td>Fahad Al-Mudairis</td>
</tr>
<tr>
<td>12:00pm</td>
<td>Luncheon</td>
<td>All</td>
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## Agenda…

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<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
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<tbody>
<tr>
<td>1:00</td>
<td>CFD Simulation of ESP Gas-Liquid Flow Patterns and Comparison with Visualization Results</td>
<td>Jianjun Zhu</td>
</tr>
<tr>
<td>1:30</td>
<td>ESP Sand Erosion Literature Review and Test Flow Loop Design</td>
<td>Haiwen Zhu</td>
</tr>
<tr>
<td>2:00</td>
<td>Viscosity Effect on ESP Performance – Modeling and Test Flow Loop Design</td>
<td>Jiecheng Zhang</td>
</tr>
<tr>
<td>2:30</td>
<td>2016 Questionnaire and Project Discussions</td>
<td>Holden Zhang</td>
</tr>
<tr>
<td>3:00pm</td>
<td>Adjourn</td>
<td></td>
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</tbody>
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Tulsa University Artificial Lift Projects

TUALP 2016 Questionnaire and Project Discussions

Holden Zhang
McDougall School of Petroleum Engineering
The University of Tulsa

- TUALP researches are guided by Members’ interest
  - New members’ inputs
  - Previous questionnaire results are used for other members
  - Please let me know of any specific topics you are interested in
### 2016 Questionnaire Results

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<th>GE</th>
<th>IMP</th>
<th>IEC</th>
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<td>CFD Simulation and Experiments of ESP Sand Erosion</td>
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<td>Experiments, CFD Simulation and Mechanistic Modeling of ESP Performance under Gassy Conditions</td>
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</table>

### No. 1 and 2

- **Study of Gas/Oil/Water Flow and Emulsion Characterization in ESPs**
  - Combines oil viscosity effect, oil/water flow, gas/liquid and three-phase flow
  - Hattan Banjar (PhD Candidate) leads this project
  - Jiecheng Zhang (MSc Student)
- **Experiments and CFD Simulation of ESP Sand Erosion**
  - Haiwen Zhu (PhD Candidate) leads this project
  - Experimental flow loop construction underway
No. 3 and 4

- Experiments, CFD Simulation and Mechanistic Modeling of ESP Performance under Gassy Conditions
  - Jianjun Zhu (PhD candidate) leads this project
  - Made significant test results and modeling progresses

- Experimental Study of High Speed ESP Performance
  - Ready to start once a ESP system is available
  - Potential

No. 5 and 6

- Mechanistic Modeling of ESP Performance for High-Viscosity Oil and Gas-Liquid Flows
  - Framework developed by Holden Zhang
  - Enhanced through continuous experiments and modeling

- Problematic Case Characterization and Data Interpretation for Well Surveillance
  - Starting with state-of-the-art review
  - Mechanistic modeling and simulations
No. 7

- Combination of
  - Modeling of Multiphase Flow in Horizontal Wells with Distributed Influxes for Artificial Lift Application
  - Transient Gas Lift Modeling
  - Unified Modeling of Transient Multiphase Flow in Well and Pipeline
- Fahad (PhD Candidate) leads this project

No. 8 and 9

- ESP Testing at High Pressure and Temperature
  - Potential, dependent on availability of ESP system
- Downhole Gas Separation and Slug Elimination
  - New designs proposed by Holden Zhang
  - Haiwen Zhu (PhD Candidate) works on this project
eLynx Interest

- Shutdown/restart impacts on ESP
- CFD Simulation/testing of ESP’s impellers plugging (due to sand, scale etc.)
  - Investigations of pressure, temperature during plugging process, etc.
- Optimization practices in gas-lift in terms of injection/drainage valve locations and their rates

IMP Interest

- Development of an expert system for selection of artificial lift system
- Optimization methodologies for operating gas lift and ESP systems
  - Dual ESP system
- Failure analysis of ESP systems
- Methodologies/best practice to maximize ESP life span
- Study of chemical inhibitor (asphaltene dispersant) through ESP to prevent and control deposition
KOC Visit after SPE ATCE

- Reported TUALP progresses
- Discussed KOC interest
  - Asphaltenes
  - CO₂, H₂S corrosions (cable, seal)
  - Dogleg ESP installation
  - Automatic ESP control
  - Heat transfer
  - Heavy oil
  - AL screening
  - ESP depth setting
- KOC may arrange ESP for testing

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2016 Budget

<table>
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<th>Income</th>
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<th>Actual</th>
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<td>90610 Professional Part-Time</td>
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<td>90701 Technician - B. Sams</td>
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<td>Total Expenses</td>
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TUALP Financial

- Financially very strong during a market downturn
- Significant investment on facility buildup
- Membership outlook in 2017
  - Member pullouts due to financial constraints
  - Possible new members

Adjourn

- 2017 Spring ABM
  - In Woodlands, TX, in conjunction with SPE ESP Symposium
  - April 24 (Monday), 2017
- Thanks for your support!
Tulsa University Artificial Lift Projects

TUALP Researches and Outlook

Holden Zhang
McDougall School of Petroleum Engineering
The University of Tulsa

Artificial Lift Industry Needs

- Increase cost efficiency
  - Design and operation optimizations
  - Based on accurate model predictions
- Improve reliability
  - Performance of artificial lift systems
  - Effects of sand, scale, HPHT, …
Artificial Lift Industry Needs…

- Meet new challenges
  - Horizontal well, slugging, fast decline…
  - Extreme flow conditions
- Lead new trends
  - Data integration
  - Intelligent fields (wells) powered by transient models

High Oil Viscosity and Oil/Water Emulsion in ESPs

- Oil viscosity effects on ESP performance
- Oil/water emulsion rheology
  - Effective viscosity
  - Inversion point
  - Shear effect
  - Droplet size
  - Stage effect
Ongoing Project (Hattan Banjar)

- Study of oil/water flow and emulsion characterization in ESPs
  - Measure ESP stage performance
  - Oil viscosity effect
  - Mechanistic modeling
  - CFD simulation
  - Three-phase flow?

Gas Entrainment in ESP

- ESP performance degradation with gas
- Gas lock and instabilities
- Pressure and stage effects
Ongoing Project (Jianjun Zhu)

- Experimental study and CFD simulation of ESP performance under gassy conditions
  - Measurements
  - Surfactant effect
  - CFD simulations
  - Modeling

ESP from GE

- Old pump replaced with new one
A New Flow Loop for High Flow Rate/High Oil Viscosity ESP Test

- High-viscosity oil and oil/water flow loop being built, 3”, 10,000 bpd

Ongoing Project (Jiecheng Zhang)

- Experiments and modeling of ESP performance for high-viscosity oil
  - Wider flow rate
  - Oil water emulsions
  - Model validation

Viscosity Effect on ESP Single-Phase Performance
ESP Mechanistic Modeling

- Mechanistic modeling of ESP performance
  - Based on overall pump geometry, fluid viscosities, densities, interfacial tension and flow rates
  - High oil viscosity
  - Gas-liquid flow
  - Oil-water flow
  - Gas-oil-water flow

Sand Production with ESP

- Sand erosion
- Abrasion
- ESP performance change
Ongoing Project (Haiwen Zhu)

- Experiments and CFD simulation of ESP sand erosion
  - Experimental measurement and observation
  - CFD simulation of sand particle trajectory and accumulation
  - Identify areas vulnerable to sand erosion

New ESP and Skid

- New ESP donated by Baker Hughes
- Skid designed and made at TUALP
Transient Multiphase Pipe Flow Modeling

- Gas lift – casing heading
- Horizontal well slugging
- Severe slugging
- Start-up and shut-in...

Ongoing Project (Fahad Al-Mudairis)

- Transient multiphase pipe flow modeling
  - Developed a unified transient model for gas-liquid pipe flow
  - Development of unified transient model for gas-oil-water pipe flow under way
New Design – Self-Stabilizing Gas Lift Valve

- Self stabilized by flow
- Small pressure drop
- Can avoid damage due to high pressure drop and high shear
- Patent approved

Liquid Loading in Gas Well

- Reduce production rate
- Eventually kill well
Ongoing Project (Weiqi Fu)

- Plunger lift modeling and optimization
  - Transient mechanistic model
  - Cover all phases of plunger lift cycle
  - Incorporate inflow and pipeline to separator

Downhole Gas Separation

- Gas affects ESP performance
- Separation limited by space and affected by slugging
- Most current methods have limitations
  - Low efficiency
  - High resistance
  - Poor slug handling
  - High power consumption
  - ……
Ongoing Project (Haiwen Zhu)

- CFD simulation of downhole gas separation
  - Evaluate different downhole gas separation methods
  - Select best design
  - Performance modeling

New Design – Eccentric Pipe-in-Pipe Downhole Gas Separator

- High efficiency and low cost
- Low pressure drop
- Sufficient length for slug elimination
- Sand handling
- Patent pending
Smart Field Development

- Data integration
- Problem diagnosis
- Optimization

Ongoing Project (Rachna Nanda Kumar)

- Problem Diagnosis and Data Analytics for Well Surveillance
  - State-of-the-art review
  - Problematic case characterization
  - Problematic case simulations with software and models
  - Mechanistic model validation with field data
  - Integration of mechanistic models with well surveillance
TUALP Research Perspective

● Every TUALP research project dedicates to an industry need
● Systematic approaches
● Develop and maintain best models
● Lookout for new challenges
● Always innovative

TUALP Facility Buildup

● Recently acquired two high pressure separators
  ➢ Horizontal 30”X10’, WP 1440 psig
  ➢ Vertical 36”X10’, WP 1440 psig
New WorkStation Funded by IPM Project

- CFD simulations, prioritized for IMP visiting scholars
- 40 core
Entrained gas deteriorates ESP performance and causes surging or gas locking

Mechanistic models needed to predict ESP performance under gassy flow conditions

Experimental data needed to compare with simulation results and validate mechanistic model predictions
Objectives

- Test ESP performance with gas-liquid flows
  - Investigate effects of multistage, viscosity, intake GVF and pressure, interfacial tension, etc.
- Develop mechanistic model for the prediction of ESP gas-liquid flow performance
  - Transition boundaries of flow patterns
  - Two-phase modeling considering flow patterns
  - Develop closure relationships

Outline

- Experimental study update
- Mechanistic modeling update
- Conclusions
- Near future work
Experimental Study Update

- Experimental facility
- Test matrix
- Single-phase test results
- Two-phase test results
  - Data processing
  - No surfactant injection
  - With surfactant injection
    - Case 1: 0.13 vol% IPA
    - Case 2: 0.52 vol% IPA
- Discussions

Experimental Facility

- Schematic of ESP two-phase testing loop
Experimental Facility...

- Stage-by-stage measurement
  - 13 absolute pressure sensors
  - 7 differential pressure sensors
  - 2 temperature RTD
  - 2 Coriolis flowmeter sensors
  - 1 rotary speed and torque sensor

Data acquisition system (DAQ)


cell phone

cell phone

Test Matrix

- **Single-phase tests**

<table>
<thead>
<tr>
<th>Rotational Speed (rpm)</th>
<th>Liquid Flow Rate (bpd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3500, 3000, 2400, 1800</td>
<td>100, 200, ...</td>
</tr>
</tbody>
</table>

- **Two-phase tests**

<table>
<thead>
<tr>
<th>Surfactant volumetric Concentration</th>
<th>Rotational Speed (rpm)</th>
<th>Intake Pressure (psig)</th>
<th>Liquid Flow Rate (bpd)</th>
<th>Gas Flow Rate (lb/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>3500, 1800</td>
<td>50, 100, 150</td>
<td>300, 600, ...</td>
<td>0.01, 0.02, 0.03, ..., 0.5</td>
</tr>
<tr>
<td>0.13%</td>
<td>3500, 1800</td>
<td>50, 100, 150</td>
<td>300, 600, ...</td>
<td>0.01, 0.02, 0.03, ..., 0.5</td>
</tr>
<tr>
<td>0.52%</td>
<td>3500, 1800</td>
<td>50, 100, 150</td>
<td>300, 600, ...</td>
<td>0.01, 0.02, 0.03, ..., 0.5</td>
</tr>
</tbody>
</table>


Single-phase Test Results

- **Tap water, no surfactant injection**

```plaintext

```

```plaintext

```
Two-phase Test

- Two-phase tests include
  - Water-air
  - Water-air, 0.13 vol% IPA
  - Water-air, 0.52 vol% IPA
- Surging tests and mapping tests
- Data processing method
  - Air property calculation
  - Gas volumetric fraction (GVF)

\[
Q_L = \frac{m_L}{\rho_L} \quad Q_G = \frac{m_G}{\rho_G} \quad GVF = \frac{Q_G}{Q_G + Q_L}
\]

Two-phase Test...

- Surging test: constant liquid flow rate, gas flow rate increases from 0 until ESP pressure increment approaches zero
- Mapping test: constant gas volumetric flow rate, varied liquid flow rates
Air Properties

- Based on CIPM-81

**Density**

\[ \rho = \frac{p M_a}{Z R T} \left[ 1 - x_v \left( 1 - \frac{M_v}{M_a} \right) \right] \] Kg/m³

\[ M_a = 28.9635 + 12.011 \left( x_{CO_2} - 0.0004 \right) \] g/mol

\[ p_{SV} = 1 \times \exp \left( A T^2 + B T + C + \frac{D}{T} \right) \] Pa

\[ f = \alpha + \beta p + \gamma^2 \]

\[ x_v = hf(p, t) \frac{p_{SV}(t)}{p} = f(p, t_r) \frac{p_{SV}(t_r)}{p} \]

---

**Compressibility Z**

\[ Z = 1 - \frac{P}{T} \left[ a_0 + a_1 t + a_2 t^2 + \left( b_0 + b_1 t \right) x_v + \left( c_0 + c_1 t \right) x_v^2 \right] + \frac{P^2}{T^2} \left( d + e x_v^2 \right) \]

**Constants**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.000012811805</td>
<td>0.00000162419</td>
</tr>
<tr>
<td>B</td>
<td>-0.019509874</td>
<td>-0.000000028969</td>
</tr>
<tr>
<td>C</td>
<td>34.04926034</td>
<td>0.0000000001088</td>
</tr>
<tr>
<td>D</td>
<td>-6.3536311</td>
<td>0.000005757</td>
</tr>
<tr>
<td>a</td>
<td>1.00062</td>
<td>0.00019297</td>
</tr>
<tr>
<td>b</td>
<td>-0.0000002589</td>
<td>-0.000002285</td>
</tr>
<tr>
<td>c</td>
<td>0.000000000173</td>
<td>-0.0000001034</td>
</tr>
</tbody>
</table>

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Oct 28, 2016
Isopropyl Alcohol (IPA)

- It reduces interfacial tension between water and air

\[
\sigma = \sigma_0 \left(1 - 0.411 \log \left(1 + \frac{x}{a_{MM}}\right)\right)
\]

Meissner & Michaels (1949):

8 hr injection: IPA vol% = 0.13%, \(\sigma = 0.0669\) N/m
16 hr injection: IPA vol% = 0.52%, \(\sigma = 0.0635\) N/m

Surging Test Results with Water
Mapping Test Results with Water

Surging Test Results with 0.13 vol% IPA

\( \sigma = 0.0669 \text{ N/m} \)
Mapping Test Results with 0.13 vol% IPA
\[ \sigma = 0.0669 \text{ N/m} \]

Surging Test Results with 0.52 vol% IPA
\[ \sigma = 0.0635 \text{ N/m} \]
Mapping Test Results with 0.52 vol% IPA

\[ \sigma = 0.0635 \text{ N/m} \]

**Surging Test Result Comparison**

- **Intake pressure effect**

  ![Graphs showing pressure increment vs. QL for different intake pressures and speeds.]

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Oct 28, 2016
Surging Test Result Comparison…

- **Surfactant concentration effect**

Mapping Test Result Comparison

- **Intake pressure effect**
Mapping Test Result Comparison...

- Surfactant concentration effect

Mechanistic Modeling Update

- Single-phase modeling in ESP
- Transition boundaries
  - Dispersed bubble flow to bubbly flow
  - Bubbly flow to intermittent flow
  - Intermittent flow to annular flow
- Two-phase modeling in ESP
  - Dispersed bubble flow
  - Bubbly flow
  - Intermittent flow
  - Annular flow
- Results and discussions
Single-phase Flow Modeling

- Euler theory for modeling centrifugal pump hydraulic performance
  - Based on conservation law of angular momentum
  - No consideration of friction, recirculation, leakage, etc.
- Head losses in centrifugal pump are significant for predicting ESP performance
- Zhang (2013) established a new framework for calculating head losses in centrifugal pump

Euler Head in Centrifugal Pump

- Conservation of angular momentum in rotating centrifugal pump
  \[
  \ddot{T} = \frac{dL}{dt} = \frac{d(m\ddot{v} \times \ddot{r})}{dt}
  \]
- Ideal, no losses
  \[
  \ddot{T} \cdot \ddot{\Omega} = \Delta P \cdot \dot{Q}
  \]
  \[
  \frac{\Delta P \cdot \dot{Q}}{\Omega} = \frac{d(m\ddot{v} \times \ddot{r})}{dt} \Rightarrow \Delta P \cdot \dot{Q} \cdot \Delta t = m(\ddot{C}_2 \times \ddot{r}_2 - \ddot{C}_1 \times \ddot{r}_1) \cdot \ddot{\Omega}
  \]
  \[
  \Rightarrow \frac{\Delta P}{\rho} = (\ddot{C}_2 \times \ddot{r}_2 - \ddot{C}_1 \times \ddot{r}_1) \cdot \ddot{\Omega} = \ddot{C}_2 \cdot (\ddot{\Omega} \times \ddot{r}_2) - \ddot{C}_1 \cdot (\ddot{\Omega} \times \ddot{r}_1) = \ddot{C}_2 \cdot \ddot{U}_2 - \ddot{C}_1 \cdot \ddot{U}_1
  \]
  \[
  \Rightarrow H = \frac{\ddot{C}_2 \cdot \ddot{U}_2 - \ddot{C}_1 \cdot \ddot{U}_1}{g}
  \]
Euler Head in Centrifugal Pump...

- **Velocity triangle**

\[
H_E = \frac{C_2 \cdot \bar{U}_2 - \bar{C}_1 \cdot \bar{U}_1}{g} = \frac{U_2 C_2 w - U_1 C_1 w}{g} = \frac{U_2^2 - U_1^2}{2g} + \frac{W_2^2 - W_1^2}{2g} + \frac{C_2^2 - C_1^2}{2g}
\]

\[
C_{1M} = \frac{Q}{2\pi r_2 h}
\]

\[
C_{2M} = \frac{Q}{2\pi r_2 h}
\]

\[
\Rightarrow H_E = \frac{\Omega^2 (r_2^2 - r_1^2)}{g} - \frac{Q \Omega}{2\pi g h} \left( \frac{1}{\tan \beta_2} - \frac{1}{\tan \beta_1} \right)
\]

Real Head in Centrifugal Pump

- **No pre-rotation at entrance:** \( U_1 = W_1 \cos \beta_1 \)

\[
H_E = \frac{\Omega^2 r_2^2}{g} - \frac{Q \Omega}{2\pi g h \tan \beta_2}
\]

- **Real head must include all losses**

\[
H = H_E - h_{\text{friction}} - h_{\text{shock}} - h_{\text{leakage}} - h_{\text{recirculation}} - h_{\text{diffuser}} - h_{\text{disk}}
\]
Single-phase Modeling

- Followed Zhang (2013) modeling method
- Efforts focus on improving closure relationships
- At $Q_B$, velocity triangle matches design, and no slip occurs
- Recirculation occurs when $Q < Q_B$
- Fluid viscosity effect is considered in shear velocity when $Q < Q_B$
- At $Q > Q_B$, theoretical head needs to be modified to account for velocity slippage

Recirculation Loss Modeling

- $Q < Q_B$
  \[ C_{2P} = C_{2B} \frac{Q}{Q_B} \]
  \[ V_S = U_2 \frac{Q_B - Q}{Q_B} \]
  \[ C_2^2 - C_{2P}^2 = V_S^2 - (C_{2P} - C_{2F})^2 \]
  \[ \Rightarrow C_{2P} = \frac{C_2^2 + C_{2F}^2 - V_S^2}{2C_{2F}} \]

- Recirculation flow
  \[ C_{2F} = C_{2F} + s(C_{2P} - C_{2F}) \]
  \[ s = \begin{cases} \left( \frac{\mu_w}{\mu} \right)^{0.5} & \mu \neq \mu_w \\ 1 + 0.02 \text{Re}_C^{0.2} & \mu = \mu_w \end{cases} \]
  \[ \text{Re}_C = \frac{\rho V_2 D_C}{\mu} \]
  \[ D_C = \frac{2\pi R_2}{Z_1} \sin \beta_2 - T_B \]
Recirculation Loss Modeling…

- **$Q > Q_B$**
  \[
  C_{2F} = C_{2B} \frac{Q}{Q_B} \quad V_S = U_2 \frac{Q - Q_B}{Q_B}
  \]
  \[
  C_2^2 - C_{2E}^2 = V_S^2 - \left(C_{2F}^2 - C_{2E}^2\right)^2
  \]
  \[
  \Rightarrow C_{2E} = \frac{C_2^2 + C_{2F}^2 - V_S^2}{2C_{2F}}
  \]

- **Recirculation loss**
  \[
  h_{\text{recirculation}} = \frac{C_2^2 - C_{2E}^2}{2g}
  \]

Recirculation Loss Modeling…

- **Recirculation loss modeling in literature**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulich (1999)</td>
<td>$h_{\text{recirculation}} \approx 0$</td>
</tr>
<tr>
<td>Yoon et al. (1998)</td>
<td>$h_{\text{recirculation}} = k_{\text{rec}} \sinh(3.5a_2^2)D_1^2U_2^2/g$</td>
</tr>
<tr>
<td>Sun &amp; Prado (2002)</td>
<td>$\alpha_2 = \arcsin \left(\frac{Q}{2\pi r b_2(U_2^2 + W_2^2 - 2U_2 W_2 \cos \beta_2)}\right)$</td>
</tr>
<tr>
<td>Bing et al. (2012)</td>
<td>$D_f = 1 + \frac{W_2}{W_1} \left(\frac{U_2}{U_1}\right) \left(\frac{N_a}{\pi}\right) \left(1 - \left(\frac{D_1}{D_2}\right)^2 + \frac{D_1t}{D_2} - 1\right)$</td>
</tr>
<tr>
<td>Tuzson (2000)</td>
<td>$h_{\text{recirculation}} = 0$ for $Q &gt; Q_{\text{BEP}}$</td>
</tr>
<tr>
<td>Thin et al. (2008)</td>
<td>$h_{\text{recirculation}} = k_{\text{rec}} \omega^3 D_1^2 \left(\frac{Q}{Q_{\text{BEP}}}\right)^{2.5}$ for $Q \leq Q_{\text{BEP}}$</td>
</tr>
</tbody>
</table>
Friction Loss Modeling

- Friction loss

\[ h_{\text{friction}} = h_{FI} + h_{FD} \]

\[ h_{FI} = f_{FI} \frac{V^2 I_l}{2gD_I} \quad h_{FD} = f_{FD} \frac{V^2 D_D}{2gD_D} \]

- Friction factors in impeller channel and diffusor channel, \( f_{FI} \) and \( f_{FD} \), can be obtained by Blasius or Churchill’s correlations

Friction Loss Modeling…

- Friction loss modeling in literature

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ito (1959)</td>
<td>( h_{\text{friction}} = \frac{2 f_{\gamma \beta \omega} Q^2}{8 g D_H \pi^2 b_m^2 \sin^3 \beta_m} \frac{r_2 - r_1}{r_1 r_2} )</td>
</tr>
<tr>
<td>Jones (1976)</td>
<td>( f_{\gamma \beta \omega} = F_{\gamma} F_{\beta} F_{\omega} f )</td>
</tr>
<tr>
<td>Churchill (1977)</td>
<td></td>
</tr>
<tr>
<td>Shah (1978)</td>
<td></td>
</tr>
<tr>
<td>Sun (2003)</td>
<td></td>
</tr>
<tr>
<td>Wiesner (1967)</td>
<td>( h_{\text{friction}} = b_2 \frac{(D_2 - D_1)(W_1 + W_2)^2}{8 g \sin \beta_2 r_H} )</td>
</tr>
<tr>
<td>Sun and Prado (2002)</td>
<td></td>
</tr>
<tr>
<td>Thin et al. (2008)</td>
<td></td>
</tr>
<tr>
<td>Ito and Nanbu (1971)</td>
<td>( h_{\text{friction}} = N_a f_{\gamma \beta \omega} \frac{s (W_1^2 + W_2^2)}{D_H} )</td>
</tr>
<tr>
<td>Bing et al. (2012)</td>
<td></td>
</tr>
</tbody>
</table>
Shock Loss Modeling

- Shock loss:
  \[ h_{\text{shock}} = h_{TI} + h_{TD} \]
  \[ h_{TI} = f_{TI} \frac{V_i^2}{2g} \quad h_{TD} = f_{TD} \frac{V_D^2}{2g} \]

- Literature models

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stepanoff (1957), Amaral (2007), Thin et al. (2008)</td>
<td>[ h_{\text{shock}} = k_{\text{shock}} (Q - Q_{BEP})^2 ]</td>
</tr>
<tr>
<td>Wiesner (1967), Sun and Prado (2002), Thin et al. (2008)</td>
<td>[ h_{\text{shock}} = \frac{k_{\text{shock}}}{2g} \left( \frac{Q - Q_{BEP}}{Q_{BEP}} U_1 \right)^2 ]</td>
</tr>
</tbody>
</table>

Leakage Loss Modeling

- Leakage loss
  \[ h_{\text{leakage}} = h_{\text{contraction}} + h_{\text{expansion}} + h_{\text{leakage}} \]
  \[ = 0.5 \frac{V_L^2}{2g} + 1.0 \frac{V_L^2}{2g} + f_{\text{Lk}} \frac{V_L^2 L_g}{2g S_L} \]

- Literature models

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aungier (1995), Bing et al. (2012)</td>
<td>[ h_{\text{leakage}} = \frac{Q_{c1} U_{c1} U_2}{2Q' g} ]</td>
</tr>
</tbody>
</table>
# Other Losses

## Diffuser loss

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ito (1959), Jones (1976) Churchill (1977) Shah (1978), Sun (2003)</td>
<td>[ h_{diffuser} = -\frac{F_r F_\beta F Q^2}{8 g D_H \pi^2 b_m^2 \sin^3 \beta_m} \frac{r_{3diff} - r_{2diff}}{r_{3diff} r_{2diff}} ]</td>
</tr>
<tr>
<td>Sun and Prado (2002) Bing et al. (2012)</td>
<td>[ h_{diffuser} = N_a (F_r F_\beta) \frac{S (V_{2d}^2 + V_{3}^2)}{4g} ]</td>
</tr>
<tr>
<td>McDonald (2001) Amaral (2007)</td>
<td>[ h_{diffuser} = \frac{(V_{2d}^2 - V_{3}^2)}{2g} - C_p \frac{V_{3}^2}{2g} ]</td>
</tr>
</tbody>
</table>

\[ C_p = \frac{(p_3 - p_2)}{0.5 \rho V_{3}^2} \]

\[ V_{2d} = \frac{Q}{\pi (r_{2diff}^2 - r_{1diff}^2)} \]

\[ V_{3} = V_{1} \]

## Disk loss

<table>
<thead>
<tr>
<th>Reference</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun and Prado (2002) Amaral (2007)</td>
<td>[ h_{disk} = \frac{(V_{2d}^2 - V_{3}^2)}{2g} \frac{\text{REP}}{10^9} ]</td>
</tr>
<tr>
<td>Thin et al. (2008)</td>
<td>[ h_{disk} = f_{disk} \omega^3 r_{3}^3 \frac{10^9}{Q} ]</td>
</tr>
<tr>
<td>Van Esch (1997) Kruyt (2003)</td>
<td>[ h_{disk} = C_m \omega^3 r_{3}^3 \frac{2gQ}{Q} ]</td>
</tr>
<tr>
<td>Gulich (1999) Ladouani (2009)</td>
<td>[ \begin{align*} h_{disk} &amp;= \frac{k_{RF}}{g} \left( \frac{r_{3}^3}{Q} \left( 1 - \left( \frac{D_1}{D_2} \right)^5 \right) \right) \ k_{RR} &amp;= \frac{\pi r_{2}^2}{2 R_e h} \left( 0.02 \frac{1 + h/r_2}{1 + h/(2r_2)} \right) \ f_{th} &amp;= \exp \left( -2 \times 10^{-5} \left( \frac{v}{10^{-6}} \right)^{1.34} \right) \ h &amp;= 0.05 r_{2} \end{align*} ]</td>
</tr>
</tbody>
</table>
Two-phase Modeling in ESP

- Based on Zhang (2003, JERT) unified two-phase model in pipe for all inclination angles
- Flow pattern transition boundaries in ESP impeller are mechanistically modeled
- Two-phase model for predicting in-situ gas void fraction under each flow pattern is formulated
- A comprehensive mechanistic model to predict ESP two-phase performance is developed

Two-phase Modeling in ESP...

- Slug dynamics in ESP

Variables

\[ V_T \] Slug translational velocity
\[ V_F \] Film velocity
\[ V_C \] Gas core velocity
\[ V_S \] Slug velocity
\[ \theta \] Inclination angle
\[ H_{LF} \] Film liquid holdup
\[ S_F \] Perimeter wetted by liquid film
\[ H_{LS} \] Slug liquid holdup
\[ L_S \] Slug length
\[ L_F \] Film length
\[ L_U \] Slug unit length
\[ A_F \] Cross sectional area occupied by liquid film
\[ A_C \] Cross sectional area occupied by gas core
\[ S_C \] Perimeter wetted by gas core
\[ S_I \] Interfacial perimeter
Two-phase Modeling in ESP...

- **Continuity equations**
  \[
  H_{LS}(v_T - v_S) = H_{LF}(v_T - v_F) + H_{LC}(v_T - v_C) \\
  (1 - H_{LS})(v_T - v_S) = (1 - H_{LF} - H_{LC})(v_T - v_C)
  \]

- **Continuity equations of slug unit**
  \[
  l_U = l_F + l_S \\
  l_U v_{SL} = l_S H_{LS}v_S + l_F(H_{LF}v_F + H_{LC}v_C) \\
  l_U v_{SG} = l_S(1 - H_{LS})v_S + l_F(1 - H_{LF} - H_{LC})v_C
  \]

- **Entrainment fraction**
  \[
  F_E = \frac{H_{LC}v_C}{H_{LF}v_F + H_{LC}v_C}
  \]

Two-phase Modeling in ESP...

- **Momentum balance equations**
    \[
    \left. \frac{dp}{dr} \right|_{\text{streamline}} = \left[ -\rho_p \frac{dW_p}{dr} + \rho_p \Omega^2 r + \left( \frac{dp}{ds} \right)_{f,p} \frac{ds}{dr} - \frac{M_{p,s}}{\alpha_p} \frac{ds}{dr} \right]_{\text{streamline}}
    \]
  - Multiplied by \(dr/ds\):
    \[
    \frac{dp}{ds} = \left[ a + b \frac{dW_p}{ds} + c \left( \frac{dp}{ds} \right)_{f,p} - d \frac{M_{p,s}}{\alpha_p} + e \rho_p \Omega^2 r \right]_{\text{streamline}}
    \]
    \[\begin{align*}
    a & \text{ – pressure drop term} \\
    b & \text{ – advection term} \\
    c & \text{ – friction term} \\
    d & \text{ – interfacial momentum transfer term} \\
    e & \text{ – centrifugal acceleration term}
    \end{align*}\]
Two-phase Modeling in ESP...

- **Momentum balance in ESP**

\[
\begin{align*}
p_2 - p_1 &= \rho_L \left( \frac{v_T - v_F}{l_F} \right) v_s - \tau_l S_l + \frac{\tau_F S_F}{H_L A} + \rho_L \Omega^2 R_l |_{\text{streamline}} \\
p_2 - p_1 &= \rho_C \left( \frac{v_T - v_C}{l_F} \right) v_s - \tau_l S_l + \frac{\tau_F S_F}{(1 - H_L A)} + \rho_C \Omega^2 R_l |_{\text{streamline}}
\end{align*}
\]

- **Combined momentum equation**

\[
\begin{align*}
\rho_L \left( \frac{v_T - v_F}{l_F} \right) v_s - \rho_C \left( \frac{v_T - v_C}{l_F} \right) v_s - \tau_l S_l - \tau_F S_F \left( \frac{1}{H_L A} + \frac{1}{1 - H_L A} \right) + (\rho_L - \rho_C) \Omega^2 R_l |_{\text{streamline}} &= 0
\end{align*}
\]

---

### Transition Boundary DB to BF

- **Dispersed bubble flow to bubbly flow**

\[
d_{\text{max}} \leq d_{CD}
\]

\[
d_{\text{max}} = d_{32} / 0.6 = 10.056 \left( \frac{v_{SG}}{v_M} \right) \left( \frac{\sigma}{\rho_c} \right)^{3/5} \left( \frac{\Delta P g}{\rho_c v} \right)^{-2/5} \left( \frac{\rho_c}{\rho_d} \right)^{1/5}
\]

\[
d_{CD} = 2 \left( \frac{0.4 \sigma}{(\rho_L - \rho_G) g_c} \right)^{0.4} = 2 \left( \frac{0.4 \sigma}{(\rho_L - \rho_G) \Omega^2 R_l} \right)^{0.4}
\]

\[
\Rightarrow \lambda_{\text{crit}} = \frac{2 \left( \frac{0.4 \sigma}{(\rho_L - \rho_G) \Omega^2 R_l} \right)^{0.4}}{10.056 \left( \frac{\sigma}{\rho_c} \right)^{3/5} \left( \frac{\Delta P g}{\rho_c v} \right)^{-2/5} \left( \frac{\rho_c}{\rho_d} \right)^{1/5}}
\]
Transition Boundary BF to IT

- Bubbly flow to intermittent flow
  - Maximum packing occurs
  - Critical gas void fraction in ESP

\[ \alpha_{\text{Crit}} = \frac{\pi}{6} - \left( \frac{\pi}{6} \cdot \frac{1}{4} \right) \exp \left( - \frac{N}{N_{\text{BEP}}} \right) \]

\[ \begin{align*}
N = 0, & \quad \alpha_{\text{Crit}} = 0.25, \text{ critical } \alpha_G \text{ in pipe flow} \\
N = +\infty, & \quad \alpha_{\text{Crit}} = 0.52, \text{ critical } \alpha_G \text{ of maximum packing}
\end{align*} \]

Consider force balance on bubble

\[ F_C = \frac{\pi l_B^3}{6} \left( \rho_L - \rho_G \right) R_i \Omega^2 \]
\[ F_D = C_D \rho_L \frac{V_{SR}^2 \pi l_B^3}{2} \]
\[ F_C = F_D \]

\[ V_{SR} = \frac{(Q + Q_{LK})}{(2\pi R_i - Z_i T_B)} \left( \frac{1 - \lambda}{1 - \alpha G - \lambda_G} \right) \]

\[ R_S a_G^2 + (1 - R_S) \alpha_G - \lambda_G = 0 \quad \Rightarrow \lambda_G = \alpha_G \left( 1 + (\alpha_G - 1)R_S \right) \]

\[ R_S = \frac{(2\pi R_i - Z_i T_B) Y_i}{Q + Q_{LK}} V_{SR} \]

\[ \alpha_{\text{Crit}} = 0.52 - 0.27 \exp \left( -N/N_{\text{BEP}} \right) \]
Transition Boundary IT to AN

- Intermittent flow to annular flow
  - Combined momentum equation for annular flow
    \[ -\frac{\tau_F S_F}{H_{LF} A} + \tau_I S_I \left( \frac{1}{H_{LF} A} + \frac{1}{(1-H_{LF}) A} \right) + (\rho_L - \rho_C) \Omega^2 R_i \bigg|_{\text{streamline}} = 0 \]
  - From continuity equation, liquid holdup in film:
    \[ H_{LF} = \frac{H_{LS} (v_T - v_T) + v_{SL} (v_{SG} + v_{SL} F_E) - v_T v_{SL} F_E}{v_T v_{SG}} \]

Transition Boundary IT to AN...

- \( V_F, H_{LC}, V_C \) calculation
  \[ v_F = \frac{v_{SL} (1-F_E)}{H_{LF}}, \quad H_{LC} = \frac{v_{SL} F_E (1-H_{LF})}{v_S - v_{SL} (1-F_E)}, \quad v_C = \frac{v_S - v_{SL} (1-F_E)}{1-H_{LF}} \]

- Substitute into combined momentum equation for a new value of \( V_F \)
- Finally, \( V_{SL} \) at intermittent flow to annular flow boundary is
  \[ v_{SL} = \frac{v_F H_{LF}}{1-F_E} \]
Dispersed Bubble Flow Modeling

- Neglect slippage between gas and liquid
  \[ \alpha_G = \lambda_G \Rightarrow \rho_M = (1 - \lambda_G) \rho_L + \lambda_G \rho_G \]
  \[ \rho_I = \rho_D = \rho_M \]
- \( Q < Q_B \)
  \[ P_{EE} = \rho_M \frac{U_2^2 - U_1^2}{2} + \rho_M \frac{W_1^2 - W_2^2}{2} + \rho_M \frac{C_{2E}^2 - C_1^2}{2} + \rho_M \frac{C_{2F}^2 - C_1^2}{2} \]
- \( Q > Q_B \)
  \[ P_{EE} = \rho_M \frac{U_2^2 - U_1^2}{2} + \rho_M \frac{W_1^2 - W_2^2}{2} + \rho_M \frac{C_{2E}^2 - C_1^2}{2} + \rho_M \frac{C_{2F}^2 - C_1^2}{2} \]

Bubbly Flow Modeling

- Slippage between gas bubbles and liquid
- In-situ \( \alpha_G \) in ESP impeller
  \[ \alpha_G = \frac{R_S - 1 + \sqrt{(1 - R_S)^2 + 4R_S \lambda_G}}{2R_S} \]
  \[ \rho_I = \rho_L (1 - \alpha_G) + \rho_G \alpha_G \quad \rho_D = \rho_I (1 - \alpha_G) + \rho_G \alpha_G \]
- \( Q < Q_B \)
  \[ P_{EE} = \rho_I \frac{U_2^2 - U_1^2}{2} + \rho_I \frac{W_1^2 - W_2^2}{2} + \rho_I \frac{C_{2E}^2 - C_1^2}{2} + \rho_D \frac{C_{2F}^2 - C_1^2}{2} \]
- \( Q > Q_B \)
  \[ P_{EE} = \rho_I \frac{U_2^2 - U_1^2}{2} + \rho_I \frac{W_1^2 - W_2^2}{2} + \rho_I \frac{C_{2E}^2 - C_1^2}{2} + \rho_D \frac{C_{2F}^2 - C_1^2}{2} \]
Intermittent Flow Modeling

- Governing equations
  - Continuity equations
    \[ v_S = H_{LF}v_F + (1 - H_{LF})v_C \]
    \[ l_U v_{SL} = l_S H_{LS}v_S + l_F (H_{LF}v_F + H_{LC}v_C) \]
    \[ l_U v_{SG} = l_S (1 - H_{LS})v_S + l_F (1 - H_{LF} - H_{LC})v_C \]
  - Combined momentum equation
    \[ \rho_L (v_T - v_F)(v_S - v_F) - \rho_C (v_T - v_C)(v_S - v_C) - \tau_F S_F \]
    \[ = l_F \left( \frac{1}{H_{LF}A} + \frac{1}{(1 - H_{LF})A} \right) + (\rho_L - \rho_C) \gamma^2 R_t \bigg|_{\text{streamline}} = 0 \]

- Closure relationships
  - Shear stress
    \[ \tau_F = f_F \frac{\rho_L |v_F| v_F}{2} \]
    \[ \tau_I = f_I \frac{\rho_C |v_C - v_F| (v_C - v_F)}{2} \]
  - Friction factor
    - At wall, Blasius correlation:
      \[ f_{F,c} = C \] Re
      \[ C = 0.016, n = 0.4 \] laminar
      \[ C = 0.046, n = 0.2 \] turbulent
    - At interface, Ambrosini et al. (1991):
      \[ f_I = f_G \left( 1 + 13.8 We_{0.2}^{0.16} Re_G^{0.16} \left( h_{c}^{*} - 200 \sqrt{\rho_G / \rho_L} \right) \right) \]
      \[ We_G = \frac{\rho_G v_c^2 d}{\sigma} \]
      \[ Re_G = \frac{\rho_G v_c d}{\mu_G} \]
      \[ h_c^* = \frac{\rho_G h_c \sqrt{\rho_G}}{\mu_G} \]
      \[ v_c^* = \sqrt{\frac{\tau_I}{\rho_G}} \]
Intermittent Flow Modeling…

- Taylor bubble geometries
  - Uniform film thickness $\delta_L$
    \[ \delta_L = \frac{d}{2} \left(1 - \sqrt{1 - H_{LF}}\right) \]
  - Assume $F_E = 0$, or

- Uniform slug unit length
  \[ A_c = \pi(d - 2\delta_L)^2 / 4 \quad S_L = \pi(d - 2\delta_L) \quad d_F = 4\delta_L(d - \delta_L)/4 \]
  \[ A_F = \pi\delta_L(d - 2\delta_L) \quad S_L = \pi d \quad d_C = (d - 2\delta_L) \]

- Reynolds number
  \[ \text{Re}_C = \frac{\rho_G v_C d_C}{\mu_G} \quad \text{Re}_F = \frac{\rho_L v_F d_F}{\mu_L} \]

Intermittent Flow Modeling…

- Liquid entrainment
  - Assume $F_E = 0$, or
  - Oliemans et al. (1986)
    \[ \frac{F_E}{1 - F_E} = 0.003 W e_{SG}^{1.8} F r_{SG}^{-0.92} \text{Re}_S L \text{Re}_{SG}^{-1.24} \left(\frac{\rho_L}{\rho_G}\right)^{0.38} \left(\frac{\mu_L}{\mu_G}\right)^{0.97} \]

\[ W e_{SG} = \frac{\rho_G v_{SG}^2 d}{\sigma} \quad F r_{SG} = \frac{v_{SG}}{\sqrt{g d}} \]
\[ \text{Re}_S L = \frac{\rho_L v_{SL} d}{\mu_L} \quad \text{Re}_{SG} = \frac{\rho_G v_{SG} d}{\mu_G} \]
Intermittent Flow Modeling…

● Liquid slug holdup
  ➢ Modified Zhang (2003, IJMF) model

\[ H_{LS} = \frac{1}{1 + \frac{3.16[(\rho_L - \rho_G)g_c \sigma]^{1/2}}{T_{SM}}} \]

\[ T_{SM} = \frac{1}{C_E} \left[ \frac{f_s}{2} \rho_s v_M^2 + \frac{d}{4} \rho_L L \left( v_T - v_F \right) \left( v_M - v_F \right) \right. \]

\[ + \left. \frac{d}{4} \rho_c \left( 1 - H_{LF} \right) \left( v_T - v_c \right) \left( v_M - v_c \right) \right] \]

\[ C_E = \frac{2.5 - \sin(\theta)}{2} \]

\[ \theta = -90^\circ \]

\[ \rho_s = \rho_L H_{LS} + \rho_G \left( 1 - H_{LS} \right) \quad Re_S = \frac{\rho_s v_sl}{\mu_L} \]

Intermittent Flow Modeling…

● Translational velocity

\[ v_T = c_0 v_M + 0.54 \sqrt{gd} \cos \theta + 0.35 \sqrt{gd} \sin \theta \quad \theta = -90^\circ \]

\[ \Rightarrow v_T = c_0 v_M - 0.35 \sqrt{g_c d} \sin \theta \]

\[ c_0 = \begin{cases} 1.2 & \text{laminar} \\ 2.0 & \text{turbulent} \end{cases} \]

● Slug unit liquid hold up

\[ H_{LU} = \frac{(v_T - v_{LS})H_{LS} + v_{SL}}{v_T} \]

● In-situ gas void fraction

\[ \alpha_G = 1 - H_{LU} \]
Intermittent Flow Modeling...

- Slippage between Taylor bubble and liquid
  \[ \rho_L = \rho_L (1 - \alpha_G) + \rho_G \alpha_G \]
  \[ \rho_D = \rho_L (1 - \lambda_G) + \rho_G \lambda_G \]
- Liquid densities in ESP impeller
- \( Q < Q_B \)
  \[ P_{EE} = \rho_L \left( \frac{U_1^2 - U_1'}{2} + \rho_L \frac{W_1^2 - W_1'^2}{2} + \rho_L \frac{C_{2E}^2 - C_1^2}{2} + \rho_D \frac{C_{2F}^2 - C_1^2}{2} \right) \]
- \( Q > Q_B \)
  \[ P_{EE} = \rho_L \left( \frac{U_1^2 - U_1'}{2} + \rho_L \frac{W_1^2 - W_1'^2}{2} + \rho_L \frac{C_{2E}^2 - C_1^2}{2} + \rho_D \frac{C_{2F}^2 - C_1^2}{2} \right) \]

Annular Flow Modeling

- Combined momentum equation
  \[ - \frac{\tau_F S_F}{H_{LF} A} + \tau_L S_1 \left( \frac{1}{H_{LF} A} + \frac{1}{(1 - H_{LF}) A} \right) + \left( \rho_L - \rho_C \right) \Omega^2 R_t \bigg|_{\text{streamline}} = 0 \]

- Geometrical details:
  \( \delta_L = \frac{d}{2} \left( 1 - \sqrt{1 - H_{LF}} \right) \)
  \[ A_C = \pi (d - 2\delta_L)^2 / 4 \quad S_I = \pi (d - 2\delta_L) \quad d_F = 4\delta_L (d - \delta_L)/4 \]
  \[ A_F = \pi \delta_L (d - 2\delta_L) \quad S_L = \pi d \quad d_c = (d - 2\delta_L) \]
Annular Flow Modeling…

- **Mass balance**
  \[ q_F = q_L = A_p v_{SL} (1 - f_E) = v_F A_F \]
  \[ q_C = q_G + q_E f_E = A_p (v_{SG} + v_{SL} f_E) = v_C A_C \]
  \[ \Rightarrow v_F = v_{SL} \frac{(1 - f_E) d^2}{4 \delta (d - \delta_L)} \]
  \[ v_C = \frac{(v_{SG} + v_{SL} f_E) d^2}{(d - 2 \delta_L)^2} \]

- **Shear stress**
  \[ \tau_F = f_f \frac{\rho_F v_F v_F}{2} \]
  \[ \tau_I = f_I \frac{\rho_C |v_C - v_F| (v_C - v_F)}{2} \]
  \[ f_{F,C} = C \text{ Re}^{-n} \]
  \[ f_I = f_G \left( 1 + 13.8 \text{We}_G^{0.2} \text{ Re}_G^{-0.6} \left[ h_F^+ - 200 \left( \frac{\rho_G}{\rho_L} \right) \right] \right) \]

---

Annular Flow Modeling…

- **Gas core void fraction**
  \[ \alpha_C = \frac{v_{SG}}{v_{SG} + v_{SL} f_E} \]
  \[ \Rightarrow \alpha_T = \alpha_C \left( 1 - \frac{2 \delta_L}{d} \right)^2 \]

- **Core properties**
  \[ \rho_C = \rho_G \alpha_C + \rho_L (1 - \alpha_C) \]
  \[ \mu_C = \mu_G \alpha_C + \mu_L (1 - \alpha_C) \]
  \[ \text{Re}_C = \frac{\rho_C v_C d_C}{\mu_C} \]
  \[ \text{Re}_F = \frac{\rho_F v_F d_F}{\mu_F} \]
Annular Flow Modeling...

- Slippage between gas core and liquid film
- Liquid densities in ESP impeller
  \[ \rho_l = \rho_l (1 - \alpha_g) + \rho_g \alpha_g \]
  \[ \rho_D = \rho_l (1 - \lambda_g) + \rho_g \lambda_g \]
- \( Q < Q_B \)
  \[ P_{EE} = \frac{U_2^2 - U_1^2}{2} + \rho_l \left( \frac{W_1^2 - W_2^2}{2} + \frac{C_{2E}^2 - C_1^2}{2} + \rho_D \frac{C_{2F}^2 - C_1^2}{2} \right) \]
- \( Q > Q_B \)
  \[ P_{EE} = \frac{U_2^2 - U_1^2}{2} + \rho_l \left( \frac{W_1^2 - W_2^2}{2} + \frac{C_{2E}^2 - C_1^2}{2} + \rho_D \frac{C_{2F}^2 - C_1^2}{2} \right) \]

Calculation Flow Chart

Input: pump geometrical parameters, fluid properties, flow conditions

- Single-phase flow? No
- Dispersed bubble flow? No
- Bubbly flow? No
- Intermittent/Slug flow? Yes
- Segregated/annular flow?

Output: flow pattern, flow structure, hydraulic parameters
Single-phase Modeling Results

- Comparisons with catalog and experimental curves

![Graph showing comparisons between model, experiment, and catalog results for different flow rates and viscosity values.]

- Viscosity effects: \( \rho = 1000 \text{ kg/m}^3, N = 3500 \text{ rpm} \)

![Graph illustrating the sudden rise of pump head due to hydraulic smooth flow regime at high flow rates, and the need for incorporating other types of friction losses.]

More attention should be paid at high flow rates by incorporating other types of friction losses.
Transition Boundary Modeling Results

Gamboa (2008) experiment

Model prediction

I: dispersed bubble flow
II: bubbly flow
III: intermittent flow
IV: annular/segregated flow

Surging Test Modeling Results

N = 3500 rpm, \( P_{\text{sep}} \) = 100 psig

N = 3500 rpm, \( P_{\text{sep}} \) = 150 psig

N = 1800 rpm, \( P_{\text{sep}} \) = 100 psig

N = 1800 rpm, \( P_{\text{sep}} \) = 150 psig
Mapping Test Modeling Results

- $N = 3500 \text{ rpm}, P_{\text{sep}} = 100 \text{ psig}$

Needs more mechanistic considerations

- $N = 1800 \text{ rpm}, P_{\text{sep}} = 100 \text{ psig}$
Conclusions

- Surfactant effects on ESP pressure increment under gassy flow conditions experimentally studied
- Comparison shows ESP performance much better with surfactant injection
- A mechanistic model for predicting ESP performance under both single-phase and gas-liquid flows is developed
- Model can be used to predict ESP flow pattern transition boundaries, pressure increment, and also incorporated into unified model to predict two-phase pipe flow behavior with ESP installation

Near Future Work

- Further validations of the mechanistic model with corresponding experimental data are needed
- The user interface based on Fortran and PyQt5 is ongoing
- Take surfactant effects into mechanistic modeling of ESP two-phase performance
Tulsa University Artificial Lift Projects

Review of Problem Diagnosis and Data Analytics for Well Surveillance

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Industry Trend

● Hot topics: Smart well, Digital field, Big data, etc.
  ➢ Massive amounts of data collected
  ➢ How to make use of the data
● Data can help monitor wells, identify problems and provide solutions
Industry Trend...

- Current downsides
  - Long process, requires human presence to understand data and find problem
  - Long periods of shut-in because of problem diagnosis time

Objectives

- Reduce diagnosis time and improve accuracy
  - Get rid of human necessity
  - Automate problem diagnosis process so that computer systems can diagnose problems instantaneously
  - Automate well surveillance to predict problems before they occur
Outline

- Highlights from literature review
- Proposed methodology
- Research plan

Literature Review

- Schipperjin et al. (2009) – ETL: Extract, Transform and Load
  - Extract data from SOR (System of Records)
  - Classify attributes based on pre-set values
    e.g.: production decline – none, slight, etc.
  - Analyze performance classes
    e.g.: pump performance
  - Logic rounds: Predetermined order of evaluation – saves time
    e.g.: evaluate status of well first (if shut down, further analysis not required)
**Literature Review**

- **Schipperjin et al. (2009)**
  - Users liked transparency of the system compared to AI

- **Al-Jasmi et al. (2013)**
  - Collected data from bottom hole to crude treatment facilities
Al-Jasmi et al. (2013)

- KPI shown relative to bounds (if exceeded, alarm sets off)

Target values fed into system: find production losses and gains

Pattern recognition based on 30/90 day history to predict problems

Injector, producer relation established
Al-Jasmi et al. (2013)

- Artificial Neural Networks:
  - Finds $q_o$ and $q_{w_i}$ in case of missing data using historical data and real time $P_{wh}$ and WC
  - Forecast production using 30/90 day production data

- Neural network and injector-producer relation proved very useful
- Neural networks much faster than numerical reservoir simulation
- Despite being faster, neural networks were not relied upon completely
Literature Review…

- Ahmad et al. (2015)
  - Dynamic Production Management System: Steady state and transient flow modelling
  - Data control unit: Filter out bad data, GIGO

![Diagram](image)

Literature Review…

- Ahmad et al. (2015)
  - Based on SS analysis, gas lift analysis is triggered
  - This optimization workflow proposes new optimized gas lift settings (GLO set points)
  - Conventionally, this would be the end of the workflow but there are few additional steps after this
Ahmad et al. (2015)

- GLO set points are verified using a transient simulator to check for stability of changes (takes very long to simulate transient flow)
- If stable, automatic update changes and predictions
- Background: Run the set points using a numerical simulation to verify impact on reservoir deliverability

When the paper was written, workflows were not yet commissioned so no validation results
Summary

- Pattern recognition by human analysis is most common as of now
- Inefficient because of long response time
- Artificial Intelligence used to predict flow as an alternative
- Users not fond of AI due to lack of transparency
- Use of SS and Transient models is the latest focus of development

Proposed Methodology

- Nodal analysis: Performed under various problematic case simulations
- Automatic data input: Collection of real time data and parameters of operation should be automatic and continuous
- 24/7 simulation: Generate predicted flow of well under normal conditions and problematic conditions
- Process: If real time data does not match predicted normal flow, system finds a match with the problematic case simulation
Research Plan

- October 2016 – May 2017: Continue literature review and run simulations for various problematic cases
- After May 2017: Masters/PhD to continue state-of-the-art review, case simulations and model development
Experimental Study of Viscosity Effect and Oil/Water Flow in ESPs

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The University of Tulsa

Outline

- Application
- Experimental system
- Experimental results
- Pipe viscometer
- CFD simulations
- Project schedule
Application

- Significant effects of fluid viscosity on ESP performance
- Only water performance is measured
- Actual flow condition very different
- Prediction model for ESP performance under higher fluid viscosity and multiphase flow conditions needed for production design and artificial lift integration

Experimental System

- Current flow loop schematic
Experimental System...

- Upgrade in oil filling/gas releasing ports
  - Schedule 80 instead of Schedule 40
- New batch of Non-Detergent-20 oil
  - Clear yellow
  - Old oil contaminated

Experimental System...

![Graph showing density vs temperature](image)

- ND20 (Old)
- ND20 (New)
Experimental System…

![Graph showing viscosity vs. temperature with data points and lines representing different conditions.]

Experimental Results

![Graph showing viscosity vs. water ratio with various data points indicating different studies and expected values.]

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Experimental Results...

ND20 Emulsion at 88 °F

51% water

Experimental Results...
Experimental Results...

61% water

\[ \rho_m|_T = \rho_n|_T \times f_w + \rho_o|_T \times (1 - f_w) \]

ND20 Emulsion at 88 °F
\[
\rho_{\text{eff}} = \rho_m | f_w + \rho_v | f \times (1 - f_w)
\]

Experimental Results…

ND20 Emulsion at 88 °F

61% Water Ratio

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Experimental Results...

Heat exchanger:
- Fluid flow path dip in heat exchanger
- Due to gravity, water may be left behind in the lower section
- Pipe in pipe heat exchanger in new flow loop
Experimental Results...

- At ~61% water ratio
  - Emulsion is water continuous with 30 cP viscosity
  - Emulsion is unstable at lower flowrates
    - <400 bpd changes to oil continuous and viscosity reaches higher than 500 cP
    - This observation is more clear for lower rpm values (2500 and 2000 RPM)
    - This is due to water segregation along loop and water accumulation at heat exchanger

- Inversion point ~59% water
- Emulsion behaves as Newtonian fluid

Experimental Results...

- ND-20 oil (new) is tested at 88 and 104 °F
  - To confirm ESP stage performance with old oil
  - To compare between previous setup and current setup of pipe viscometer
  - To validate pipe viscometer results with rheometer results
Experimental Results...

ND20 at 88 °F, μ = 94 cP

Vol. Flowrate (bpd)

DP Stage 3 (psig)

3500 RPM Experiment
3300 RPM Experiment
2500 RPM Experiment
2000 RPM Experiment
3500 RPM Experiment 2
3300 RPM Experiment 2
2500 RPM Experiment 2
2000 RPM Experiment 2

Experimental Results...

ND20 at 104 °F, μ = 57 cP

Vol. Flowrate (bpd)

DP Stage 3 (psig)

3500 RPM Experiment
3300 RPM Experiment
2500 RPM Experiment
3500 RPM Experiment 2
3300 RPM Experiment 2
2500 RPM Experiment 2

Pipe Viscometer

Previous Setup at 88 °F, μ = 94 cP

Previous Setup at 104 °F, μ = 57 cP

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Pipe Viscometer...

Current Setup at 88 °F, μ = 94 cP

Current Setup at 104 °F, μ = 57 cP
Objectives

- Compare stage performance with experimental results
- Understand multiphase flow behavior in ESP stage

Considerations

- Viscosity:
  - Single phase (Rheometer)
  - Two phase (pipe viscometer)
- Two phase will be replaced by single phase oil of equivalent viscosity

Meshing:

- Using Turbogrid
- 7.8 M elements
CFD Simulations...

- 3 full stages:
  - Turbulence: 5%
  - Stage interface: frozen rotor
  - No slip on all walls
  - No coalescence model
  - Particle drag model: Schiller & Naumann (1933)
  - Turbulence models:
    - SST for water
    - $k-\omega$ model for oil and oil-water
  - Energy model: Isothermal
  - Roughness: 500 $\mu$m
  - Physical timescale: $1/\omega$
  - Convergence: 0.0001 RMS

CFD Simulations...

- Boundary conditions:
  - Inlet:
    - Mass flowrate: Defined
    - Frame type: Rotating at given speed
  - Outlet:
    - Static pressure: 0 relative pressure
**CFD Simulations**

**Project Schedule**

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- DAS Communication
- Literature Review
- Facility Upgrade
- Two Phase Experiments
- Two Phase CFD Simulation
- Modeling and Model Validation
Tulsa University Artificial Lift Projects

Unified Transient Model for Gas-Oil-Water Flow in Wells and Pipelines

Fahad Al-Mudairis
McDougall School of Petroleum Engineering
The University of Tulsa

Outline

- Objectives
- Literature review
- Three-phase flow patterns
- Transient three-phase model development
- Primary results
- Conclusions
- Time schedule
Objectives

- Develop transient gas-oil-water flow model for simulation and analysis of various steady and unsteady state production processes
  - Stability analysis
  - Transient process simulation
  - Transient design optimization
- Compare with experiments, field data and other transient simulators

Literature Review

Three-Phase Steady State Studies

- Taitel et al. (1995) developed model based on three-layer stratified flow
- Khor et al. (1997) extended Taitel et al. (1995) model using different equations for shear stresses
Literature Review
Three-Phase Transient Studies

- Bonizzi et al. (2003) developed a model based on two-fluid and drift flux methods to simulate three-phase stratified and slug flows in horizontal and slightly inclined pipes.
- Shirdel and Sepehrnoori (2016) proposed a transient three-phase flow model that consists of a two-fluid model between liquid and gas and a drift-flux model between water and oil in liquid phase for wellbores.

Three-Phase Flow Patterns
Stratified Flow
Three-Phase Flow Patterns

Intermittent Flow

Intermittent-Oil Continuous

Intermittent-Water Continuous

Three-Phase Flow Patterns

Intermittent Flow

Intermittent-Stratified Slug

Intermittent-Mixed Slug
Three-Phase Flow Patterns

Annular Flow

- Annular-Oil Continuous
- Annular-Water Continuous

Dispersed/Bubble Flow

- Dispersed/Bubble-Oil Continuous
- Dispersed/Bubble-Water Continuous
Overall Flow Chart for Three-Phase Unified Model

Transient Three-Phase Model Development

- Mass conservation equations
  - Three-layer stratified flow
  - Film region in slug flow with stratified film and slug
  - Slug region in slug flow with stratified film and slug
  - Mass source in slug flow

- Momentum conservation equations
  - Three-layer stratified flow
  - Film region in slug flow with stratified film and slug
  - Slug region in slug flow with stratified film and slug
Mass Conservation Equations
Three-Layer Stratified Flow

\[ -\left[ \rho_o A H_{OF} v_{OF} + \frac{d}{dz} \left( \rho_o A H_{OF} v_{OF} \right) \right] \Delta z \]

\[ \rho_o A H_{OF} v_{OF} \]

\[ \frac{d}{dt} \left( \rho_o A H_{OF} \right) \Delta z \]

Oil (incompressible)
\[ \frac{\partial}{\partial t} \left( H_o \right) = -\frac{\partial}{\partial z} \left( H_o v_{OF} \right) + G_o \]

Water (incompressible)
\[ \frac{\partial}{\partial t} \left( H_w \right) = -\frac{\partial}{\partial z} \left( H_w v_{WF} \right) + G_w \]

Gas
\[ \frac{\partial}{\partial t} \left( \rho_g H_g \right) = -\frac{\partial}{\partial z} \left( \rho_g H_g v_C \right) + G_g \]
Mass Conservation Equations
Film Region in Slug Flow

- Oil film (incompressible)
  \[ \frac{\partial}{\partial t} (H_{OF}) = -\frac{\partial}{\partial z} (H_{OF}v_{OF}) + \left[ (1 - H_{WGS}) (1 - \alpha_{os}) (v_t - v_{os}) - H_{OF} (v_t - v_{OF}) \right] \frac{v_{OF}}{l_F} + G_O \]

- Water film (incompressible)
  \[ \frac{\partial}{\partial t} (H_{WF}) = -\frac{\partial}{\partial z} (H_{WF}v_{WF}) + \left[ H_{WGS} (1 - \alpha_{w}) (v_t - v_{w}) - H_{WF} (v_t - v_{WF}) \right] \frac{v_{WF}}{l_F} + G_W \]

- Gas core
  \[ H_C = 1 - H_{OF} - H_{WF} \]
Mass Conservation Equations
Slug Region in Slug Flow

- Oil in slug region (incompressible)
  \[
  \frac{\partial}{\partial t} \left( (1 - H_{WS}) (1 - \alpha_{os}) \right) = \\
  - \frac{\partial}{\partial z} \left( (1 - H_{WS}) (1 - \alpha_{os}) v_{os} \right) - \frac{\left[ (1 - H_{WS}) (1 - \alpha_{os}) v_T v_{os} - H_{OF} (v_T - v_{of}) \right]}{l_s} + G_O
  \]

- Water in slug region (incompressible)
  \[
  \frac{\partial}{\partial t} \left( H_{WS} \left( 1 - \alpha_{ws} \right) \right) = \\
  - \frac{\partial}{\partial z} \left( H_{WS} \left( 1 - \alpha_{ws} \right) v_{WS} \right) - \frac{\left[ H_{WS} \left( 1 - \alpha_{ws} \right) v_T v_{WS} - H_{WF} (v_T - v_{WF}) \right]}{l_s} + G_W
  \]
Mass Conservation Equations

Slug Region in Slug Flow...

- Gas in slug region

\[
\frac{\partial}{\partial t} \left[ \rho_g (1 - H_{WGS}) \alpha_{OS} + H_{WGS} \alpha_{WS} \right] = \\
- \frac{\partial}{\partial z} \left[ \rho_c (1 - H_{WGS}) \alpha_{OS} v_{OS} \right] - \frac{\partial}{\partial z} \left( \rho_c H_{WGS} \alpha_{WS} v_{WS} \right) \\
- \rho_g \left[ (1 - H_{WGS}) \alpha_{OS} (v_T - v_{OS}) - (1 - H_{OF}) (v_T - v_c) \right] \\
- \rho_g \left[ H_{WGS} \alpha_{WS} (v_T - v_{WS}) - (1 - H_{WT}) (v_T - v_c) \right] + G_g
\]

Mass Conservation Equations

Mass Source in Slug Flow
Momentum Conservation Equations
Three-Layer Stratified Flow

\[ \frac{d}{dt}(\rho_o A H_{of} v_{of}) - \rho_o A H_{of} v_{of}^2 + \frac{d}{dz}(\rho_o A H_{of} v_{of}^2) = -\rho_o A H_{of} g \sin \theta \Delta z \]

- Combined momentum equation between liquid and gas

\[ \rho_c \left( \frac{\partial v_c}{\partial t} + v_c \frac{\partial v_c}{\partial z} \right) - \rho_w \left( \frac{\partial v_{WF}}{\partial t} + v_{WF} \frac{\partial v_{WF}}{\partial z} \right) = \rho_o \left( \frac{\partial v_{OF}}{\partial t} + v_{OF} \frac{\partial v_{OF}}{\partial z} \right) \]

\[ -\tau_{OF} S_{OF} + \tau_{WF} S_{WF} + \tau_{il} S_{il} \left( \frac{1}{H_{WF} + H_{OF}} + \frac{1}{1 - H_{WF} - H_{OF}} \right) \]

\[ + \tau_c S_c \left( \frac{\rho_w H_{WF} + \rho_o H_{OF}}{H_{WF} + H_{OF}} - \rho_c \right) g \sin \theta = 0 \]
Momentum Conservation Equations

Three-Layer Stratified Flow…

- Combined momentum equation between oil and water

$$\rho_o \left( \frac{\partial v_{OF}}{\partial t} + v_{OF} \frac{\partial v_{OF}}{\partial z} \right) - \rho_w \left( \frac{\partial v_{WF}}{\partial t} + v_{WF} \frac{\partial v_{WF}}{\partial z} \right)$$

$$- \frac{\tau_{WF} S_{WF}}{H_{WF} A} + \tau_{OF} \frac{S_{OF} - \tau_{11} S_{11} - \tau_{12} S_{12}}{H_{OF} A} + \frac{1}{H_{WF}} + \frac{1}{H_{OF}} \left( \rho_w - \rho_o \right) g \sin \theta = 0$$

Momentum Conservation Equations

Film Region in Slug Flow
Momentum Conservation Equations
Film Region in Slug Flow...

● Combined momentum equation between liquid and gas in slug flow film region

\[ \rho_g \left( \frac{\partial v_c}{\partial t} + v_c \frac{\partial v_c}{\partial z} \right) - \rho_w \left( \frac{\partial v_{WE}}{\partial t} + v_w \frac{\partial v_{WE}}{\partial z} \right) / (H_{WF} + H_{OF}) - \rho_o \left( \frac{\partial v_{OF}}{\partial t} + v_o \frac{\partial v_{OF}}{\partial z} \right) / (H_{WF} + H_{OF}) \]

\[ + \frac{\rho_w}{H_{WF}} (v_r - v_w)(v_{WS} - v_{WF}) + \rho_o H_{OF} (v_r - v_{OF})(v_{OS} - v_{OF}) \]

\[ \frac{1}{l_p} \left( \frac{\tau_{WF} S_{WF}}{H_{WF} + H_{OF}} + \frac{\tau_{11} S_{11}}{A} \left( \frac{1}{H_{WF} + H_{OF}} + \frac{1}{1 - H_{WF} - H_{OF}} \right) \right) \]

\[ + \frac{\tau_{c} S_{c}}{A (1 - H_{WF} - H_{OF})} \left( \rho_w H_{WF} + \rho_o H_{OF} - \rho_o \right) g \sin \theta = 0 \]

Momentum Conservation Equations
Film Region in Slug Flow...

● Combined momentum equation between oil and water in slug flow film region

\[ \rho_o \left( \frac{\partial v_{OF}}{\partial t} + v_o \frac{\partial v_{OF}}{\partial z} \right) - \rho_w \left( \frac{\partial v_{WE}}{\partial t} + v_w \frac{\partial v_{WE}}{\partial z} \right) \]

\[ + \rho_w (v_r - v_w)(v_{WS} - v_{WF}) - \rho_o (v_r - v_{OF})(v_{OS} - v_{OF}) \]

\[ \frac{1}{l_p} \left( \frac{\tau_{WF} S_{WF}}{H_{WF} A} + \frac{\tau_{11} S_{11}}{H_{OF} A} \left( \frac{1}{H_{WF}} + \frac{1}{H_{OF}} \right) \right) - (\rho_w - \rho_o) g \sin \theta = 0 \]
Momentum Conservation Equations
Slug Region in Slug Flow

- Combined momentum equation between oil and water in slug body region

\[
\begin{align*}
\rho_o \left( \frac{\partial v_{os}}{\partial t} + v_{os} \frac{\partial v_{os}}{\partial z} \right) - \rho_w \left( \frac{\partial v_{ws}}{\partial t} + v_{ws} \frac{\partial v_{ws}}{\partial z} \right) \\
+ \rho_w \left( v_r - v_{ws} \right) \left( v_{ws} - v_{ws} \right) - \rho_o \left( v_r - v_{os} \right) \left( v_{os} - v_{os} \right) \\
\frac{1}{l_s} \left( \frac{\tau_{ws} S_{ws}}{H_{wgs} A} + \frac{\tau_{os} S_{os}}{A} + \frac{\tau_{ws} S_{ws}}{A} \right) \left( \frac{1}{1 - H_{wgs}} + \frac{1}{l_s} \right) \left( \rho_w - \rho_o \right) g \sin \theta = 0
\end{align*}
\]
Hydrodynamics of Oil and Water Flow

- Mixture viscosity (Brinkman, 1952)
  \[
  \frac{\mu_{LM}}{\mu_C} = (1 - \phi_{\text{Int}})^{2.5}
  \]

- Interfacial shear stress (Zhang et al., 2005)
  \[
  \tau_i = \frac{f_o \vartheta_w + f_w (1 - \vartheta_w)}{2} \sqrt{\rho_m \left[ \vartheta_w \tau_w + (1 - \vartheta_w) \tau_o \right] x (v_o - v_w)}
  \]

Interfacial Perimeter Between Oil and Water
Interfacial Perimeter Between Oil and Water...

- Wetted angle by water:
  \[ \theta_2 = \pi \theta \]

- Oil-water interfacial angle:
  \[ \theta_{2l} = \left( \frac{\sin \theta_{2l}}{\sin \theta_2} \right)^2 \left( \theta_2 + \frac{\sin^2 \theta_2}{\tan \theta_2} - \frac{\sin 2\theta_2}{2} - \pi H_w \right) \]

- Oil-water interfacial perimeter:
  \[ S_{ow} = 2 \theta_{2l} \frac{R \sin \theta_2}{\sin \theta_{2l}} \]

Mixing Status of Oil and Water

- Droplet break-up based on balance between turbulence and surface tension forces

- Laminar flow maximum droplet size (Stokes equation):
  \[ d_{\text{MAX}} = D \frac{0.145 \sigma_{ow}}{2 \mu_c \nu_M} \left( \frac{\mu_L}{\mu_c} \right)^{-1/6} \]

- Turbulent flow maximum droplet size (Weber number):
  \[ d_{\text{MAX}} = \frac{1.15}{2^{2/5}} \left( \frac{\alpha_c D}{f_c} \right)^{2/5} \left( \frac{\sigma_{ow}}{\nu_M^2 \rho_c} \right)^{3/5} \]
Mixing Status of Oil and Water…

- Oil/water dispersion exists when:
  \[ d_{\text{MAX}} \leq d_{\text{CP}} \quad \text{and} \quad d_{\text{MAX}} \leq d_{\text{CB}} \]

- Critical diameter at which droplets behave as rigid spheres (Brodkey 1967):
  \[ d_{\text{CP}} = \sqrt{\frac{0.4\sigma_{\text{OW}}}{(\rho_w - \rho_o)g}} \]

- Maximum diameter above which migration of droplets towards pipe wall takes place (Taitel and Dukler 1976):
  \[ d_{\text{CB}} = \frac{3}{8} \frac{\rho_c}{(\rho_w - \rho_o)g} \frac{f_{\text{st}}}{\sqrt{g_s}} \]

Three-Layer Stratified Flow, Water Flow Rate Change

- Length (m): 500
- Time (seconds): 10000
- Segment length (m): 10
- Time step (seconds): 1
- Outlet pressure (psia): 200
- Pipe inner diameter (m): 0.125
- Inclination angle: 0
- Oil flow rate (bpd): 500
- Water flow rate 1 (bpd): 700
- Water flow rate 2 (bpd): 1200
- GOR (scf/bbl): 500
Three-Layer Stratified Flow, Water Flow Rate Change…

Slug Flow with Stratified Film and Slug, Water Flow Rate Change

- Length (m): 500
- Time (seconds): 10000
- Segment length (m): 10
- Time step (seconds): 1
- Outlet pressure (psia): 200
- Pipe inner diameter (m): 0.125
- Inclination angle: 0.5
- Oil flow rate (bpd): 300
- Water flow rate 1 (bpd): 800
- Water flow rate 2 (bpd): 500
- GOR (scf/bbl): 500
Slug Flow with Stratified Film and Slug, Water Flow Rate Change...

 Slug Flow with Stratified Film and Mixed Slug, Oil Flow Rate Change

- Length (m): 500
- Time (seconds): 10000
- Segment length (m): 10
- Time step (seconds): 1
- Outlet pressure (psia): 200
- Pipe inner diameter (m): 0.125
- Inclination angle: 10
- Oil flow rate 1 (bpd): 2000
- Oil flow rate 2 (bpd): 1000
- Water flow rate (bpd): 2000
- GOR (scf/bbl): 500
 Slug Flow with Stratified Film and Mixed Slug, Oil Flow Rate Change...

![Graph showing liquid flow rate over time](image)

Slug Flow w/ Fully Mixed Oil and Water, Oil Flow Rate Change

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Length (m)</td>
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<tr>
<td>Segment length (m)</td>
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<tr>
<td>Time step (seconds)</td>
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<tr>
<td>Outlet pressure (psia)</td>
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<td>Pipe inner diameter (m)</td>
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<tr>
<td>Inclination angle</td>
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<tr>
<td>Oil flow rate 1 (bpd)</td>
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<tr>
<td>Oil flow rate 2 (bpd)</td>
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<tr>
<td>Water flow rate (bpd)</td>
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<td>GOR (scf/bbl)</td>
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Slug Flow w/ Fully Mixed Oil and Water, Oil Flow Rate Change…

Conclusions

- A unified transient model is being developed for gas-oil-water flow in wells and pipelines based on mass and momentum conservations.
- Four types of intermittent flow in three-phase flow.
- New model is an extension of unified transient two-phase flow model developed in 2014.
## Time Schedule

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Tulsa University Artificial Lift Projects

CFD Simulation of ESP Gas-liquid Flow Patterns and Comparison with Visualization Results

Jianjun Zhu
McDougall School of Petroleum Engineering
The University of Tulsa

Application

- Entrained gas deteriorates ESP performance and causes surging or gas locking
- Visualization experiment helps understand degradation mechanism
- CFD can simulate gas distribution in ESP
- Comparison can reveal ESP two-phase performance deterioration mechanism
Objectives

- Transient multiphase CFD simulation
  - Gas distribution and flow pattern transition
  - Compare with lab visualization results
- Reveal mechanism affecting ESP multiphase performance
- Improve mechanistic modeling

Outline

- TUALP ESP visualization studies
- Geometry and mesh
- Single-phase CFD simulation
- Multiphase CFD simulation
- Conclusions
- Near future work
Visualization Study

- Barrios (2007) and Gamboa (2008) visualization results on GC 6100 ESP

Visualization Setup

- Barrios (2007) visualization apparatus
Visualization Results…

- **900 rpm, \( Q_G = 0.35 \text{ scf/h} \)**

![Visualization Results Image]

**Numerical Methodology**

- **Governing equations**
  \[
  \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
  \]
  \[
  \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial u_i}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right) + \frac{\partial}{\partial x_j} \left( \rho u_i u_j - \rho \overline{u_i u_j} \right) + \sum f_i
  \]

- **Turbulence model**
  \[
  \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu}{\sigma_k} \right) \frac{\partial k}{\partial x_j} + G_k + G_b - \rho \varepsilon - Y_M
  \]
  \[
  \frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} + \rho C_1 \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\varepsilon}} + C_3 \varepsilon G_b
  \]

- **VOF model**
  \[
  \frac{\partial (\alpha_i \rho \overline{u_i})}{\partial t} + \frac{\partial (\alpha_i \rho \overline{u_i u_j})}{\partial x_j} = 0
  \]
Geometry and Mesh

- GC 6100 geometry

Geometry and Mesh...

- Flow domain
Structured Mesh

- ICEM multi-block mesh

Suction pipe  | Impeller  | Diffuser

Discharge section

Final mesh

8,015,880 elements
Single-phase Simulation

- \( N = 3500 \text{ rpm}, Q_{\text{BEP}} = 6100 \text{ bpd} \)
  - \( \Delta p = p_2 - p_1 + \frac{p}{2} (c_2^2 - c_1^2) \)

Two-phase Simulation

- Case 1: \( N = 900 \text{ rpm}, Q_G = 0.35 \text{ scf/h}, Q_L = 429 \text{ bpd} \)
Two-phase Simulation…

- $\alpha_G$ distribution at case 1

Two-phase Simulation…

- Gas void fraction at different locations

Simulations considered to be stable and converged
Two-phase Simulation...

- Case 2: $N = 900 \text{ rpm, } Q_G = 0.35 \text{ scf/h, } Q_L = 265 \text{ bpd}$

Two-phase Simulation...

- $\alpha_G$ distribution at case 2
Two-phase Simulation...

- Gas void fraction at different locations

![Graph showing gas void fraction over time at different locations]

Case 3: $N = 900$ rpm, $Q_G = 0.35$ scf/h, $Q_L = 127$ bpd

![Image of simulation results with pressure and flow rate data]
Two-phase Simulation…

- $\alpha_G$ distribution at case 3

Two-phase Simulation…

- Gas void fraction at different locations
Conclusions

● Single-phase CFD simulation results match experimental data well
● Mesh quality and numerical method are verified by single-phase simulations
● Multiphase CFD simulations predict flow patterns inside ESP are consistent with visualization experiments

Near Future Work

● More validations regarding comparisons of multiphase CFD simulations, incorporated with VOF model, with visualization experiments are needed
● Multiphase CFD simulations should account for variable boundary conditions, e.g.: different pump geometries, varied fluid properties, etc.
Tulsa University Artificial Lift Projects

ESP Sand Erosion Literature Review and Test Flow Loop Design

Haiwen Zhu
McDougall School of Petroleum Engineering
The University of Tulsa

Outline

- Introduction
- Objectives
- Sand Erosion Literature Review
- Test Flow Loop Design
- Future Schedule
Introduction...

• Application
  ➢ Sand is commonly produced along with fluids, which can cause many problems: pressure drop, pipe blockage, erosion, etc.
  ➢ Even a low concentration of solid particles can cause severe damage to ESP and reduce its operating life span

Introduction...

• ESP failure due to sand production
Objectives

- Experimental erosion measurements and observations
- Pump performance deviation observation and analysis
- CFD simulation of particle trajectory and distribution
- Mechanistic ESP erosion prediction model development

Sand Erosion Review

- Erosion is a complex phenomenon affected by various factors
  - Fluid and flow characteristics: flow rate, composition, density, viscosity and particle concentration
  - Component geometries and material: bend, tee, choke, ESP impeller and diffuser
  - Sand characteristics: frequency of particles hitting solid surface, shape/sharpness, hardness, size distribution
Sand Erosion Review...

- **Sensitivity analysis**
  - **Flow conditions and sand characteristics**
    - Fluid flow field
    - Particle impact velocity
    - Particle impact angle
    - Particle concentration distribution

- **Components surface material hardness**
  - Negative effect: higher surface hardness results in higher erosion resistance (Finnie et al., 1967)
  - Positive effect: Ductility allows surface to distribute particle impact kinetic energy by plastic deformation (Levy and Hickey, 1982)
  - Toughness could be a better indicator (Mazdak et al., 2014)
Sand Erosion Review…

● Sensitivity analysis
  ➢ Sand particle characteristics
    ▶ Sharpness
      ✩ Particle shape can change erosion rate by an order of magnitude (Levy and Chik, 1983)
    ▶ Particle size (e.g. larger particle size)
      ✩ Less particle number and lower impact velocity
      ✩ Less particle-particle interaction
      ✩ Less affected by turbulence and lose less momentum when flow through viscous sub-layer
      ✩ Higher kinetic energy

Sand Erosion Review…

● Sensitivity analysis
  ➢ Sand particle characteristics
    ▶ Particle size

Tilly (1973) Gandhi and Borse (2002)
Sand Erosion Review…

● Sensitivity analysis
  ➢ Sand particle characteristics
    ▶ Particle material hardness
      ✷ Increase hardness will increase erosion rate until a critical hardness value
      ✷ Soft particles shatter and adhere to the surface
      ✷ Beyond a critical hardness, particles do not shatter

---

Levy and Chik (1983)

<table>
<thead>
<tr>
<th>Erosive particles and erosion ratio of AISI 1020 steel</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Erosive particles</td>
<td>Density (g/cm³)</td>
<td>Mohs hardness</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>3</td>
<td>115</td>
</tr>
<tr>
<td>Ca₃(PO₄)₂</td>
<td>5</td>
<td>300</td>
</tr>
<tr>
<td>SiO₂</td>
<td>7</td>
<td>700</td>
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<tr>
<td>Al₂O₃</td>
<td>9</td>
<td>1900</td>
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<tr>
<td>SiC</td>
<td>&gt;9</td>
<td>3000</td>
</tr>
<tr>
<td>Steel grit</td>
<td>7.9</td>
<td>–</td>
</tr>
<tr>
<td>Steel shot</td>
<td>7.9</td>
<td>–</td>
</tr>
</tbody>
</table>

Oct 28, 2016

Sand Erosion Review…

● Erosion model development
  ➢ Erosion mechanism analysis
    ▶ Dry impact test
    ▶ Finite element method (FEM) analysis
  ➢ Impact velocity and angle analysis
    ▶ Mechanistic model
    ▶ CFD simulation

Vieira et al. (2016)

Shimizu et al. (2001)
Sand Erosion Review...

- Erosion mechanism analysis
  - Wear types based on involved body number
    - Two body wear
      - Hard particle slides on a softer surface
    - Three body wear
      - Hard abrasive grains present between two soft sliding surfaces

Two body wear

Three body wear

---

Sand Erosion Review...

- Erosion mechanism analysis
  - Wear types based on erosion mechanism
    - Deformation wear, $W_D$
      - When elastic limit is exceeded, plastic deformation appear at the maximum stress location
    - Cutting wear, $W_C$
      - Particle strikes a surface could cause a cutting wear if shearing strength is exceeded
Sand Erosion Review...

- Erosion mechanism analysis
  - Bitter (1963)
    - Two particle velocity components:
      - Normal to body surface \( (V_\perp) \)
      - Parallel to body surface \( (V_\parallel) \)
        - Particle still has a horizontal velocity component \( (V_\parallel) \) when it leaves body surface, \( W_{C1} \)
        - Horizontal velocity component \( (V_\parallel) \) becomes zero during collision, \( W_{C2} \)

\[
W_D = \frac{1}{2} \frac{M(V_p \sin \alpha - K)^2}{\varepsilon_p} \quad (V_p \sin \alpha \geq K)
\]

- \( \alpha \) – impact angle
- \( M \) – total mass of impinging particles
- \( \varepsilon \) – energy needed to move a unit volume of material from body
- \( V_p \) – velocity of particle
- \( K \) – particle velocity at incipient erosion
Sand Erosion Review…

- Erosion mechanism analysis
  - Cutting wear, $W_C$ (Bitter, 1963)
    
    \[
    W_{C1} = 2M \frac{C_k V_p \sin(\alpha - K)}{\sqrt{V_p \sin \alpha}} \left( V_p \cos \alpha - \frac{C_k (V_p \sin \alpha - K)^2}{\sqrt{V_p \sin \alpha}} \varepsilon_c \right) \quad (\alpha \leq \alpha_0)
    \]
    \[
    W_{C2} = \frac{1}{2} M \left[ V_p^2 \cos^2 \alpha - K (V_p \sin \alpha - K)^2 \right] \quad (\alpha > \alpha_0)
    \]

  - Cutting wear, $W_C$

  \[
  C_k = \frac{0.288}{y} \sqrt{\frac{d}{y}}
  \]

  (Ductile)

  (Brittle)

Sand Erosion Review…

- Erosion mechanism analysis
  - Finnie (1978)
    
    \[
    ER = \frac{c V_p^2 \rho_w}{8 \sigma_y} \left[ \cos \alpha - \frac{3 \sin \alpha}{2} \right] \sin \alpha \quad (\alpha \leq 18.5^\circ)
    \]
    \[
    ER = \frac{c \rho_w (V_p \sin \alpha)^2}{24 \sigma_y} \cot \alpha \quad (\alpha > 18.5^\circ)
    \]

  - Edwards (2000)
    
    \[
    ER_{\text{cutting}} = \frac{75}{2 \sqrt{29}} \left( \frac{V}{C_k} \right) \rho_w \sqrt{\sin \alpha \sin \alpha}
    \]
    \[
    ER_{\text{deformation}} = \frac{\rho_w (V \sin \alpha - D_k)^2}{2 \varepsilon}
    \]
    \[
    ER = ER_{\text{cutting}} + ER_{\text{deformation}}
    \]
Empirical erosion correlation
- Erosion models can be summarized into an empirical correlation based on extensive database:

\[ ER = AV_p^n F(\alpha) \]

- \( A \) – empirical constant
- \( n \) – empirical constant
- \( F(\alpha) \) is function of impact angle
- \( V_p \) – velocity of particle

Critical erosion velocity (API 14E)

\[ V_e = \frac{C}{\sqrt{\rho_m}} \]

- \( V_e \) – fluid erosional velocity
- \( C \) – empirical constant
- \( \rho_m \) – mixture density
Sand Erosion Review…

- Empirical erosion correlation
  - Critical velocity is developed assuming an acceptable erosion rate (Salama, 2000)

\[ ER = \frac{1}{S_m} \frac{WV}{D^2 \rho_w} \]

\[ V_e = S \frac{D \sqrt{\rho_m}}{\sqrt{W}} \]

- \( V_m \) – gas-liquid mixture velocity
- \( W \) – sand mass flow rate
- \( S \) – empirical constant
- \( d \) – particle diameter
- \( D \) – pipe internal diameter

\[ h = F_M F_S F_P F_{r/D} \left( \frac{W V_p}{D_0^3} \right)^{1.73} \]

\[ F_{r/D} = \exp \left( - \left( 0.1 \times \frac{\rho_f^{0.4} \mu_f^{0.65}}{d_p^{0.3}} + 0.015 \times \rho_f^{0.25} + 0.12 \right) \left( \frac{d}{2D} - 0.15 \right) \right) \]

- \( H \) – penetration rate
- \( F_M, F_S, F_P \) – empirical factor
- \( D_0 \) – reference pipe diameter (1-in)
- \( r \) – elbow radius
- \( \rho_f, \mu_f \) – gas-liquid fluid density and viscosity
Sand Erosion Review...

- Empirical erosion correlation
  - McLaury and Shirazi (2000)

  - Stagnation length concept
  - Stagnation length vs. pipe inner diameter
  - Particle impact velocity

  - Mechanistic erosion prediction model in elbows (McLaury and Shirazi, 2004)
    - Annular flow
      - Particles are assumed to be uniformly distributed in liquid phase without slippage
    - Slug flow
      - Erosion is assumed to be caused by sand particles moving within liquid slug
    - Bubbly and churn flow
      - Assume no-slip flow
Sand Erosion Review…

● CFD erosion simulation
  ➢ Prediction procedure
    ▶ CFD simulation to determine flow field
    ▶ Particle tracking to identify particle trajectories
    ▶ Fortran subroutines or erosion models to predict erosion rate

Sand Erosion Review…

● CFD erosion simulation
  ➢ Flow model (CFD software)
    ▶ Navier-Stokes equations
  ➢ Multiphase flow model
    ▶ Volume of fluid, Mixture, Eulerian
  ➢ Turbulent flow model
    ▶ $k-\varepsilon$
    ▶ $k-\omega$
    ▶ Reynolds Stress
    ▶ Large Eddy Simulation
Sand Erosion Review…

- CFD erosion simulation
  - Particle tracking models
    - Discrete phase models (DPM) or Eulerian-Lagrangian models
      - Solve flow field first, then calculate particle trajectory
    - Eulerian-Eulerian models
      - Simulate liquid and granular phases simultaneously

- CFD erosion simulation
  - Fortran subroutines or erosion models (ERC-2003, Russel 2004)
    
    \[ ER = AV_p^n F(\alpha) \]
    
    \[ F(\alpha) = b \alpha^2 + c \alpha \quad (\alpha \leq \alpha_0) \]
    
    \[ F(\alpha) = x \cos^2 \alpha \sin(w \alpha) + y \sin^2 \alpha + z \quad (\alpha > \alpha_0) \]

  - A, b, c, w, x, y and z are empirical constants
Sand Erosion Review…

- CFD erosion simulation for ESP
  - Marsis and Russell (2013)
    - $k-\varepsilon$ model
    - Discrete phase model ($DPM$), Eulerian-Eulerian model
  - ERC-2003 (Russell et al. 2004), ERC-2008 (Russell et al. 2008)

Sand Erosion Review…

- CFD erosion simulation for ESP
  - Pirouzpanah and Morrison (2014)
    - $k-\varepsilon$ model
    - Eulerian-Eulerian model
    - New empirical-numerical erosion model
    
    $$EF = \left(\frac{\alpha_s}{\sqrt[0.08]{V_s}}\right)^{0.07} \left(\frac{k_w}{k_w}\right)^{1.25}$$
    
    $$ER = 0.0163EF^2 + 0.8774EF$$
Test Flow Loop

Sand erosion flow loop schematic

Test Flow Loop...

Sand erosion flow loop design Sketchup
Skid Construction

62nd Advisory Board Meeting
Oct 28, 2016

Skid Construction…
## Test Flow Parts

### Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Name</th>
<th>Number</th>
<th>Technical parameter</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pump system</strong></td>
<td>VFD</td>
<td>1</td>
<td>50 HP; 380-480 V; 1-3 phase AC; Input 120 HZ; Output 0-500 HZ</td>
<td>FUJI Electric</td>
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<tr>
<td></td>
<td>Motor</td>
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<td>50 HP; 208-230/480 V; 126.0-114.0/57.1 A; 3 phase; 60/50 HZ; Output 0-500 HZ</td>
<td>WEG</td>
</tr>
<tr>
<td></td>
<td>Thrust chamber</td>
<td>1</td>
<td>HTC 1.XE HSG_BHI</td>
<td>Baker Hughes</td>
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<tr>
<td></td>
<td>ESP</td>
<td>1</td>
<td>4-in 12-stages ESP</td>
<td>Baker Hughes</td>
</tr>
<tr>
<td></td>
<td>Gas compressor</td>
<td>1</td>
<td>From current facility</td>
<td>TUALP</td>
</tr>
<tr>
<td><strong>Control and measurement</strong></td>
<td>Control valve</td>
<td>1</td>
<td>1/2&quot;; Pressure range 7-15 psi; Rated Cv 1.0</td>
<td>Emerson</td>
</tr>
<tr>
<td></td>
<td>Other valve</td>
<td>5</td>
<td>Ball valve and gate valve</td>
<td>Grainger</td>
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<td></td>
<td>Slurry flow meter</td>
<td>1</td>
<td>2&quot;; Range 230-6800 bpd; Error 0.15%; Max sand volume concentration 5%</td>
<td>Endress Hauser</td>
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<tr>
<td></td>
<td>Gas flow meter</td>
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<td>CMF025M; 1/4&quot;; 4-80 lb/min; Error 0.1%</td>
<td>Emerson</td>
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<td></td>
<td>Differential pressure transmitter</td>
<td>3</td>
<td>Range 0.075-7.5 psi; 4-20 mA HART; Error 0.025%</td>
<td>Endress Hauser</td>
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<tr>
<td></td>
<td>Pressure transmitter</td>
<td>2</td>
<td>Range 6-600 psi; 4-20 mA HART; Error 0.025%</td>
<td>Endress Hauser</td>
</tr>
<tr>
<td></td>
<td>Temperature transmitter</td>
<td>2</td>
<td>Range -200-600 °C; Pressure up to 7250 psi</td>
<td>Endress Hauser</td>
</tr>
<tr>
<td></td>
<td>Pressure regulator</td>
<td>2</td>
<td>Range 0-120 psi</td>
<td>SOR Inc</td>
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</tbody>
</table>
Test Flow Parts...

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Name</th>
<th>Number</th>
<th>Technical parameter</th>
<th>Manufacturer</th>
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<tbody>
<tr>
<td>Separation Storage</td>
<td>Separator</td>
<td>1</td>
<td>From current facility</td>
<td>TUALP</td>
</tr>
<tr>
<td></td>
<td>Storage tank</td>
<td>1</td>
<td>From current facility</td>
<td>TUALP</td>
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<td>Data acquisition</td>
<td>NI cFP-1804</td>
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<td>Ethernet/Serial Interface for NI Compact FieldPoint</td>
<td>National Instruments</td>
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<tr>
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<td>NI cFP-AI-111</td>
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<td>16-Channel Analog Current Input Module for Compact FieldPoint</td>
<td>National Instruments</td>
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<td>NI cFP-AO-200</td>
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<td>8-Channel Analog Current Output Module for Compact FieldPoint</td>
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<td>NI cFP-CB-1</td>
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<td>Integrated Connector Block for Wiring to Compact FieldPoint I/O</td>
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<td>Power supply</td>
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<td>24 VDC (adjustable) output, 4.17 A, 100 W, 85-264 VAC / 100-375 VDC input, 1-phase</td>
<td>Automationdirect</td>
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<td>Terminal blocks</td>
<td>Konnect-It fuse terminal block, green and yellow, 26-8 AWG</td>
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<td>Konnect-It fuse terminal block, green and yellow, 26-8 AWG</td>
<td>Automationdirect</td>
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<tr>
<td>Circuit protection Blocks</td>
<td>Current limiting, 4 A, 277 VAC / 48 VDC, 1-pole, C curve, UL 489 listed, 10 kA SCCR,</td>
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<td>Current limiting, 4 A, 277 VAC / 48 VDC, 1-pole, C curve, UL 489 listed, 10 kA SCCR, Automationdirect</td>
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<td>Electrical enclosure</td>
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<td>20&quot;x20&quot;x8&quot;</td>
<td>Hoffman</td>
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<td>Computer</td>
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Near Future Schedule

- **Construction schedule**

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<tr>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
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</tbody>
</table>

- Literature review and CFD simulation
- Flow loop construction
- Data acquisition
- Debug
Tulsa University Artificial Lift Projects

Viscosity Effect on ESP Performance – Modeling and Flow Loop Design

Jiecheng Zhang
McDougall School of Petroleum Engineering
The University of Tulsa

Outline

• Introduction
• Mechanistic Modeling
• Experimental Program
• Flow Loop Design
• Future Schedule
Introduction

- ESP is widely used in oil production
- Production optimization is achieved with accurate ESP performance prediction
- Oil viscosity significantly affects ESP performance
- Crude oil viscosity dramatically different due to composition difference

Viscosity Effect Modeling

- Impossible to experimentally characterize each ESP for wide viscosity and flow ranges
- CFD simulation is time-consuming and result not convenient to use
- Mechanistic model can be developed based on physical principles and easy to use
Objectives

- Construct flow loop for testing ESP performance with viscous oil and water at relatively high flow rate
- Measure ESP performance with different fluid viscosities, flow rates and rotational speeds
- Develop mechanistic model for prediction of ESP performance
- Validate model with experimental results

Mechanistic Modeling

- Zhang (2013)
  - Developed a mechanistic model
  - ESP performance prediction for single-phase fluid
  - Started from Euler’s Equation
    \[ H_E = \frac{U_2 C_2 V - U_1 C_1 V}{g} \]
Mechanistic Modeling...

- Zhang (2013)...

\[ H_E = \frac{U_2^2 - U_1^2}{2g} + \frac{W_1^2 - W_2^2}{2g} + \frac{C_2^2 - C_1^2}{2g} \]

▲ First term is static head due to centrifugal force
▲ Second term is static head due to velocity change
▲ Third term is dynamic head

- Zhang (2013)...

➢ First term
   ▲ Impeller angular velocity
     \[ \Omega = \frac{2\pi N}{60} \]
   ▲ Tangential velocity of impeller at inlet
     \[ U_1 = R_1 \Omega \]
   ▲ Tangential velocity of impeller at outlet
     \[ U_2 = R_2 \Omega \]
Mechanistic Modeling...

- Zhang (2013)...

  Second term
  - Meridional velocity at impeller inlet
    \[ c_{1M} = \frac{Q + Q_{1K}}{(2\pi R_1 - Z_i T_B) y_{i1}} \]
  - Meridional velocity at impeller outlet
    \[ c_{2M} = \frac{Q + Q_{1K}}{(2\pi R_2 - Z_i T_B) y_{i2}} \]
  - Relative velocity at impeller inlet
    \[ \omega_1 = \frac{c_{1M}}{\sin \beta_1} \]
  - Relative velocity at impeller outlet
    \[ \omega_2 = \frac{c_{2M}}{\sin \beta_2} \]

Mechanistic Modeling...

- Zhang (2013)...

  Third term
  - Absolute velocity at impeller inlet
    \[ c_1 = \sqrt{c_{1M}^2 + \left( U_1 - \frac{c_{1M}}{\tan \beta_1} \right)^2} \]
  - Absolute velocity at impeller outlet
    \[ c_2 = \sqrt{c_{2M}^2 + \left( U_2 - \frac{c_{2M}}{\tan \beta_2} \right)^2} \]
Mechanistic Modeling...

- Zhang (2013)...

  ➢ When $Q < Q_{BMP}$
    ▶ Fluid velocity at impeller outlet
      \[ C_{2F} = C_{2B} \frac{Q}{Q_{BMP}} \]
    ▶ Effective velocity
      \[ C_{2E} = C_{2F} \]
    ▶ Therefore
      \[ H_{EE} = H_E + \frac{C_{2E}^2 - C_2^2}{2g} \]

- Zhang (2013)...

  ➢ When $Q > Q_{BMP}$
    ▶ Fluid velocity at impeller outlet
      \[ C_{2F} = C_{2B} \frac{Q}{Q_{BMP}} \]
    ▶ Shear velocity
      \[ V_S = U_2 \frac{Q - Q_{BMP}}{Q_{BMP}} \]
    ▶ $C_{2P}$ is projection of $C_2$ onto $C_{2B}$
      \[ C_2^2 - C_{2P}^2 = V_S^2 - (C_{2F} - C_{2P})^2 \]
    ▶ Solve for $C_{2P}$
      \[ C_{2P} = \frac{C_2^2 + C_{2F}^2 - V_S^2}{2C_{2F}} \]
Mechanistic Modeling...

- **Zhang (2013)**...
  - When $Q > Q_{BMP}$...
    - Effective velocity
      \[ C_{2E} = C_{2F} + \sigma (C_{2P} - C_{2F}) \frac{Q - Q_{BMP}}{Q_{BMP}} \]
      where $\sigma$ is velocity reduction due to recirculation
    - Therefore
      \[ H_{EE} = H_{E} + \frac{C_{2E}^2 - C_{2}^2}{2g} \]

- **Head Change**
  - Friction losses
    - Friction loss in impeller
      \[ H_{FI} = f_{FI} \frac{V_{I}^2 L_{I}}{2g D_{I}} \]
      where $f_{FI} = f(Re_{I}, \varepsilon/D_{I}), \quad Re_{I} = \frac{\rho V_{I} D_{I}}{\mu}, \quad D_{I} = \frac{4Vol_{I}}{A_{SI}}$
    - Friction loss in diffuser
      \[ H_{FD} = f_{FD} \frac{V_{D}^2 L_{D}}{2g D_{D}} \]
      where $f_{FD} = f(Re_{D}, \varepsilon/D_{D}), \quad Re_{D} = \frac{\rho V_{D} D_{D}}{\mu}, \quad D_{D} = \frac{4Vol_{D}}{A_{SD}}$
Mechanistic Modeling...

- Head Change...
  - Friction losses...
    - Representative velocity in impeller channel
      \[ V_I = \frac{W_1 + W_2}{2} \]
    - Representative velocity in diffuser channel
      \[ V_D = \frac{Q}{A_D Z_D} \]
    - Where \( A_D = \frac{V_{01D}}{L_D} \)

- Head losses due to turns
  - Turning head loss for impeller
    \[ H_{TI} = f_{TI} \frac{V_I^2}{2g} \]
    - Where \( f_{TI} \) is local drag coefficient
  - Turning head loss for diffuser
    \[ H_{TD} = f_{TD} \frac{V_D^2}{2g} \]
    - Where \( f_{TD} \) is local drag coefficient
Mechanistic Modeling...

- For all flow rates
  \[ H_{EE} = H_E + \frac{C_{2E}^2 - C_2^2}{2g} - H_{FI} - H_{TI} \]
- Most working conditions considered
- Predict ESP performance easily in a computer program

Experimental Program

- Stainless steel flow loop
  - 3-inch diameter
- Flow rate
  - 0 to 10,000 bpd
- Mineral oils with different viscosities
  - Up to 300 cP
  - Monitored with a pipe viscometer
    with a hydraulic development section
- Temperature controlled
  - Heat exchanger
  - Insulation
- Can be used for oil-water experiments
  - Viscosity up to 1,000 cP
Experimental Program...

- **Test Matrix**

<table>
<thead>
<tr>
<th>$\mu$ (cP)</th>
<th>10, 30, 50, 100, 150, 200, 250, 300</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (rpm)</td>
<td>2400, 2700, 3000, 3300, 3600, 3900</td>
</tr>
<tr>
<td>$Q/Q_{BEP}$</td>
<td>0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4</td>
</tr>
</tbody>
</table>

Flow Loop Design

```
Motor
ESP
Manual Valve
Control Valve
T
Drianage
T
VSD
DP
P
Input Port
Compressor
Float
Heat Exchanger
Water Pump
Water Tank
Pipe Viscometer
Low Flow Meter
High Flow Meter
Manual Valve
Control Valve
```
Flow Loop Design…

Pipe Viscometer

- Hydraulic development section length
  - Laminar flow
    \[ \frac{L_e}{D} \approx 0.06Re \]
  - Turbulent flow
    \[ \frac{L_e}{D} \approx 4.4Re^{1/6} \]
Flow Loop Design...

- Pipe Viscometer...
  - Rosemount 3051S differential pressure transmitter
  - Pressure range
    - -25 inH₂O to 25 inH₂O
    - -250 inH₂O to 250 inH₂O
    - -1000 inH₂O to 1000 inH₂O
  - Compared with viscosity temperature curve

<table>
<thead>
<tr>
<th>Viscosity [cP]</th>
<th>10</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>500</th>
<th>700</th>
<th>1000</th>
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<tbody>
<tr>
<td>Flow Rate [bpd]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>500</td>
<td>0.27</td>
<td>1.36</td>
<td>2.72</td>
<td>5.45</td>
<td>8.17</td>
<td>13.62</td>
<td>19.07</td>
<td>27.24</td>
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<tr>
<td>1000</td>
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<td>27.24</td>
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<td>272.39</td>
<td>381.34</td>
<td>544.77</td>
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</tr>
</tbody>
</table>

Flow Loop Design...

- Pipe Viscometer...
  - 20 ft long
    - Pressure Drop [inH₂O]
      - Viscosity [cP]  | 10 | 50 | 100 | 200 | 300 | 500 | 700 | 1000 |
      - Flow Rate [bpd] |    |    |     |     |     |     |     |      |
      - 500           | 0.14| 0.68| 1.36| 2.72| 4.09| 6.81| 9.53| 13.62|
      - 1000          | 0.43| 1.36| 2.72| 5.45| 8.17|13.62|19.07|27.24 |
      - 2000          | 1.69| 2.72| 5.45| 10.90|16.34|27.24|38.13|54.48 |
      - 3000          | 3.38| 4.09| 8.17|16.34|24.51|40.86|57.20|81.72 |
      - 5000          | 8.18|10.77|13.62|27.24|40.86|68.10|95.34|136.19|
      - 10000         | 27.71|42.13|43.09|54.48|81.72|136.19|190.67|272.39|

- 10 ft long
  - Pressure Drop [inH₂O]
    - Viscosity [cP]  | 10 | 50 | 100 | 200 | 300 | 500 | 700 | 1000 |
    - Flow Rate [bpd] |    |    |     |     |     |     |     |      |
    - 500           | 0.14| 0.68| 1.36| 2.72| 4.09| 6.81| 9.53| 13.62|
    - 1000          | 0.43| 1.36| 2.72| 5.45| 8.17|13.62|19.07|27.24 |
    - 2000          | 1.69| 2.72| 5.45| 10.90|16.34|27.24|38.13|54.48 |
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    - 5000          | 8.18|10.77|13.62|27.24|40.86|68.10|95.34|136.19|
    - 10000         | 27.71|42.13|43.09|54.48|81.72|136.19|190.67|272.39|
Flow Loop Design...

- **Pipe in Pipe Heat Exchanger**
  - **Inside pipe**
    - Stainless steel
    - Inner diameter: 3”
    - Outer diameter: 3.5”
  - **Outside pipe**
    - Schedule 40 PVC
    - Inner diameter: 5.047”
    - Outer diameter: 5.563”
  - **Flexible coupling for connection**

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<th>Flow Loop Design...</th>
<th>Heat Transfer Media</th>
<th>Hot Fluid</th>
<th>Cold Fluid</th>
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<td>Outlet Temperature [°C]</td>
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<td>Density [kg/m³]</td>
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<td>Specific Heat [W/K]</td>
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<td>Heat Transfer Area [ft²]</td>
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<td>Length [ft]</td>
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62nd Advisory Board Meeting
Oct 28, 2016
Flow Loop Design...

- **Input Port**
  - Reducing tee
    - 3” x 1”
  - Concentric reducer
    - 3” x 1”
  - Clear PVC pipe
    - Fluid input
    - Liquid level observation
## Future Schedule

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62nd Advisory Board Meeting

Oct 28, 2016
Tulsa University Artificial Lift Projects (TUALP)  
2016 Questionnaire Results

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<th>Research Topics</th>
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