Research and Development on Critical (Sonic) Flow of Multiphase Fluids through Wellbores in Support of Worst-Case-Discharge Analysis for Offshore Wells

Project Overview and Deliverable Status

Saeed Salehi, PhD Principal Investigator
Friday, October 12th 2018
C.1 INTRODUCTION

In the wake of the 2010 *Deepwater Horizon* incident and pursuant to regulations (30 CFR 550.213(g), 550.219, 550.243(h), and 550.250), BOEM has since revised and the requirements for Worst Case Discharge (WCD) Scenario calculations submitted by operators conducting oil and gas exploration and production in the Outer Continental Shelf (OCS) of the Gulf of Mexico (GOM). In response to the growing need for consistent WCD reporting, the Society of Petroleum Engineers (SPE) published a Technical Report (March 2015) on the *Calculation of Worst-Case Discharge (WCD)*. The report represented the consensus viewpoints of subject matter experts aimed at developing a consensus guideline for WCD analysis so that “operators and regulators can have confidence that the methods employed are both reasonable and consistent.” (p.3). The SPE report noted two areas for recommended research: (1) appropriate correlations for high-rate flow in large-diameter pipe; and (2) sonic velocity flow limitations on WCD calculations. The first area of research is currently studied under Contract Award: M1SPC00007. The second recommended area of research stems from the viewpoint that critical (sonic) flow limitations are expected to have only a small effect on well discharge rates in WCD analyses.
Sonic Velocity Limitation

At very high gas discharge rates to a low-pressure environment, the well exit velocity may approach sonic velocity and limit the gas flow rate by critical flow choking. This would only apply to wells with a discharge point above sea level allowing flow to the atmosphere. Most Nodal analysis software packages include a sonic velocity check at each calculation node.

For most cases of practical interest, critical flow limitations are expected to have only a small effect on well discharge rate. As a result, sonic velocity flow limitations should generally be ignored for WCD calculations unless special conditions apply. However, where applicable, it may be invoked by an operator with proper justification. However, until further research is conducted, BOEM will not be applying sonic velocity to the WCD calculation.
C.2 OBJECTIVE

The main objective of this project is to secure one contractor who can demonstrate the applicability of current (or novel) analytical, numerical, or empirical methods for predicting critical (sonic) discharge flow rate, pressure, and velocities of multiphase fluids exiting wellbores in Gulf of Mexico OCS Worst-Case-Discharge scenarios. To accomplish this goal, several milestones will be administered to encapsulate the body of work needed to investigate existing and novel approaches to better understand multiphase critical flow in GOM Deepwater projects. The study objectives are to complete the following:
University of Oklahoma Study Goals

• Prevailing WCD models lack an accurate pressure drop prediction at sonic and supersonic conditions.
  – Models don’t account for flow regime development of two-phase flow that may attain sonic condition at the wellbore exist due to the dramatic pressure drop.
  – Lack of theoretical models and experimental data of two-phase flow at high Mach number (Ma > 0.3)
  – Subsonic/supersonic conditions lead to the generation of shock waves in the system, which was not included in past studies.
• Goal is to develop a mechanistic model to predict two-phase flow characteristics for different WCD scenarios in the wellbore at high Mach number.
• Goal is to also provide a computational tool that predicts WCD rate under various operational conditions.
University of Oklahoma Team

Saeed Salehi, PI

Rida Elgaddafi
Post-Doc Associate

Raj Kiran
PhD Candidate

Ramadan Ahmed, Co-PI

Olawale Taye
Post-Doc Associate

Jeff McCaskill
Technician and Equipment Specialist
<table>
<thead>
<tr>
<th>Deliverable(s) / Milestone(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion of Technical Report for Literature Study and Theoretical Studies</td>
</tr>
<tr>
<td>Completion of Technical Report for Models CFD Simulations/WCD Model</td>
</tr>
<tr>
<td>Completion of Technical Report for Laboratory Results</td>
</tr>
<tr>
<td>Completion and Development of WCD Model and Computational Tool</td>
</tr>
<tr>
<td>Completion of Draft Reports</td>
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## Progress

<table>
<thead>
<tr>
<th>Deliverables</th>
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</tr>
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<tbody>
<tr>
<td>Literature Review and Theoretical Studies Report</td>
<td>January 5(^{th}), 2018</td>
</tr>
<tr>
<td>CFD Simulation/WCD Model Technical Reports</td>
<td>March 24(^{th}), 2018</td>
</tr>
<tr>
<td>Technical Report for Laboratory Results</td>
<td>April 24(^{th}), 2018</td>
</tr>
<tr>
<td>Completion of WCD Model and Computational Tool</td>
<td>October 12, 2018</td>
</tr>
<tr>
<td>Final Report</td>
<td>October 3, 2018</td>
</tr>
</tbody>
</table>

- Kick off meeting, October 24\(^{th}\), 2017
Methodology and Scope

- **Literature Review**: Review preceding experimental and theoretical studies
- **Computational Fluid Dynamics**: Develop a simulation model for predicting TP characteristics
- **Experimental study**: Measuring two-phase characteristics under a wide range of fluid velocity
- **WCD Computational Tool**: Two-phase flow mechanistic model, PVT model and Nodal Analysis
University of Oklahoma (OU): High Velocity Experimental Setup

- A new flow loop has been developed to perform high-velocity two-phase flow loop.
University of Oklahoma (OU) WCD Computational Tool

- Programming Language:
  - C++ (main program)
  - VBA (interface)

- Computer requirements for execution:
  - Excel 2013 Macro-Enabled Office

- Interface:
  - Handles up to 15 layers including open hole properties
  - Users can validate the input data
  - Visualize the results using customized plots

Input data
- Reservoir properties
- Wellbore properties

Interface

Output
### WCD Computational Tool

**University of Oklahoma (OU):**

- Casing Inner Diameter, Dc (inch): 6 (2-100)
- Casing Roughness, epsilonc (inch): 0.009 (>0)
- Hole Diameter, Dh (inch): 5 (>Ds)
- Cased Hole Diameter, Dsh (inch): 7 (>Ds)
- Hole Roughness, epsilonh (inch): 0.009 (>0)
- Measured Depth, MD (ft): 2000 (>0)
- Wellhead Pressure, Pw (psia): 100 (>Pv)
- Surface temperature, Ts (deg. F): 40 (>0)
- Length of Open Hole Section, Loh (ft): 50 (>0)
- Number of Producing Layers, Npl: 3 (1-15)
- Hole diameter being liner, Dlh (inch): 5 (>Dlh>Dih)
- Liner Inner Diameter, DI (inch): 5.5 (>D<d<dc)
- Liner Roughness, epsilonl (inch): 0.009 (>0)
- Casing Shoe Depth, LCS (ft): 2000 (>0)
- Kickoff Point, KOP (ft): 1000 (>0)
- Well Inclination from Vertical, theta (deg.): 45 (0.45)

**Well Type:** Induced Well

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**The UNIVERSITY of OKLAHOMA**

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**Mesoab School of Petroleum and Geological Engineering**
Other Available Tools for WCD

- **High velocity region**
- **Transient region**
- **Low velocity region**

OU WCD Computational Tool

- **Single phase region**
- **Low velocity region**
- **Transient region**
- **High velocity region**
- **Sonic region**
• Project Sponsor: US Department of the Interior, Bureau of Ocean Energy Management (BOEM)
Thank you !!!
Experimental Setup and Procedure

Ramadan Ahmed, Co-Principal Investigator
Oct, 12th 2018
Outline

- Introduction
- Flow Loop Components
- Problems and Challenges
- Measuring Techniques
- Test Type and Procedure
A new flow loop has been developed to perform high-velocity two-phase flow loop.

The loop has two 18-ft long test sections:
- 3.25” Pipe section
- 3.25” X 1.315” Annular section

Ranges of test parameter
- Liquid rate: 5 to 240 gpm
- Gas rate: 8 to 320 lbm/min
Flow Loop
Photo
Schematic
Flow Loop Components

- Test section
- Air supply system
- Water circulation system
- Data acquisition system
Test Sections

**Sensors**
- Differential pressure
- Static Pressure
- Temperature

**Valves**
- Holdup
- Safety
- Check

**Others**
- Visualization system
- Air accumulators
- Perforated disks
Inlet Section

- Holdup valve
- Mixing section
- Water injection
- Liquid-level measuring dp meter
Compressors

- Atlas Copco 1600 cfm
- Atlas Copco 1800 cfm (Rented)
- Sullair/Doosan 1600 cfm (Rented)

Valves

- Inlet
- Bypass (not used)
- Flow regulating

Sensors

- Flow meters (F1 and F2)
- Pressure
- Temperature
Air Supply System - Photo

- Inlet Valve
- Flowmeters
- Manifold
- Control Valve
Water Circulation System

Equipment
- Water tank
- Water pumps with VFD control

Valves
- Relief
- Bypass (not used)

Sensors
- Flow meter (F3)
- Pressure
- Temperature
Equipment

Water Tank

Primary Water Pump

Secondary Water Pump
Problems and Challenges

- Equipment failure: inner pipe support failure and view port leaks
- Water hammer and pressure surge causing leaks and pipe failure
- Vibrations
- Instrument failure: flow meters and pressure sensors
Measuring Techniques

- **Pressure drop:** Two differential pressure sensors
  Accuracy 0.05%, Measuring Range ± 40 and 200 in H₂O

- **Flow Rate:** Coriolis flow meters
  Accuracy 0.35%
  Accuracy 0.05%, Measuring Range 550 and 2564 lb/min

- **Liquid Holdup:** Differential pressure sensor
  Accuracy 0.05%, Measuring Range ± 200 in H₂O
Test Procedure – Holdup Experiment

1. Start the data acquisition program.
2. Drain liquid from the test section to prevent liquid hammers.
3. Inject air into the loop at low rate and increase it gradually to the desired rate.
4. Inject liquid at low rate and increase it gradually to the desired rate.
5. Record the flow pattern using a high-speed camera when steady state flow establishes.
6. Quickly close the holdup and inlet valves and stop the liquid circulation pump.
7. Record liquid holdup when the liquid level measurement establishes.
8. Slowly depressurize the test section using the backpressure valve.
9. Save all recorded measurements and close the data acquisition program.
Holdup Experiment - Measurements

[Graphs showing flow rate and differential pressure over time, with video recording indicated.]
Test Procedure – Variable Rate Experiment

1. Start the data acquisition program.
2. Drain liquid from the test section to prevent liquid hammers.
3. Inject air into the loop at low rate and increase it gradually to the desired rate.
4. Inject liquid at low rate and increase it gradually to the desired rate.
5. Maintain steady state flow condition for more than a minute.
6. Increase the gas rate.
7. Repeat Steps 5 and 6 until the gas rate reaches the maximum flow rate.
8. Save all recorded measurements and close the data acquisition program.
Variable Rate Experiment - Measurements

### Flow Rates

<table>
<thead>
<tr>
<th>Time</th>
<th>Qg (lbm/min)</th>
<th>QL (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18:14</td>
<td></td>
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<tr>
<td>18:28</td>
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<tr>
<td>18:43</td>
<td></td>
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<tr>
<td>18:57</td>
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<td></td>
</tr>
<tr>
<td>19:12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Differential Pressure (in H2O/in)

<table>
<thead>
<tr>
<th>Time</th>
<th>DP1</th>
<th>DP2</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>18:00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18:14</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>18:28</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>18:43</td>
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<tr>
<td>18:57</td>
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<tr>
<td>19:12</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Thanks
Research and Development on Critical (Sonic) Flow of Multiphase Fluids through Wellbores in Support of Worst-Case-Discharge Analysis for Offshore Wells

Modeling Two-Phase Flow and WCD Rate in Pipe

Rida Elgaddafi, Postdoctoral Research Associate

Oct 12th, 2018
Outlines

- Introduction
- Statement of problem
- Objectives
- Methodology and scope
- Literature review findings
- Two phase flow model (CFD)
- WCD Computational Tool (WCD-CT)
- Two-phase flow mechanistic models
- Comparative study
- Conclusions
Introduction

- WCD is the daily rate of an uncontrolled flow of hydrocarbons from all producible reservoirs into open wellbore. (BOEM)
- WCD is a result of blowout, which has constantly been a concern for oil and gas industry in the US.
- During the last 15 years, 58 blowout incidents in the US Gulf of Mexico and 36 blowouts in the rest of the world were occurred. (BSEE)
- Multiphase flow is a common occurrence during the blowout incidents.
- Accurate prediction of WCD scenario is strongly related to accuracy of two-phase flow model.
Statement of problem

- Blowout incidents of oil and gas offshore wells can cause an environmental hazard.

- Prevailing WCD models lack an accurate pressure drop prediction at sonic and supersonic conditions.

- Development of the two-phase flow in the wellbore which may attain sonic condition at the exist due to the dramatic pressure drop.

- Determining two-phase flow characteristics in the wellbore is more challenging compared to that of the single phase.

- Lack of theoretical models and experimental data of two-phase flow at high Mach number (Ma > 0.3)
Objectives

- Better understanding of physical phenomena associated with WCD scenario, particularly behavior of two-phase flow at high Mach number.
- Developing a simulation model using ANSYS to predict pressure profile in the wellbore.
- Developing a mechanistic model to predict two-phase flow characteristics for different WCD scenarios in the wellbore at high Mach number.
- Provide a computational tool that predicts WCD rate under various operational conditions.
Methodology and Scope

Literature Review
- Review preceding experimental and theoretical studies

Computational Fluid Dynamics
- Develop a simulation model for predicting TP characteristics

Experimental study
- Measuring two-phase characteristics under a wide range of fluid velocity

WCD Computational Tool
- Two-phase flow mechanistic model and Nodal Analysis
The experimental study reveals that the trend of pressure drop changes at a higher velocity in comparison to the trend at lower velocities.

In multiphase flow, the speed of sound is different from that of single-phase flow.

Subsonic/supersonic conditions lead to the generation of shock waves in the system, which was not included in past studies.

Though, the two-phase flow characteristics have been extensively studied for low velocities (Mach number <0.3) in vertical pipes, it lacks significantly at the subsonic and supersonic front.
• Very limited theoretical and experimental studies were carried out to investigate two-phase flow phenomena in annuli.

• Post CFD simulation model of two-phase flow in the wellbore are limited to relatively low gas and liquid superficial velocities.

• Existing CFD simulations of sonic and supersonic conditions are merely developed for single-phase converging-diverging nozzle flows.

• Various flow patterns can be developed in the wellbore, which significantly effect pressure gradient and ultimately estimation of the WCD.
• **Experimental Study (Luo et al. 2016)**
  - Distance between pressure transducer = 8 m
  - Test section ID = 2.5 in

- Superficial gas velocity = 20 – 160 m/s
- Superficial Liquid velocity = 1.0 – 1.95 m/s
Experimental Studies

- Luo et al. (2016)
- Perez (2008)
- Waltrich et al. (2015)
Literature Review - Comparative Analysis

<table>
<thead>
<tr>
<th>Reference</th>
<th>Test section ID (mm)</th>
<th>$V_{sl}$ (m/s)</th>
<th>$V_{sg}$ (m/s)</th>
<th>Flow pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biria (2013)</td>
<td>50.8</td>
<td>0.12 – 0.72</td>
<td>0.33 – 8.27</td>
<td>Bubbly and Slug</td>
</tr>
<tr>
<td>Perez (2008)</td>
<td>38 - 67</td>
<td>0.2 – 0.7</td>
<td>0.16 – 3.83</td>
<td>Bubble, slug and churn</td>
</tr>
<tr>
<td>Waltrich et al.</td>
<td>50.8 – 305</td>
<td>0.12 – 0.73</td>
<td>0.31 – 31.0</td>
<td>Bubbly, slug, churn and annular flow</td>
</tr>
</tbody>
</table>

Pressure gradient (KPa/m) vs. Superficial gas velocity (m/s)

Liquid holdup, HL (%) vs. Superficial gas velocity (m/s)
Literature Review - Factors Affecting WCD

Wellbore conditions

- Liquid and gas flow rates
- Pipe size & roughness
- Fluid properties
- Flow patterns
- Volumetric liquid Holdup
- Pressure gradient

Reservoir Parameters

- Reservoir pressure & temperature
- Absolute & relative Permeability
- Productivity
- Bottom-hole flowing pressure
- Gas-oil ratio
- Height of pay zone

WCD rate
Computational Fluid Dynamic – CFD Model

❖ Fundamentals of CFD Model (ANSYS Fluent)

• Conservation of mass (continuity equation)

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \]

• Conservation of momentum

\[ \frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\vec{\tau}) + \rho \vec{g} + \vec{F} \]

❖ Modelling Multiphase Flow

✓ Mixture Model
✓ Volume of Fluid (VOF) Model
✓ Eulerian Models
✓ Hybrid model

❖ Turbulence Model

✓ K – \( \varepsilon \) model
✓ K – Omega model
CFD Model – Solver setup

Flow Geometry
- Desired dimensions (2 m long)

Mesh Generation
- ICEM software
- Mesh sensitivity analysis

Model setup
- Pressure based solver
- Transient or steady state
- Multiphase model
- Turbulence model
- Material
- Boundary conditions

Solution
- Solution method
- Solution control
- Initialization
- Run calculation
## CFD Model – Validation

### Experimental Data [Ohnuki and Akimoto (2000)]

<table>
<thead>
<tr>
<th>Case</th>
<th>Flow pattern</th>
<th>Pipe diameter (in)</th>
<th>$V_{SG}$ (m/s)</th>
<th>$V_{SL}$ (m/s)</th>
<th>CFD (DP/DL) (KPa/m)</th>
<th>Exp. (DP/DL) (KPa/m)</th>
<th>Existing model (DP/DL) (KPa/m)</th>
<th>Error (%)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>bubble</td>
<td>8</td>
<td>0.03</td>
<td>0.18</td>
<td>9.50</td>
<td>9.05</td>
<td>9.43</td>
<td>5</td>
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<tr>
<td>2</td>
<td>bubble</td>
<td>8</td>
<td>0.03</td>
<td>1.06</td>
<td>9.65</td>
<td>9.7</td>
<td>9.5</td>
<td>0.5</td>
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<tr>
<td>3</td>
<td>bubble</td>
<td>8</td>
<td>0.26</td>
<td>1.06</td>
<td>8.05</td>
<td>8.5</td>
<td>8.9</td>
<td>-5</td>
</tr>
</tbody>
</table>
CFD Model – Results

- **Pressure & Velocity Profile**

  - Static pressure (Pa) vs. Distance (m)
  - Velocity Magnitude (m/s) vs. Cross-section (m)

- **Turbulence Flow Characteristics**

  - Turbulent Kinetic Energy (m$^2$/s$^2$) vs. Cross-section (m)
  - Turbulent Dissipation Rate (m$^2$/s$^2$) vs. Cross-section (m)

- Vg = 0.03 m/s, Vl = 1.06 m/s
- Vg = 0.26 m/s, Vl = 1.06 m/s
- Vg = 0.03 m/s, Vl = 1.06 m/s
- Vg = 0.26 m/s, Vl = 1.06 m/s
CFD Model – Validation (OU Data)

Single phase flow simulation

Liquid flow rate (gal/min)

ΔP (in H₂O)

Two phase flow simulation

Superficial gas velocity (m/s)

DP/DL (Kpa/m)

Exp. Data
Simulation Model

Exp. Data
Simulation

Exp. Data
Simulation Model
CFD Model – High Velocity

**CFD Model for OU Lab-Setup**

- Pressure based solver
- Specify fluid test (air compressibility)
- Active energy equation
- Multiphase model (hybrid model)
- Turbulence model (SST k-ω model)
- Boundary condition (pressure inlet boundary)
- Solution method
- Solution control
Pressure, Density & Mach number Profile

- **Static pressure × 10^5 (Pa)**
  - 15 psi (simulation data - Gas velocity 41.56 m/s)
  - 50 psi (simulation data - Gas velocity 90.2 m/s)
  - 32 psi (Experimental data - 141 m/s)

- **Density (Kg/m³)**
  - Test section (m): 0 1 2 3 4 5 6
  - Static pressure: 3.0 2.0 1.0 0.0

- **Mach number**
  - Test section (m): 0 1 2 3 4 5 6
  - Mach number: 0.0 0.2 0.4 0.6 0.8 1.0 1.2

- **Pressure, Density & Mach number Profile**
WCD - Computational Tool

- Nodal Analysis Technique
- PVT Model
- Production Model
- Reservoir Model
- Hydrodynamic Flow Model
WCD CT- Nodal Analysis

Nodal Analysis

- Pressure based matching
- Flow rate based matching

Output

- WCD rate
- Gas and water flow rate
- Surface pressure
- Nodal curve (IPR) for each Layer
Fluid flow in the Wellbore

- **Single phase flow**
  - Liquid flow
  - Gas flow

- **Two-phase flow**
  - Bubbly flow
  - Dispersed bubble flow
  - Slug flow
  - Churn flow
  - Annular flow
  - Mist flow

Schematic of expected two-phase flow pattern in the wellbore (Modified after Hasan and Kabir 1988)
### Existing Two-Phase Flow Model

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>FLOW PATTERN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pagan et al. (2017)</td>
<td>Churn &amp; Annular</td>
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<tr>
<td>Ansari et al. (1994)</td>
<td>Dispersed, Bubble, Slug &amp; Annular</td>
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<tr>
<td>Tengesdal et al. (1999)</td>
<td>Bubble, Slug, churn &amp; Annular</td>
</tr>
<tr>
<td>Sylvester (1987)</td>
<td>Slug</td>
</tr>
<tr>
<td>Yao and Sylvester (1987)</td>
<td>Annular – Mist</td>
</tr>
</tbody>
</table>

(Shoham, 2005)
WCD Model

- Single Phase flow model
- Bubble flow model
- Low velocity slug model
- High velocity slug model
- Annular flow model
- Hybrid model
Mechanistic Model for Two-Phase Flow in Pipe – Validation

Low Flow Conditions (Exp. Data from Hernandez Perez 2008)

- Superficial Liquid velocity = 0.73 m/s
- Pipe ID = 1.5 in
- Superficial gas velocity = 0.40 – 3.85 m/s.
- Slug flow pattern
- Discrepancy between predicted & measured < 7%

- Superficial Liquid velocity = 0.1 m/s
- Pipe ID = 1.5 in
- Superficial gas velocity = 0.23 – 4.28 m/s.
- Slug flow pattern
- Discrepancy between predicted & measured < 7%
Mechanistic Model for Two-Phase Flow in Pipe – Validation

**High Flow Conditions (OU – Lab Data)**

- Liquid flow rate = 200 gpm ($V_{sl} = 2.41$ m/s)
- Pipe ID = 3.25 in
- Superficial gas velocity = 9.21 – 78 m/s.
- **Slug flow pattern**
- Discrepancy between predicted & measured < 20%

- Liquid flow rate = 240 gpm ($V_{sl} = 2.86$ m/s)
- Pipe ID = 3.25 in
- Superficial gas velocity = 9.22 – 68 m/s.
- **Slug flow pattern**
- Discrepancy between predicted & measured < 25%
### High Flow Conditions (OU – Lab Data)

<table>
<thead>
<tr>
<th></th>
<th>Modified Model</th>
<th>Exp. Data</th>
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<tbody>
<tr>
<td>DP/DL (Kpa/m)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Superficial gas velocity (m/s)</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

- **Liquid flow rate = 60 gpm \( V_{sl} = 0.72 \text{ m/s} \)**
- **Pipe ID = 3.25 in**
- **Superficial gas velocity = 29 – 117 m/s.**
- **Annular flow pattern**
- **Discrepancy between predicted & measured < 20%**

<table>
<thead>
<tr>
<th></th>
<th>Modified Model</th>
<th>Exp. Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP/DL (Kpa/m)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Superficial gas velocity (m/s)</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

- **Liquid flow rate = 80 gpm \( V_{sl} = 0.93 \text{ m/s} \)**
- **Pipe ID = 3.25 in**
- **Superficial gas velocity = 27 – 107 m/s.**
- **Annular flow pattern**
- **Discrepancy between predicted & measured < 25%**
Mechanistic Model for Two-Phase Flow in Pipe – Validation

- Large Pipe Diameter (12 in) (Exp. Data from Waltrich et al. 2015)

- Superficial liquid velocity $V_{sl} = 0.73$ m/s
- Pipe ID = 12 in
- Superficial gas velocity = 0.31 – 7.5 m/s.
- Discrepancy between predicted & measured < 25%

- Superficial liquid velocity $V_{sl} = 0.46$ m/s
- Pipe ID = 12 in
- Superficial gas velocity = 1.18 – 7.7 m/s.
- Discrepancy between predicted & measured < 18%
Comparison Between CFD and Mechanistic Model

**Single phase flow comparison**

- **Exp. Data**
- **Correlation**
- **Simulation**

![Graph showing single phase flow comparison](image)

**Two phase flow comparison**

- **Simulation Model**
- **Mechanistic Model**
- **Exp. Data**

![Graph showing two phase flow comparison](image)

- Superficial liquid velocity $V_{sl} = 0.23$ m/s
- Pipe ID = 3.25 in
- Superficial gas velocity = 9.14 – 61 m/s.
Comparison Between CFD and Mechanistic Model

Large pipe (22-in)

<table>
<thead>
<tr>
<th>Pipe Diameter</th>
<th>Vsg (m/s)</th>
<th>Vsl (m/s)</th>
<th>DP/DL (Sim)</th>
<th>DP/DL (Model)</th>
<th>Discrepancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1.12</td>
<td>0.46</td>
<td>2.985</td>
<td>4.24</td>
<td>30%</td>
</tr>
<tr>
<td>22</td>
<td>7.65</td>
<td>0.46</td>
<td>0.655</td>
<td>1.15</td>
<td>43%</td>
</tr>
</tbody>
</table>
Comparative analysis shows good agreement between LSU data and other available measurements.

WCD rate is not only reliant on conditions of the wellbore section but it is also influenced by the fluid properties and reservoir characteristics.

An acceptable agreement was obtained between simulation predictions of the pressure drop and experimental data at various test conditions.

An accurate WCD – computational tool is developed to predict the daily uncontrolled flow of hydrocarbons from all producible reservoirs into open wellbore.

The modified mechanistic model demonstrated good agreement between predicted and measured pressure gradient in the wellbore which provides a strong confidence in WCD rate predictions.
Acknowledgement

Project Sponsor: US Department of the Interior, Bureau of Ocean Energy Management (BOEM)
Thank you !!!
Research and Development on Critical (Sonic) Flow of Multiphase Fluids through Wellbores in Support of Worst-Case-Discharge Analysis for Offshore Wells

EXPERIMENTAL STUDY OF TWO-PHASE FLOW IN PIPE AND ANNULUS

Fajemidupe, Olawale, Ph.D.
Postdoctoral Research Associate
October, 12th 2018
Outlines

• Objectives
• Preliminary Tests
• Flow Regimes
• Liquid Holdup
• Pressure Gradient in Two-Phase Flow
• Indication of Sonic Condition
• Conclusions
Objectives

- To Improve understanding of the impact of high Mach number (0.3 – 1+ Mach) flow on WCD calculation
- Identify and investigate flow patterns (churn, annular, and mist) and flow geometry variation (tubing and annulus pipe).
- To Investigate two-phase flow behavior in vertical pipe and annulus at high superficial gas velocities.
Schematics of the Experimental Flow Loop

Legend:
- BPC: Backpressure chok
- BPV: Backpass valve
- CAM: Video camera
- CV: Check valve
- C01: Air compressor #1
- C02: Air compressor #2
- F1: 2" Coriolis flow meter
- F2: 2" Coriolis flow meter
- F3: 3" Coriolis flow meter
- HV: Hold-up valve
- HT: Inline water heater
- P: Pressure transmitter
- P01: Water pump #1
- P02: Water pump #2
- RS: Relief system
- T: Temperature transmitter
- ATS: Annular test section
- PTS: Pipe test section
- V01: Water tank
- ΔP: Diff. pressure transmitter

Legend: Pipe Fittings
- B: Bushing
- C: Cross
- F: Flange
- R: Reducer
- T: Tee
- CO: Connector

Legend: Pipe Size vs. Color
- Pink: 4"
- Purple: 6"
- Green: 3"
- Red: 2"
- Blue: 3/4"
- Broken lines: Hose lines
Pressure loss ($\Delta P$) in any circular duct is related to diameter ($D$), length ($L$), fluid density ($\rho$) and mean fluid velocity ($V$). Thus:

$$\Delta P = f_f \frac{2L}{D} \rho V^2$$

Chen (1979) Friction Factor equation

$$\frac{1}{\sqrt{f_D}} = -2.0 \log \left[ \frac{\varepsilon}{3.7065D} - \log \left( \frac{1}{2.8257} \left( \frac{\varepsilon}{D} \right)^{1.1098} + \frac{5.8506}{Re^{0.8981}} \right) \right]$$

where $f_D$ is Darcy friction factor, which is defined as fourfold Fanning friction factor, $\varepsilon$ is the pipe roughness, $Re$ is a Reynold number.
Preliminary Test
(Single Phase Liquid Flow Test)

Pipe

Annulus
DP cell sensor is utilized to measure residual liquid column in the test section using hydrostatic pressure concept.

- **DP liquid holdup measurement approach**

\[
H_L = \frac{P_{wf}/\rho_l g}{H_T A} = \frac{P_{wf}}{\rho_l g H_T}
\]

- \(P_{wf}\) is the bottom-hole pressure, \(A\) is the cross-section area of the test section, \(\rho_l\) represents liquid density, \(g\) depicts the gravity, and \(H_T\) is the total height of the test section.
Preliminary Test (Liquid Holdup Validation) Cont.

- Volumetric liquid holdup equation:

\[ H_L = \frac{V_L}{V_T} \]

- where \( H_L \) is liquid holdup, \( V_L \) is the liquid volume, \( V_T \) is the total volume of the test
Preliminary Test (Liquid Holdup Validation) Cont.

<table>
<thead>
<tr>
<th>$Q_L$ (GPM)</th>
<th>$Q_g$ (lb/min)</th>
<th>$H_L$ (DP Cell) %</th>
<th>(Volumetric $H_L$) %</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>25</td>
<td>7</td>
<td>8.0</td>
<td>1.0</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>14</td>
<td>12.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Flow Regime (Churn Flow)

- The classification of flow regimes is an important part of two-phase flow analysis.

- It aids to develop or select an appropriate flow model to predict two-phase behavior in vertical pipe and annulus.

- Two-phase flow regimes depend on parameters such as liquid and gas velocities, pipe geometries, and fluid properties.

- Churn flow occurs at high gas flowrate with moderate liquid flowrate. It can be described as a chaotic frothy mixture of gas-liquid moving upward and downward in the entire pipe.
Flow Regime (Annular Flow)

• The flow regime occurred at high gas and liquid velocities

• Liquid films flow around the wall of the pipe due to high energetic gas-phase velocity and the gas flows at the core with entrained droplets
Flow Regime Map for Annulus

- Churn Flow
- Annular Flow
- Slug & Churn Flow Region
- Annulus Region Flow

Liquid Superficial Velocity (m/s)

In-Situ Gas Superficial Velocity (m/s)
Flow Regime Comparison for Pipe

- OU Churn Flow
- OU Annular Flow
- LSU 2015 4-inch Data (Churn Flow)
- LSU 2015 4-inch (Annular Flow)
- Ali 2009 (Churn Flow)
- Zabaras 2013 (Churn Flow)
- Zabaras 2013 (Semi Annular)
Flow Regime Comparison for Annulus

- Caetano's Annular Flow
- Caetano's Churn Flow
- OU Churn Flow
- OU Annular Flow

![Graph showing flow regimes comparison](image)
Holdup Measurement in Pipe (OU)

Liquid Holdup (-)

In-Situ Gas Superficial Velocity (m/s)

- 0.23 m/s
- 0.70 m/s
- 1.4 m/s
Holdup Measurement in Annulus (OU)

Liquid Holdup (\(\cdot\))

In-Situ Gas Superficial Velocity (m/s)

- Vsl 0.12 m/s
- Vsl 0.29 m/s
- Vsl 0.58 m/s
Comparison of Liquid Holdup with LSU data

Liquid Holdup (\(\theta\)) vs. In-situ Gas Superficial Velocity (m/s)

- 0.23 m/s (OU Data)
- 0.70 m/s (OU Data)
- 1.4 m/s (OU Data)
- LSU 2015 4-inch Data (0.15 m/s)
- LSU 2015 4-inch Data (0.46 m/s)
Pressure Gradient in Two-Phase Flow

The total pressure drop for gas-liquid flow per unit length of a pipe consists of three components:

1. Hydrostatic Component
2. Acceleration Component
3. Frictional component

\[
\left( \frac{\Delta P}{L} \right)_{t} = \left( \frac{\Delta P}{L} \right)_{h} + \left( \frac{\Delta P}{L} \right)_{a} + \left( \frac{\Delta P}{L} \right)_{f}
\]
Pressure Gradient in Two-Phase Flow

- The existence of hydrostatic component of two-phase pressure drop is due to differences in the density between the gas and liquid phase and the influence of the gravity.

- The acceleration component of pressure drop is usually small and can be neglected.
Schematic Pressure Gradient Behavior in Vertical Two-Phase Flow (Shoham, 2005)
Pressure Gradient at Sonic Boundary (Pipe)

In-Situ Gas Superficial Velocity (m/s)

Pressure Gradient (kPa/m)

Sonic Boundary

- 0.058 m/s
- 0.12 m/s
- 0.18 m/s
- 0.23 m/s
- 0.35 m/s
Indication of Sonic Condition

- Upstream Vs Gas Superficial Velocity
- Shock Wave
- Shock Wave Sound
- Pressure Reversal
Sample of Supersonic Video ( $V_{sl} = 0.058 \text{ m/s}$, $V_{sg} = 162.57 \text{ m/s}$, Pipe ID: 0.083M )
Pressure Gradient Without Sonic Boundary (Pipe)

![Graph showing pressure gradient versus in-situ gas superficial velocity for different velocities: 0.47 m/s, 0.70 m/s, 0.93 m/s, 1.4 m/s, 1.87 m/s, 2.33 m/s, 2.80 m/s.](image)

- Pressure Gradient (kPa/m)
- In-Situ Gas Superficial Velocity (m/s)
Pressure Gradient (Annulus)

Pressure Gradient (kPa/m)

Gas Superficial Velocity (m/s)

- Vsl 0.12 m/s
- Vsl 0.29 m/s
- Vsl 0.58 m/s
- Vsl 1.17 m/s
- Vsl 1.47 m/s
- Vsl 0.88 m/s
- Vsl 2.35 m/s
- Vsl 1.76 m/s
Upstream Pressure VS Gas Superficial Velocity (Annulus)
Conclusions

- Pressure gradient increases with gas superficial velocities. However, it sharply decreases as the flow approaches sonic flow condition at low superficial liquid velocities in pipe.

- Pressure gradient slightly increased with liquid superficial velocity at fixed gas superficial velocity. The friction component of the total pressure gradient dominated the two-phase flow in this research.

- Liquid holdup decreases with increase in gas superficial velocity.

- Two different flow regimes with transition (churn, annular and transition between churn and annular) were encountered in this investigation.
Thank You
Research and Development on Critical (Sonic) Flow of Multiphase Fluids through Wellbores in Support of Worst-Case-Discharge Analysis for Offshore Wells

WCD Tool Demonstration, Comparative Study and Review of Questions from Workshop #2

Raj Kiran, Research Assistant
October, 12th 2018
Outline

- Introduction
- CFD Modeling
- Sonic Modeling
- WCD Computational Tool
  - Capability
  - User interface
  - Demonstration
  - Comparative study with prosper
  - Sensitivity analysis
- Conclusions
Introduction

Open Questions and Concerns about WCD

**Influx Related Problems**
- Multiphase flow properties especially in supersonic and subsonic conditions
- Effect of pressure and temperature on flow characteristics
- Effect of geometry on flow properties
- Flow development in the annulus and pipe

**In-situ/Operational Gaps**
- Well characteristics ($k, \Phi, J$)
- Well depth
- Gas in place
- Reservoir thickness
- Gas solubility in oil
- Gas liquid ratio

* $k$: Permeability; $\Phi$: Porosity; $J$: Productivity Index

Photograph Courtesy: Kiran and Salehi, 2017

Way Forward

- Literature Review
- Experiment
- CFD Modeling
- WCD Model
- WCD Computational Tool

The UNIVERSITY of OKLAHOMA
Mewbourne School of Petroleum and Geological Engineering
1. Goals
2. Domain

3. Geometry
4. Mesh
5. Physics
6. Solver setting

7. Computation

8. Results
Experimental data simulation

• Simulation results for air-water flow using VOF approach

<table>
<thead>
<tr>
<th>$V_{sg}$ (m/s)</th>
<th>$V_{sl}$ (m/s)</th>
<th>Pattern</th>
<th>Simulated Pressure Gradient (Pa/m)</th>
<th>Experimental Pressure Gradient (Pa/m)</th>
<th>Error</th>
<th>Slip ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.069</td>
<td>1.545</td>
<td>DB</td>
<td>11231</td>
<td>11500</td>
<td>-3%</td>
<td>0.045</td>
</tr>
<tr>
<td>0.002</td>
<td>0.0375</td>
<td>BB</td>
<td>7741</td>
<td>7003</td>
<td>10.5%</td>
<td>0.053</td>
</tr>
<tr>
<td>0.040</td>
<td>0.090</td>
<td>BB</td>
<td>8340</td>
<td>8859</td>
<td>-5.85%</td>
<td>0.444</td>
</tr>
<tr>
<td>0.437</td>
<td>0.101</td>
<td>SL</td>
<td>5056</td>
<td>5086</td>
<td>-0.6%</td>
<td>4.327</td>
</tr>
<tr>
<td>1.972</td>
<td>1.959</td>
<td>SL</td>
<td>5783</td>
<td>8459</td>
<td>-32%</td>
<td>1.007</td>
</tr>
<tr>
<td>21.893</td>
<td>0.111</td>
<td>AN</td>
<td>1042.5</td>
<td>2254</td>
<td>-48.6%</td>
<td>197.234</td>
</tr>
<tr>
<td>16.61</td>
<td>0.523</td>
<td>AN</td>
<td>3574</td>
<td>4671</td>
<td>-23.5%</td>
<td>31.759</td>
</tr>
<tr>
<td>21.256</td>
<td>0.111</td>
<td>AN</td>
<td>1008</td>
<td>2125</td>
<td>-52.5%</td>
<td>191.495</td>
</tr>
<tr>
<td>16.68</td>
<td>0.548</td>
<td>AN</td>
<td>5115</td>
<td>7685</td>
<td>50.22%</td>
<td>30.438</td>
</tr>
</tbody>
</table>

• Simulation for air-water flow using Eulerian approach

<table>
<thead>
<tr>
<th>$V_{sg}$ (m/s)</th>
<th>$V_{sl}$ (m/s)</th>
<th>Pattern</th>
<th>Simulated Pressure Gradient (Pa/m)</th>
<th>Experimental Pressure Gradient (Pa/m)</th>
<th>Error</th>
<th>Slip ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>0.10</td>
<td>SL</td>
<td>5056</td>
<td>5086</td>
<td>-0.6%</td>
<td>4.327</td>
</tr>
<tr>
<td>13.02</td>
<td>0.30</td>
<td>AN</td>
<td>2486</td>
<td>3176</td>
<td>-22.2%</td>
<td>43</td>
</tr>
</tbody>
</table>
CFD Modeling and its significance

- Superimposed experimental data for 20 GPM liquid rate with the upstream pressure is 37 psi.
- Similar trends for simulation and experiment.
- The liquid velocity in the simulation is much higher than that of experimental condition.
- The experimental conditions required to achieve the sonic condition.
- Several simulation data was used to validate the mechanistic models.
High Mach number flow

- Experimental data superimposed on the well-known chart for the speed of sound as a function of the void fraction of two-phase mixtures given by Kieffer (1977).

These shaded experimental data is the case of Mach number above 1.
Sonic Modeling

• Sonic velocity prediction based on studies from Kieffer (1977) and Wilson and Roy (2008).
  - Model uses Pressure and volumetric gas distribution.
  - Comparison between fluid velocity and sonic velocity.
  - In case of match, sonic condition is established.
  - Flow is decoupled and limited by sonic condition.
  - Well flow pressure calculated using the sonic velocity.
If $P < 100 \text{ bar}$

$$V_{\text{sound}} = (80.44P^{0.6337})x^2 - (-0.0607P^2 + 23.23P + 74.42)x + 30.52P^{0.672} + 20$$

Otherwise

$$V_{\text{sound}} = (1804P^{-0.01989})x^2 - (0.0002878P^2 + 0.8032P + 1884)x + 220.4P^{0.2486} + 20$$

where $P$ is the pressure in Pa, $x$ is volume fraction of gas given by the following formula:

$$x = \frac{V_{sg}}{V_{sg} + V_{sl}}$$

where $V_{sg}$ is the superficial gas velocity and $V_{sl}$ is the superficial liquid velocity. The details of this model will be provided in the report for the WCD tool.
Sonic Velocity Comparison

- Reasonable agreement between model and experimental data
- Model under predicts the sonic speed
How the sonic model works?

Two conditions can prevail in wellbore

Subsonic conditions

- Mach number less than 1
- Wellhead pressure as defined by user
- Fluid velocity governed by bottom-hole and wellhead pressure

Sonic conditions

- Mach number 1 at the exit
- Wellhead pressure controlled by sonic condition
- Fluid velocity governed by sonic velocity at the exit
How the sonic model works?

1. Start
2. Input reservoir and well properties
3. Do the calculation for nodal analysis
4. Is there any grid with fluid velocity greater than sonic velocity?
   - Yes: Consider the exit velocity as sonic velocity
     - Pwh = Pwh + ΔP, and perform the calculation for full wellbore
     - Is there any grid with fluid velocity greater than sonic velocity except at exit?
       - Yes: Display the results
       - No: Display the results
   - No: Display the results
WCD Tool

- Programming Language
  - C++ (main program)
  - VBA (interface)
- Computer requirements for execution
  - Macro-Enabled 2013 MS-Excel (For 2010 another version of program)

Feedback

Validation

Input data
- Reservoir properties
- Wellbore properties

Interface

Output

Main Program
Capability

- Handles up to 15 layers including open hole properties.
- Users can validate the input data.
- Visualization of the results using customized plots.
- Combined plot of velocities and flow pattern.
- Overall WCD, gas flow, and water flow rates.
- WCD, gas flow and water flow rates, well flow pressure, GOR, productivity index for each layer.
- Sonic condition in the wellbore.
- IPR Plots for each layer and corresponding discharge rate.
- Flow properties in tabulated form for each layer.
- Visualization of flow pattern from the bottommost of well.
How this tool is different?

Traditional available software

- Reservoir model only works in this zone
- No consideration of flow patterns/pressure drop

Flowing bottom hole is considered at this point

OU WCD Computational Tool

- Reservoir model and hydraulics model, both works simultaneously

Flowing bottom hole is considered at the bottom-most point of the wellbore
How this tool is different?

Traditional available software

Water is coming from this perforated zone

Layer 1

Can not be simulated

OU WCD Computational Tool

Water is coming from this perforated zone

Layer 1

Can simulate any position of layers
How this tool is different?

Traditional available software

OU WCD Computational Tool

- $\frac{\partial p}{\partial l}$
- $v_{sg}$

- Low velocity region
- Transient region

- Single phase region
- Low velocity region
- Transient region
- High velocity region
- Sonic region
## How this tool is different?

<table>
<thead>
<tr>
<th>Traditional available software</th>
<th>OU WCD Computational Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>❑ Only empirical correlations have been considered.</td>
<td></td>
</tr>
<tr>
<td>❑ Sonic modeling (if there) is based on single gas phase flow only.</td>
<td></td>
</tr>
<tr>
<td>❑ Never tested for high flow rates.</td>
<td></td>
</tr>
<tr>
<td>❑ When the flow is friction dominated, the pressure gradients increases. Empirical models were never tested for experimental data in these conditions.</td>
<td></td>
</tr>
<tr>
<td>❑ Mechanistic model is used.</td>
<td></td>
</tr>
<tr>
<td>❑ Sonic modeling is based on two phase flow condition.</td>
<td></td>
</tr>
<tr>
<td>❑ Tested for high flow rates.</td>
<td></td>
</tr>
<tr>
<td>❑ When the flow is friction dominated, the pressure gradients increases. The hydraulics model is tested for that.</td>
<td></td>
</tr>
</tbody>
</table>
## How this tool is different?

<table>
<thead>
<tr>
<th>Traditional available software</th>
<th>OU WCD Computational Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>❑ To calculate WCD, the reservoir modeling and hydraulics modeling performed separately.</td>
<td>❑ Integrated the reservoir modeling and hydraulics modeling.</td>
</tr>
<tr>
<td>❑ Fluid properties input for hydraulics model is based on the reservoir models</td>
<td>❑ Fluid properties are updated based on the input parameters while running the calculation.</td>
</tr>
<tr>
<td>❑ Average IPR and TPR curve for the system.</td>
<td>❑ Distinct IPR curves and discharge points for each layers of reservoir.</td>
</tr>
</tbody>
</table>
Assumptions

- Radial and steady state reservoirs.
- All input layers are producing with minimum of 0 flow rate.
- Geothermal temperature gradient is considered for the temperature profile.
- The bottom-most layer is always considered to be producing (if negative flow encountered, update the input with upper layer as bottom-most layer).
- Different reservoirs are not communicating to each other.
• Seven tabs in ribbon.
• Each tab is for distinct task.
Input page for wellbore properties.

The bottom layer cannot produce under this condition, consider removing it.
Users can visualize the number of layers, wellbore type and path.

Button to display the well profile

The bottom layer cannot produce under this condition, consider removing it.
Users can visualize the number of layers, casing inner diameter, open hole diameter, and liner diameter.

Button to display the wellbore schematic.

The bottom layer cannot produce under this condition, consider removing it.
WCD Tool

 Updates the input file to run the main program.

 Runs the main program

 Reads the output file generated from the main program

 The bottom layer cannot produce under this condition, consider removing it.
If the reservoir pressure is low, the software will point out this anomaly and will display:

The bottom layer cannot produce under this condition, consider removing it.
Reservoir properties for flow

15 layers overall

Note for the way the layer properties should be entered

Note: Layer numbering is from bottom to top. First input the bottommost layer as first layer and then afterwards. Payzone Bottom Depth should be in terms or measured depth
User can select any of four reservoir fluid.
User can choose any of three formation types:

- Unconsolidated sand
- Consolidated sand
- Limestone

Note: Layer numbering is from bottom to top. First input the bottom most layer as first layer and then afterwards. Payzone Bottom Depth should be in terms or measured depth.
WCD Tool

• User can validate the input data.
• It will provide feedback in case of any errors.

Note: Layer numbering is from bottom to top. First input the bottom most layer as first layer and then afterwards. Payzone Bottom Depth should be in terms or measured depth.
WCD Tool

Display for WCD rate, Gas rate, and Water rate

Display for well flow pressure, oil flow rate, gas flow rate, water flow rate, productivity index, and GOR for each layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>Well Flow Pressure (psi)</th>
<th>Oil Flow Rate (stb/day)</th>
<th>Gas Flow Rate (MMscfd)</th>
<th>Water Flow Rate (Bbl/day)</th>
<th>Productivity Index (STB/day/psi)</th>
<th>GOR (scf/STB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8458.5</td>
<td>273067.0</td>
<td>866.42</td>
<td>8.75</td>
<td>107.06</td>
<td>3172.9</td>
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<tr>
<td>2</td>
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<td>13</td>
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</tr>
</tbody>
</table>

Sonic Condition is achieved
Normalized Superficial gas velocity

Normalized Superficial liquid velocity

Flow pattern

Zone 0 and 1: Single phase flow
Zone 2: Bubbly flow
Zone 3: Low velocity slug
Zone 4: Hybrid slug flow
Zone 5: Slug flow
Zone 6: High velocity slug flow
Zone 7: Hybrid annular region
Zone 8: Annular flow region
Zone 9: Sonic Zone
WCD Tool

Flow pattern zones

Zones description

Flow patterns along the measured depth
User can choose and see any of these six plots in the window below.
WCD Tool

Radius Vs Depth

Pressure Gradient Vs Depth

Superficial liquid velocity Vs Depth
Superficial gas and sonic velocity vs. Depth

Pressure vs. Depth

Flow Pattern vs. Depth
- **IPR Plots**
- Shows Oil and Gas flow rate with respect to well flow pressure
- User can visualize the flow rate from different layers
Oil flow rate Vs. Well flow pressure

Gas flow rate Vs. Well flow pressure

Discharge flow rate with well flow pressure
Comparative study with Prosper

Work flow

- Defining the system
- PVT Data
- IPR Data
- Equipment Data
- Analysis

Diagram:

- PVT Data
  - SolutionGOR
  - Oil Gravity
  - Gas Gravity
  - Water Salinity
  - Mole Percent H2S
  - Mole Percent CO2
  - PVT Matched
  - Use Tables

- IPR Data
  - Reservoir Model
  - M&G Skin Model
  - Perm(k) Reduction Model
  - Relative Permeability
  - Correction For Vogel
  - Reservoir Pressure
  - Reservoir Temperature
  - Water Cut
  - TotalGOR
  - ACF: 168140.3
  - Formation PI (No Skin): 45.50
  - Skin: 0.15

- Equipment Data
  - Deviation Survey
  - Surface Equipment
  - Downhole Equipment
  - Geothermal Gradient
  - Average Heat Capacities
  - Gauge Details

- Analysis
  - Inflow
  - System
  - Gradient
  - VLP
  - Choke Performance
  - Tubing Correlation Comparison
  - Pipeline Correlation Comparison
  - Gradient Matching
  - VLP/IPR Matching
  - PipeLine Matching
  - Generate for GAP
  - BHP From WHP

Sources:
- Glagov et al
- Boem
Comparative study

Methodology

- Inflow performance relation (IPR) and vertical lift performance (VLP) curves simulated
- IPR curves generated using the Darcy reservoir model
- Bubble point pressure: Glasø method
- Viscosity: Beggs et al. method
- VLP Curves:
  - (a) Hagedorn Brown (HB); (b) Beggs and Brill (BB); (c) Petroleum Experts (PE); (d) Mukherjee Brill (MB); (e) Fancher Brown (FB); (f) Duns and Ros (DR); and (g) Petroleum Experts 2 (PE 2)
## Comparative study

### Case study

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Oil Gravity</td>
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<td>°API</td>
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<tr>
<td>Gas specific gravity</td>
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<tr>
<td>Bubble point pressure</td>
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<td>psi</td>
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<td>Reservoir pressure</td>
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<td>Gas oil ratio</td>
<td>235</td>
<td>scf/STB</td>
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**The UNIVERSITY of OKLAHOMA**

Mewbourne School of Petroleum and Geological Engineering

**BOEM**

Bureau of Ocean Energy Management
Comparative study

VLP Curves

- HB: Hagedorn Brown
- BB: Beggs and Brill
- PE: Petroleum Experts
- MB: Mukherjee Brill
- FB: Fancher Brown
- DR: Duns and Ros
- PE 2: Petroleum Experts 2

Each method gives distinct discharge rate
## Comparative study

### Case study: under subsonic conditions

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<thead>
<tr>
<th>Case</th>
<th>Oil Gravity</th>
<th>Gas specific gravity</th>
<th>Bubble Point Pressure</th>
<th>Reservoir Pressure</th>
<th>GOR</th>
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Case study: under subsonic conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>WCD Rate</th>
<th>WCD Rate</th>
<th>Diff.</th>
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### Case study: under sonic conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Oil Gravity</th>
<th>Gas specific gravity</th>
<th>Bubble Point Pressure</th>
<th>Reservoir Pressure</th>
<th>GOR</th>
<th>WCD Rate</th>
<th>WCD Rate</th>
<th>Diff.</th>
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<td>°API</td>
<td>(psi)</td>
<td>(psi)</td>
<td>scf/STB</td>
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Comparative study

Case study: GoM

<table>
<thead>
<tr>
<th>Reservoir Properties</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Reservoir temperature</td>
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<tr>
<td>Reservoir permeability</td>
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<td>Dietz shape factor</td>
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<td>Reservoir pressure</td>
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<table>
<thead>
<tr>
<th>Well Properties</th>
<th>Value</th>
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<tr>
<td>Well type</td>
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<tr>
<td>Measured Depth</td>
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<td>Casing inner diameter</td>
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<td>Liner inner diameter</td>
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<td>Open hole diameter</td>
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<tr>
<td>Casing shoe depth</td>
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<td>ft</td>
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<tr>
<td>Length of open hole section</td>
<td>5076</td>
<td>ft</td>
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</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>Oil Gravity</th>
<th>Bubble Point Pressure</th>
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<tbody>
<tr>
<td>1</td>
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<td>5500</td>
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<tr>
<td>2</td>
<td>45</td>
<td>6900</td>
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## Comparative study

### Case study: GoM

<table>
<thead>
<tr>
<th>Case</th>
<th>WCD Rate</th>
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<th>Diff.</th>
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<tr>
<td></td>
<td>OU Model</td>
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Conservative
Sensitivity Analysis

Change in Permeability

- WCD RATE (STB/day)
- Gas Rate (MMscf/day)
- Permeability (mD)

- WCD Rate
- Gas Rate
Change in Payzone Bottom Depth

- WCD Rate
- Gas Rate

Change in Payzone Height

- WCD Rate
- Gas Rate
Sensitivity Analysis

Change in Reservoir Pressure

- WCD Rate
- Gas Rate

Change in Skin

- WCD Rate
- Gas Rate
Conclusion

• CFD Modeling:
  - Used in setting-up experimental facility
  - Predicting the experimental condition required for sonic flow
  - Mechanistic model validation

• Calculated sonic velocity is in reasonable agreement with experimental data.

• WCD Computational Tool:
  - New approach for sonic modeling for WCD calculation.
Conclusion

• WCD Computational Tool:
  - The tool integrates the reservoir and well model and works simultaneously.
  - Fluid properties are updated based on the input parameters while running the calculation.
  - Distinct IPR curves and discharge points for each layers of reservoir.
  - Comparative study of the new tool with Prosper software shows good agreement.
  - Sensitivity analysis shows the expected trends with respect to different well and reservoir properties.
Future Recommendation

- Investigation of larger diameter with high velocity with experiments.
- Implementation of transient reservoir model.
- Including heat transfer model.
- Broadening the scope of WCD model to simulate the production scenarios.
Acknowledgement

- Project Sponsor: US Department of the Interior, Bureau of Ocean Energy Management (BOEM)
- Jeff McCaskill
Thank you !!!