Experimental Investigation of Flow Models Applied to Worst-Case-Discharge Calculations

New Orleans, LA – Workshop #2 - Sept 28, 2016
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Outline

✓ Overview of Project Objectives and Deliverables
✓ Literature Review Findings and Conclusions
✓ Experimental Investigation
✓ Evaluation of Flow Models to Predict Experimental Data
✓ Comparison of Flow Models Applied to WCD Calculations
✓ Conclusions
✓ Future Projects
Project Motivation [1]

- **Blowouts Happen!**

- For **effective contingency** plans, we need **accurate oil spill predictions!**

- For accurate predictions, **we need reliable models!**

- Industry and **regulatory agencies need guidance** from unbiased experts (**universities** and research institutions)

- **Improvement is needed** to avoid future **large environmental and economical impacts**
"Most flow correlations were developed for small diameter pipe, so their **applicability to larger-diameter pipe** and open hole is uncertain."

"The committee proposes that **further research and development** be conducted on appropriate correlations **for high-rate flow in large diameter pipe.**"
Statement of the Problem [1]

Select outflow correlation (TPR)

- Set a discharge point
- General correlations
- Duns and Ross (1963)
- Beggs and Brills (1973)
- Fancher-Brown (1963)

Need correlations for high-rate flow in large diameter pipe

WCD predictions are directly dependent to flowing bottomhole pressure of the well:
Statement of the Problem [3]

- $q$ is calculated using reservoir and fluid properties, and $p_{wf}$:

$$ q \propto \frac{kh(p_e - p_{wf})}{B_0 \mu \ln \left(\frac{r_e}{r_w}\right)} $$

(reservoir and fluid properties)

(for $p_{wf} > p_{bp}$)

- $p_{wf}$ is obtained from **wellbore flow correlations** and wellhead conditions:

$$ p_{wf} = p_{wh} + \int_{0}^{L} \frac{dp}{dz} \, dz $$

(generic pressure gradient equation)

- Flow regimes
- Superficial velocities
- Pressure & temperature
- Fluid properties
Statement of the Problem [4]

- The use of flow correlations for large diameter pipes is NOT well understood:

Two-Phase flow in a vertical pipe (ID = 10 in)

Ali (2009)
Objective

The goal of this project is to examine the validity of current industry standard flow correlations used in WCD calculations.

Scope of Work:

- Task 1 - A complete literature review
- Task 2 - A comparison between the different flow models applied to WCD
- Task 3&4 – Build apparatus & Generate data for large-diameters pipes and high-velocity flows
- Task 5&6 – Analyze experimental data & Compare with flow models results
Literature Review (Task 1)
Flow rate and total discharge estimations in gas-well blowouts

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ABSTRACT

The model considers flow in the tubing, annulus and riser, and the multiphase flow system. To gauge safety concerns, a computationally efficient, yet very detailed, multiphase model of blowout flow is presented in this paper, coupling the flow in a reservoir with wellbore and surface blowout systems. The model considers the multiphase nature of the flow.
BOEM’S ENGINEERING WORKFLOW

Generate WCD Rate

Reservoir model (IPR)

Wellbore flow models

WCD₁  WCD₂

Tubing Curve: Directional Survey, Drilling Program, Casing Design, and Open Hole Configuration

Reservoir Simulator: Enter Rock and Fluid Properties to determine Absolute Open Flow at Reservoir Nodal Analysis: Enter Fluid Parameters

BOEM, 2015, Worst Case Discharge Program Overview, Office of Resource Evaluation Reserves Section, presentation slides
PRESSURE DROP (ΔP) PREDICTION MODELS

- **Empirical Correlations** (strongly based on data)

- **Drift-Flux models** (additional physics but still based on data)

- **Mechanistic Models** (1D solution of conservation equations but also uses empirical correlations)

- **CFD Models** (3D-transient solution of conservation equations but needs calibration and computationally expensive)
Sources of Errors on Flow Models [1]

- Errors in Fluid Properties & Calculation Direction
### Sources of Errors on Flow Models [2]

#### Review of Conditions Used to Develop Flow Models

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Fluid</th>
<th>Pipe ID (in)</th>
<th>Pipe length (ft)</th>
<th>liquid rate (bbl/d)</th>
<th>Gas rate (Mscf/d)</th>
<th>Fluid properties</th>
<th>Degree From horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poettmann and Carpenter (1952)</td>
<td>Oil/gas, gas/oil/water</td>
<td>2.2 1/4 3</td>
<td>1100-11,000</td>
<td>5 - 1,400 (oil)</td>
<td>18 - 1,630</td>
<td>30°-54° API: 0.8-1.15 Gas SG 0.2 &lt; GOR &lt; 41 Mscf/bbl</td>
<td>90</td>
</tr>
<tr>
<td>Baxendell and Thomas (1961)</td>
<td>Gas/oil</td>
<td>2 7/8, 3 1/2</td>
<td>6,250</td>
<td>200-5,100 (oil)</td>
<td>N/A</td>
<td>Oil: 34° API 2.58 cp at 160° F 120 &lt; GOR &lt; 160 vol/vol</td>
<td>90</td>
</tr>
</tbody>
</table>

| Duns and Ros (1963)                | 1, 5/8, 3 1/2, 6 in ID Vertical Pipe | Tested with Forties field, Ekofisk field, and Prudhoe Bay flow line data |
| Asheim (1986) (Mona)               | Developed with data from TUFFP Databank |
| Ansari (1994)                      | Validated against TUFFP Databank |
| Gomez et al. (2000)                | Used over 10000 data from SINTEF multiphase flow loop |
| OLGA-S 2000 S.S.                   |                                            |

### References

- [Hassani and Al-Hayun (2001)](http://example.com)
- [Asheim and Santoro (2002)](http://example.com)
- [Chokshi and Al-Hayun (1998)](http://example.com)

### Notes

- Tested with field data from Camacho (1970) and Reinicke et al. (1984), Govier and Fogarasi (1975)
- Evaluated with TUFFP
- Validated against TUFFP
### Review of Databases Used to Develop Flow Models

<table>
<thead>
<tr>
<th>Database</th>
<th>Fluids Description</th>
<th>ID Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINTEF multiphase flow loop (OLGA-S 2000 S.S.)</td>
<td>Nitrogen, Naphtha/diesel, lube oil</td>
<td>8 in ID</td>
</tr>
<tr>
<td>TUFFP databank</td>
<td>Oil/gas/water</td>
<td>1-8 in ID</td>
</tr>
<tr>
<td>Forties field</td>
<td>Oil/gas</td>
<td>3.958, 6.185 in ID</td>
</tr>
</tbody>
</table>
SOURCES OF ERRORS ON FLOW MODELS [4]

Review of Flow Rates Used to Develop Flow Models

\[ Q_l < 2,500 \text{ STB/D} \]
## Sources of Errors on Flow Models [5]

### Why Flow Regime Predictions are Important for WCD calculations?

<table>
<thead>
<tr>
<th>Correlations</th>
<th>Flow patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duns and Ros (1963)</td>
<td>bubble, slug, and froth</td>
</tr>
<tr>
<td>Hagedorn and Brown (1964)</td>
<td>no flow pattern consideration</td>
</tr>
<tr>
<td>Hagedorn and Brown Modified (1965)</td>
<td>bubble, slug</td>
</tr>
<tr>
<td>Orkiszewski (1967)</td>
<td>bubble, slug, annular slug transition, annular mist</td>
</tr>
<tr>
<td>Beggs and Brill Revised (1973)</td>
<td>(horizontal pipe) segregated, intermittently, distributed, froth</td>
</tr>
<tr>
<td>Gray (1974)</td>
<td>no flow pattern consideration</td>
</tr>
<tr>
<td>Govier and Foragasi (1975)</td>
<td>slug, annular mist, froth</td>
</tr>
<tr>
<td>Mukherjee and Brill (1985)</td>
<td>no flow pattern consideration</td>
</tr>
<tr>
<td>Ansari (1994)</td>
<td>bubble, slug, and annular</td>
</tr>
</tbody>
</table>

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Flow Regime Maps for Large-Diameter Pipes

Ali (2009) - Experimental conditions tested

<table>
<thead>
<tr>
<th>Study</th>
<th>Qo, BBL/D</th>
<th>Ql, GPM</th>
<th>ID, in</th>
<th>Usl, m/s</th>
<th>GLR, SCF/STB</th>
<th>Qg, MMSCF/D</th>
<th>Qg, SCFM</th>
<th>Usg, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ali</td>
<td>30,300</td>
<td>883</td>
<td>10</td>
<td>1.1</td>
<td>41</td>
<td>0.350</td>
<td>243</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Evaluation of Using CFD models for Multiphase flow in Large Pipe Diameters

Zabaras (2013) - Experimental conditions tested

<table>
<thead>
<tr>
<th>Study</th>
<th>Qo, BBL/D</th>
<th>Ql, GPM</th>
<th>ID, in</th>
<th>Usl, m/s</th>
<th>GLR, SCF/STB</th>
<th>Qg, MMSCF/D</th>
<th>Qg, SCFM</th>
<th>Usg, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zabaras</td>
<td>5140</td>
<td>150</td>
<td>11</td>
<td>0.15</td>
<td>2640</td>
<td>2.97</td>
<td>2063</td>
<td>15.9</td>
</tr>
</tbody>
</table>

![Pressure Gradient Comparison for U_sl=0.5064 ft/s](image1)

![Steady State Riser Flow](image2)
Gaps in Studies for Large-Diameter Pipes [1]

Review of Studies on Two-Phase Flows for ID > 6 in

- Zabaras et al. (2013)
- Schlegel et al. (2012)
- Ali (2009)
- Omebere et al. (90 bar) (2007)
- Omebere et al. (20 bar) (2007)
- Shen et al. (2006)
- Shen et al. (2005)
- Prasser et al. (2002)
- Yoneda et al. (2002)
- Prasser et al. (2002)
- Shen et al. (2005)
- Shen et al. (2006)
- Omebere et al. (90 bar) (2007)
- Omebere et al. (20 bar) (2007)
- Ali (2009)
- Schlegel et al. (2012)
- Zabaras et al. (2013)

Only study with high-gas/liquid flow rates, but only discloses 2 runs of pressure measurements

Liquid production rate, STB/D

Gas production rate, MMSCF/D
Gap in Studies for Large-Diameter Pipes [2]
Conclusions from Literature Review

- **Flow correlations** were originally developed and are still **NOT** verified for **LARGE-diameters** (ID < 8 in)

- **Lack of studies** on Two-Phase Flows in **large-diameters** (ID > 6) and high liquid/gas flow rates (Q_l > 30,000 bbl/d)

- “**Non-standard” flow correlations** should be evaluated to be used in WCD models

- **WCD models** vastly under studied

- **Models specifically developed for WCD scenarios ARE NEEDED!**
Experimental Investigation

(Task 3-5)
Experimental Apparatus

- Pressure transducer
- Thermocouple
- Ball valve
- Gate valve
- Control valve
- Check valve

8-in test section
12-in test section
4-in test section
2-in test section
Experimental Procedure

Pressure Gradient measurement

Liquid Holdup measurement
Flow Regime Observations

\[ D^* = \frac{D}{\sigma \rho L - \rho g} \]

\[ D^* > 30 \] (D > ~4 in)

No Slug Flow for:
Flow Regime Observations [2]

- Bubbly/non-bubbly transition zone
- Churn-to-annular transition zone
Liquid Holdup Measurements [1]

\[
1.53 \left[ \frac{g (\rho_L - \rho_g)}{\rho_L^2} \sigma \right]^{0.25} (1 - \alpha)^{0.5} \sin(\theta) = \frac{u_{sg}}{\alpha} - 1.2 (u_{sl} + u_{sg})
\]
Liquid Holdup Measurements [2]
Liquid Holdup Measurements [3]
\[ \frac{dp}{dz} = g \frac{\bar{\rho}}{g_c} + 2f\bar{\rho}u_m^2 + \frac{\rho}{144243} \Delta(u_m^2 / 2g_c) \]

where

\[ \bar{\rho} = H_l \rho_l + (1 - H_l) \rho_g \]

\( p \) pressure, \( \rho \) density, \( g \) gravitational acceleration, \( u_m \) mean velocity, \( f \) friction factor, \( g_c \) critical gravity, and \( H \) fractional flow.
Δp/Δz Measurements [2]

\[
\frac{dp}{dz} = \frac{g}{{g_c}} \bar{\rho} + \frac{2}{14} \frac{(\mu_m^2)}{g_c} + \frac{\Delta u_m^2}{44} \frac{\Delta g}{43}
\]

\[
\bar{\rho} = H_l \rho_l + (1 - H_l) \rho_g
\]
Δp/Δz Measurements [3]
Conclusions from Experimental Investigation

- As previously observed by other investigators, **slug flow** was not observed for pipe diameter larger than 4 inches.

- **Good match** between the **flow regimes, H₁ and dp/dz** measured in this study and reported by other authors.

- Surprisingly, the **pipe diameter has negligible effect** on the **dp/dz** for pipe diameters over 4 inches.

- **Liquid flow rate** has small effects on **dp/dz** for ID > 4 in, particularly for **high-liquid velocities**.

- **Axial flow development** does not seem to impact significantly the **dp/dz** in large-diameter pipes (ID > 4 in).
Evaluation of Flow Models with Experimental Data (Task 6)
Methodology for Comparison of Flow Models

<table>
<thead>
<tr>
<th>Wellbore flow model</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ansari (1994)</td>
<td>ANS</td>
</tr>
<tr>
<td>Beggs and Brill (1973)</td>
<td>BB</td>
</tr>
<tr>
<td>Beggs and Brill Revised (1979)</td>
<td>BBR</td>
</tr>
<tr>
<td>Duns and Ross (1963)</td>
<td>DR</td>
</tr>
<tr>
<td>Govier, Aziz, and Fogarasi (1972)</td>
<td>GA</td>
</tr>
<tr>
<td>Gray Original (1974)</td>
<td>GO</td>
</tr>
<tr>
<td>Gray modified (PipeSim 2011)</td>
<td>GM</td>
</tr>
<tr>
<td>Hagedorn and Brown (1964)</td>
<td>HB</td>
</tr>
<tr>
<td>Hagedorn and Brown with Duns and Ross map (PipeSim 2011)</td>
<td>HBDR</td>
</tr>
<tr>
<td>Mukherjee and Brill (1985)</td>
<td>MB</td>
</tr>
<tr>
<td>No Slip (PipeSim 2011)</td>
<td>NS</td>
</tr>
<tr>
<td>Orkiszewski (1967)</td>
<td>OR</td>
</tr>
<tr>
<td>OLGA-S 2000 V.6.7.2</td>
<td>OLGA</td>
</tr>
<tr>
<td>Computational Fluid Dynamics (Fluent)</td>
<td>CFD</td>
</tr>
</tbody>
</table>

- Common models available in commercial packages
- Models available in PIPESIM at LSU
- Include different model approaches (empirical, mechanistic, CFD)
**Comparison and Exp. Data and Flow Model Results**

- **Duns & Ros**
  - Bubble
  - Slug

- **GOVIER, AZIZ, and FOGARASI**
  - Bubble
  - Slug
  - Transition
  - Mist

- **Hagedorn & Brown Original**
  - All Slug flow for 4, 8 and 12 in ID

- **Mukherjee and Brill**
  - Bubble/Mist flow transition for 10" and 4" ID
  - Slug/Mist flow transition for 12" and 8" ID

- **OLGA**
  - Bubble
  - Slug

- **Orkiszewski**
  - All Slug flow for 4, 8 and 12 in ID

- **Beggs & Brill Original/Revised**
  - All Intermittent flow
Exp. Data and Flow Model Results for

- **DR**
- **NOSLIP**
- **ANS**
- **GAF**
- **HBO & HBRDR**
- **MB**
- **OLGA**
- **ORK**
- **BBO & BBR**

**Δp/Δz (psi/ft):**

- **12 in (usl=0.6 ft/s)**
- **11 in (usl=0.5 ft/s)**
- **8 in (usl=0.7 ft/s)**
- **12 in (usl=0.6 ft/s)**

- **All Slug**
- **All Gas**
- **All Slug**
- **All Mist**

**Air superficial velocity, $u_{sg}$ (ft/s):**

- **Transition/Intermittent boundary for 8” ID**
- **Transition/Intermittent boundary for 12” ID**
Data points from: LSU (2016), Ali (2009), Zabaras et al. (2013)
Oh My God
I NEED A BREAK....
Comparison of Flow Models Applied to WCD (Task 2)
## Results for WCD Calculations for Different Wellbore Flow Models

<table>
<thead>
<tr>
<th>Fluid Sample</th>
<th>Reservoir depth (ft)</th>
<th>Reservoir pressure (psi)</th>
<th>Reservoir Temp. (°F)</th>
<th>GOR (scf/stb)</th>
<th>$p_{bp}$ (psi)</th>
<th>$\rho_o$ (API)</th>
<th>$\mu_o$ (cp)</th>
<th>PI (STB/D/psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>16,726</td>
<td>11,305</td>
<td>210</td>
<td>1,700</td>
<td>6,306</td>
<td>28</td>
<td>0.8</td>
<td>19.05</td>
</tr>
<tr>
<td>BO1</td>
<td>19,426</td>
<td>10,391</td>
<td>166</td>
<td>1,190</td>
<td>7,693</td>
<td>25.3</td>
<td>1.49</td>
<td>19.05</td>
</tr>
<tr>
<td>BO2</td>
<td>19,553</td>
<td>12,523</td>
<td>251</td>
<td>1,562</td>
<td>5,192</td>
<td>34.5</td>
<td>0.173</td>
<td>19.05</td>
</tr>
</tbody>
</table>

![Graph showing liquid discharge rate and bottom hole pressure for different scenarios](image)

- **Base Case**: Minimizes the liquid discharge rate and maintains the bottom hole pressure within acceptable limits.
- **BO1**: Higher liquid discharge rate compared to the Base Case, with a slight increase in bottom hole pressure.
- **BO2**: Lowest liquid discharge rate among the scenarios, accompanied by the highest bottom hole pressure.

The graph demonstrates the comparative performance of the different scenarios, highlighting the trade-offs between liquid discharge rate and bottom hole pressure.
### Effect of Fluid Type

<table>
<thead>
<tr>
<th>Fluid Sample</th>
<th>Reservoir measured depth (ft)</th>
<th>Reservoir pressure (psi)</th>
<th>Reservoir Temperature (°F)</th>
<th>GOR (scf/stb)</th>
<th>Oil gravity (API)</th>
<th>PI (STB/D/psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>16,726</td>
<td>11,305</td>
<td>210</td>
<td>1,700</td>
<td>28</td>
<td>19.05</td>
</tr>
<tr>
<td>VO3</td>
<td>14,374</td>
<td>11,009</td>
<td>261</td>
<td>3,803</td>
<td>42.1</td>
<td>19.05</td>
</tr>
</tbody>
</table>

![Graph showing liquid discharge rate for Base Case and VO3](image)

- **Base Case**
- **VO3**
Effect of Roughness [1]
Effect of Roughness [2]

Length fraction of Open-hole

- 0
- 0.25
- 0.5
- 0.75
- 1

Liquid discharge rate (Mstb/d)

ANS  BBO  BBR  DR  GAF  GRAYM  GRAYO  HBO  HBRDR  MB  NoSlip  ORK  OLGA
Results for Flow Regime Prediction for Base Case
Final Remarks

✓ We have done a significant amount of work in 12 months. 😊😊

✓ Pipe diameter has a significantly smaller effect on the pressure gradient for ID over 4 inches than in pipe diameter smaller than 4 inches.

✓ Most flow models show better results for the 4-inch diameter pipe than for larger diameters.

✓ Flow models and laboratory experiments discrepancy is likely caused by the use of the slug flow regime, instead of churn flow (which is observed experimentally)
Final Remarks

✓ Different methods may be suggested for different fluid and flow conditions, making the recommended practice field specific depending on reservoir and fluid properties.

✓ Variation of reservoir fluid properties ($p_{bp}$, GOR, $\rho_o$, $\mu_o$) has a relatively small effect (up to 10%) on WCD rate estimates for black oil and volatile oil reservoirs, for the well conditions examined.

✓ Further investigations of benchmarking and calibration of exiting WCD models against representative field and fluid WCD conditions is needed!

✓ Based on preliminary comparisons, significant improvement can be achieved on wellbore flow models for WCD calculations.
Suggestion for Future Projects

- Five-year Research Plan (LSU WCD Group)

“*To foster safety on the development of new oil and gas reserves in the Gulf-of-Mexico*”

- Establish a WCD Research Center at LSU
- Organize a Industry Advisory Committee (IAC) for the WCD group
- Create a Priority List for topics to address challenges on WCD
- Organize a Joint-Industry-Project (JIP) on the validation and development of a Open-Source model for WCD calculations
- Create a Handbook/Manual/Standard and Training Courses for WCD calculations (standardization)
- Disseminate information from LSU WCD group among industry and regulatory agencies
Preliminary Priority List of Topics [1]

- Experimental work for large pipe diameters and inclined pipe! (No well is truly vertical!!!)

New design under development (Investment of ~$150,000)

Old Inclinable flow loop
Flow tests for different pressures and fluid types (fluids other than water and air)

- Industry investment already made of about ~$ 2,000,000
- Closed-loop that allow use of different fluid types (oil, gas, water, nitrogen...)
- Allow use of pressures up to 1,200 psi
- Allow tests with high-liquid rates (15,000 BBL/D) and high-gas rates (4 MMSCFD)
Preliminary Priority List of Topics [3]

- Development of a Flow Models dedicated to WCD calculations
- Development of a web tool to provide unbiased and accurate WCD calculations

Validation with 24 wells – Reinicke et al. (1987)

Validation with 12 wells – Facher and Brown (1963)