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

LSU

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

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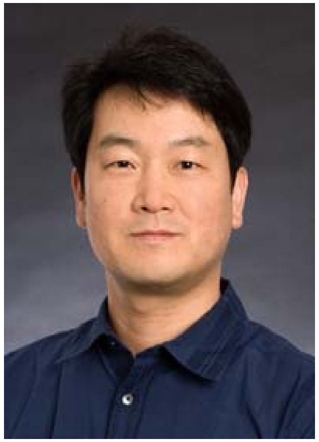

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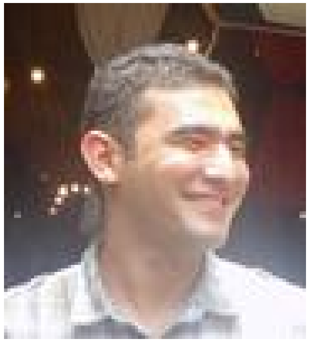

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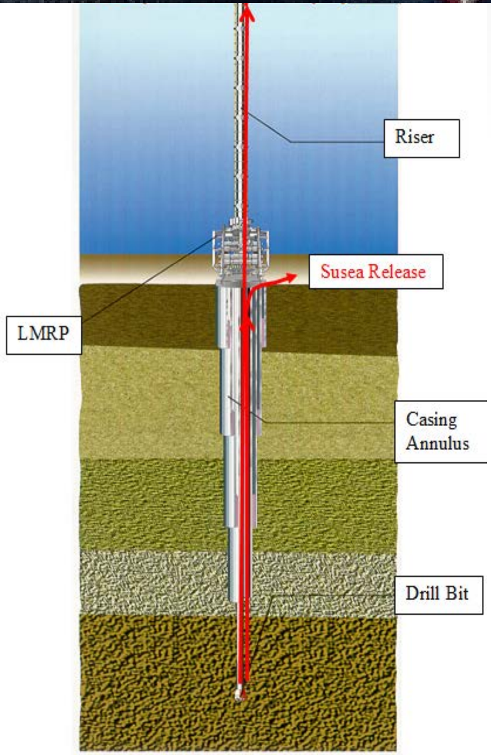
Outline

- ✓ 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**



Source: TAMU – Pemex Offshore Drilling

Project Motivation [2]

SPE International

SPE Technical Report

Calculation of

Worst-Case Discharge (WCD)

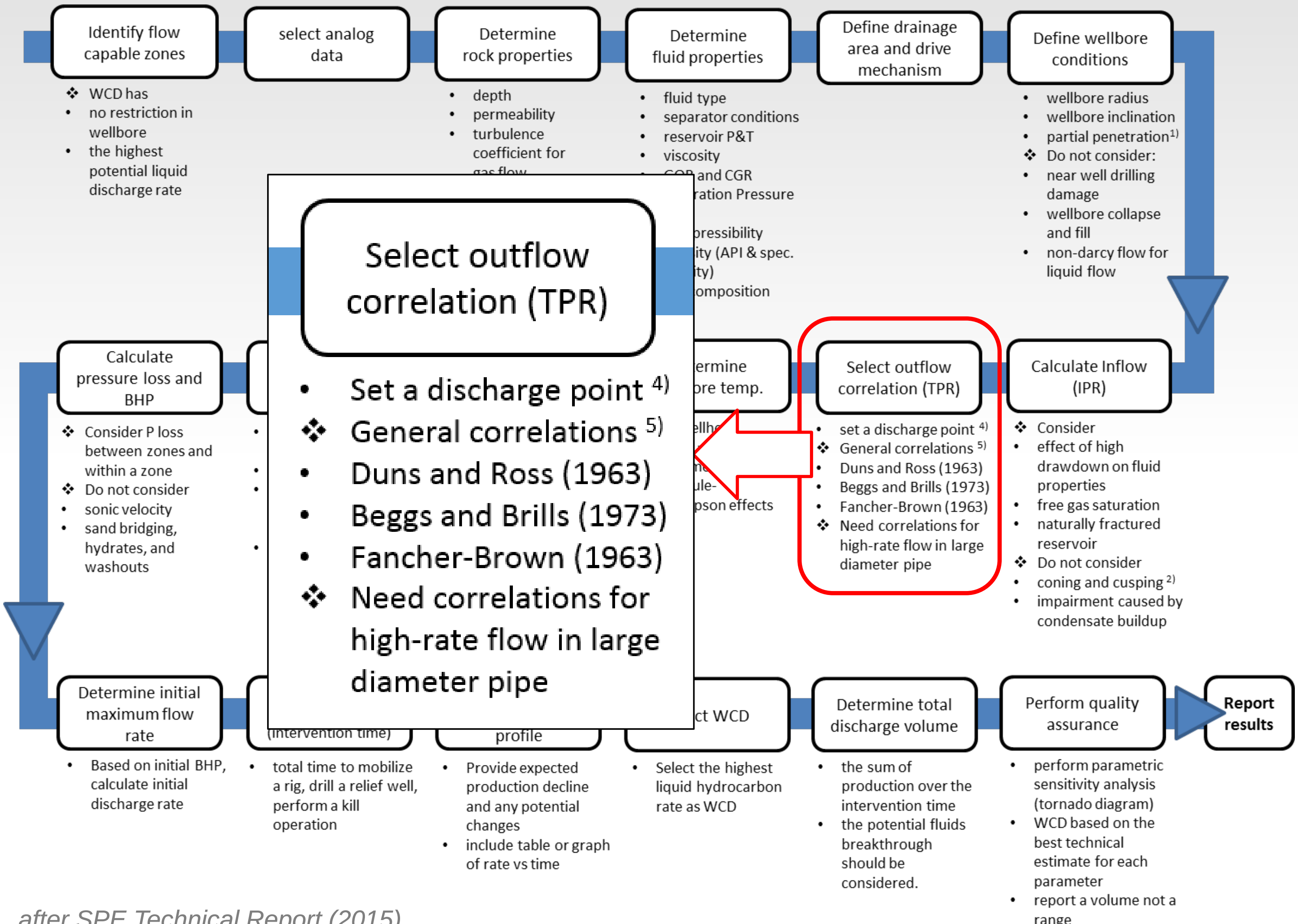
March 2015

This report represents the consensus viewpoints of subject matter experts and is intended to provide useful information to SPE members, the public, and the industry. It is not intended to take the place of advice on the application of technology to specific circumstances. Readers of this Technical Report are responsible for assessing its relevance and verifying its accuracy and their own choices, actions, and results. SPE and contributors to the Technical Report are not responsible for actions taken as a result of reading this document, nor the results of those actions.

"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.**"

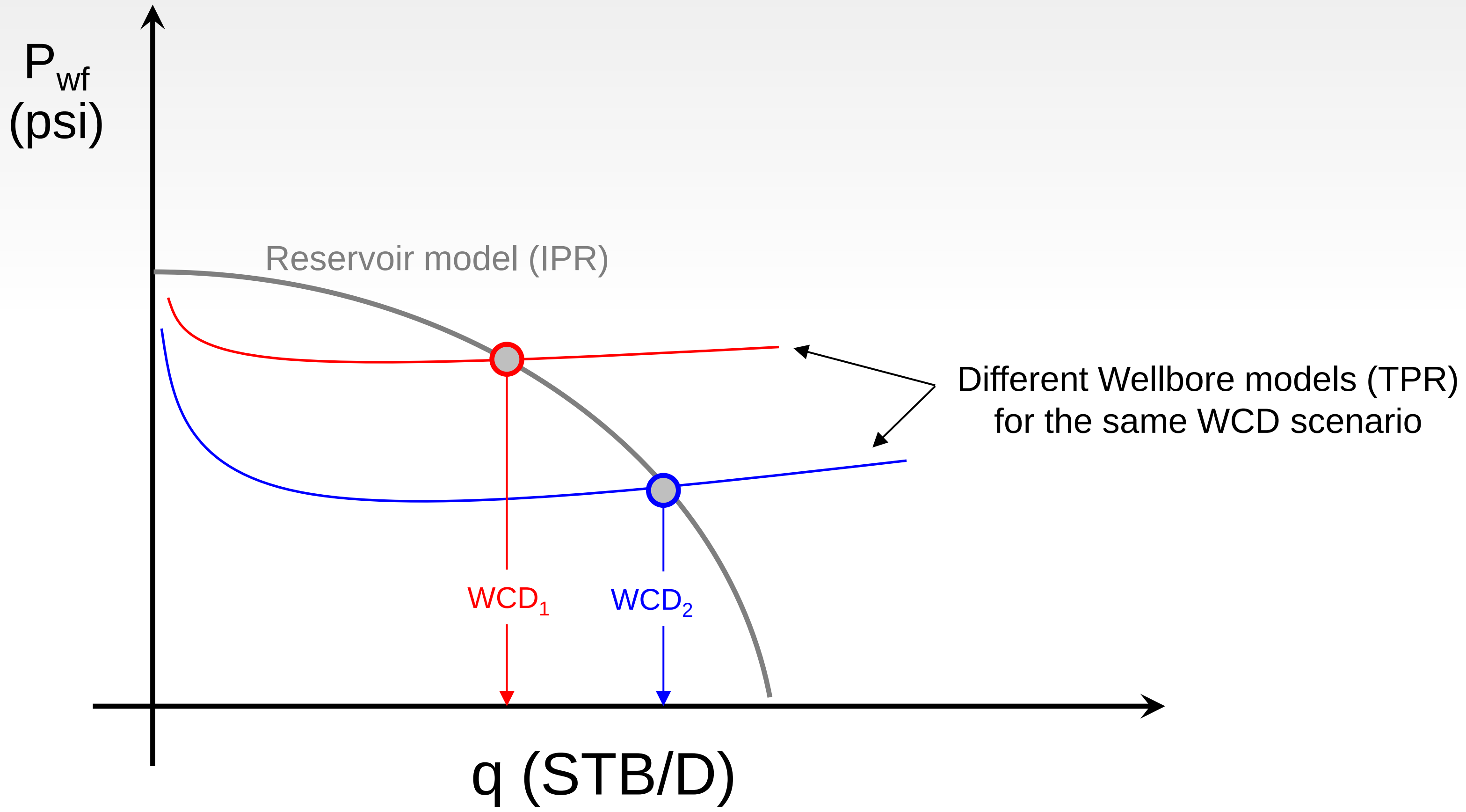
Statement of the Problem [1]



after SPE Technical Report (2015)

Statement of the Problem [2]

- **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} :

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

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

reservoir and fluid properties

- 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

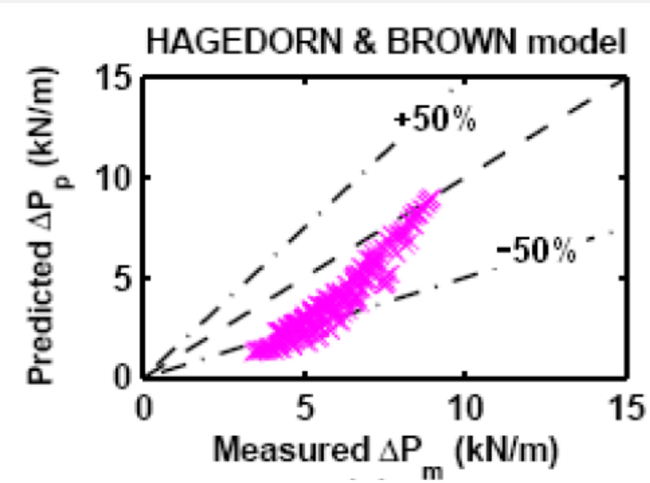
$$\frac{dp}{dz} = \frac{g}{g_c}\bar{\rho} + \frac{2f\bar{\rho}u_m^2}{g_c D} + \bar{\rho}\frac{\Delta(u_m^2/2g_c)}{\Delta z}$$

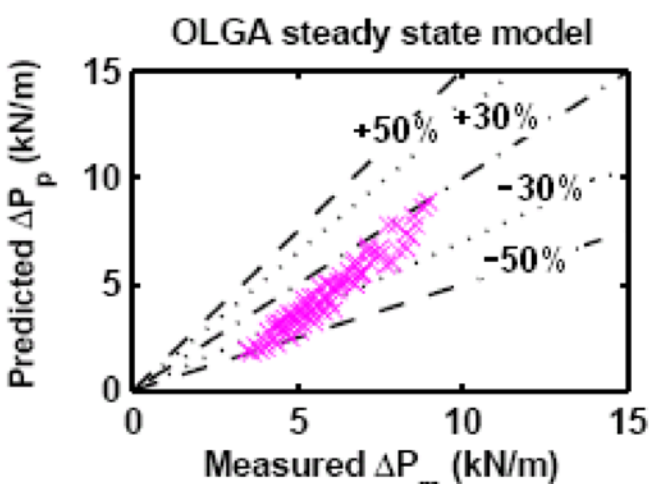
- Flow regimes
- Superficial velocities
- Pressure & temperature
- Fluid properties

Statement of the Problem [4]

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

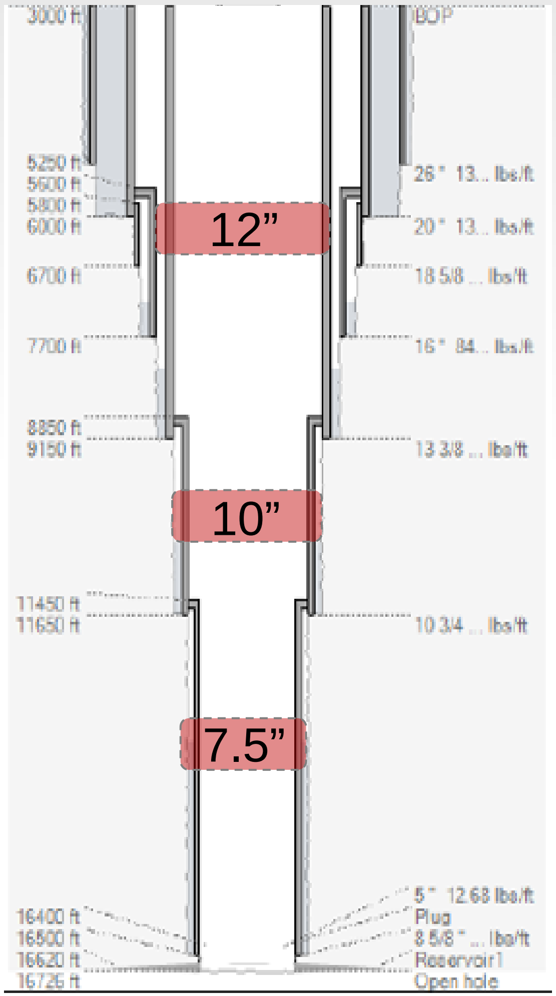
Two-Phase flow in a vertical pipe (ID = 10 in)





Ali (2009)

Well configuration for typical WCD calculation scenario



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)

Worst-Case-Discharge Vastly Under Studied

SPE 69530

A Study on Blowouts in Ultra Deep Waters

O.L.A. Santos, SPE, Petrobras

...stract

...is paper presents the preliminary results of a research ...ject on ultra deepwater blowouts. This research is a part of ...omprehensive study currently conducted by Petrobras, the ...azilian oil company, aiming at drilling and producing safely, ...terms of well control, in water depths as deep as 10000 feet ...proximately 3000 meters). Firstly, the paper presents a ...thematical procedure that predicts wellbore pressures and ...w properties during a gas blowout using an unsteady state ...del that considers the multiphase nature of the flow.

Wellbore and Near-Surface Hydraulics of a Blown-Out Oil Well

A.R. Clark, ARCO Oil and Gas Co.
T.K. Perkins, SPE, ARCO Oil and Gas Co.

Summary

A method is p... flow velocity, p... a blown-out oil... wellbore geom... wellbore and ... knowledge or e... (PI) and gas/o... given for estima... the two-phase ... above the well c...

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Flow rate and total discharge estimations in gas-well blowouts

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A R T I C L E I N F O

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Available online 1 July 2015

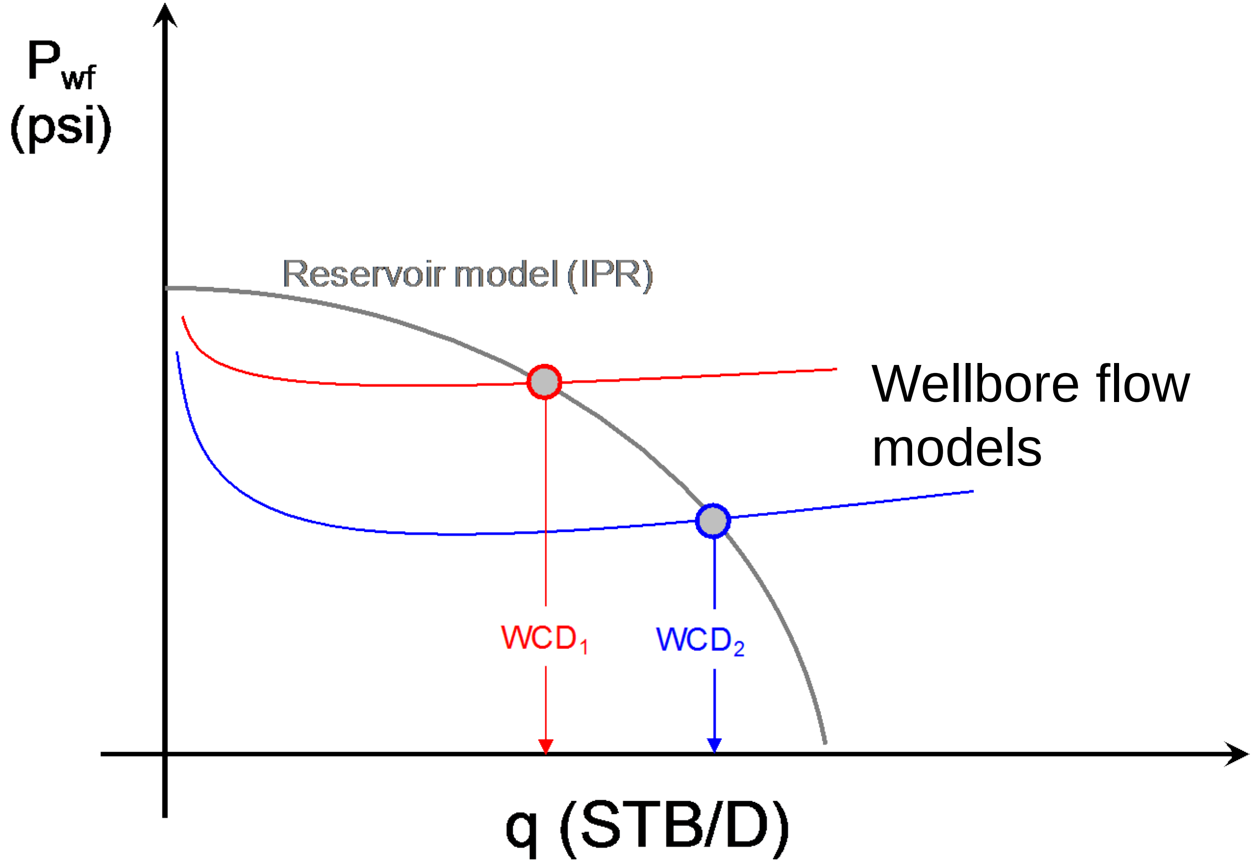
Keywords:
Total discharge in blowouts

A B S T R A C T

Despite multitier safeguards in any drilling operation, blowouts do occur. ... place, the total discharge of hydrocarbons becomes the focal point for a... operator, the service provider, and the regulatory body. Rate estimation be... scant information about the formation and fluids at the time of the acciden... guidelines require such estimates for any offshore drilling, systematic inves...

This study presents an analytical model coupling the flow in a reservoir/w... The model considers flow in the tubing, annulus and riser, and the atte... formulation/wellbore system. To gauge safety concerns, a commercially ...

BOEM'S ENGINEERING WORKFLOW



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

Generate WCD Rate

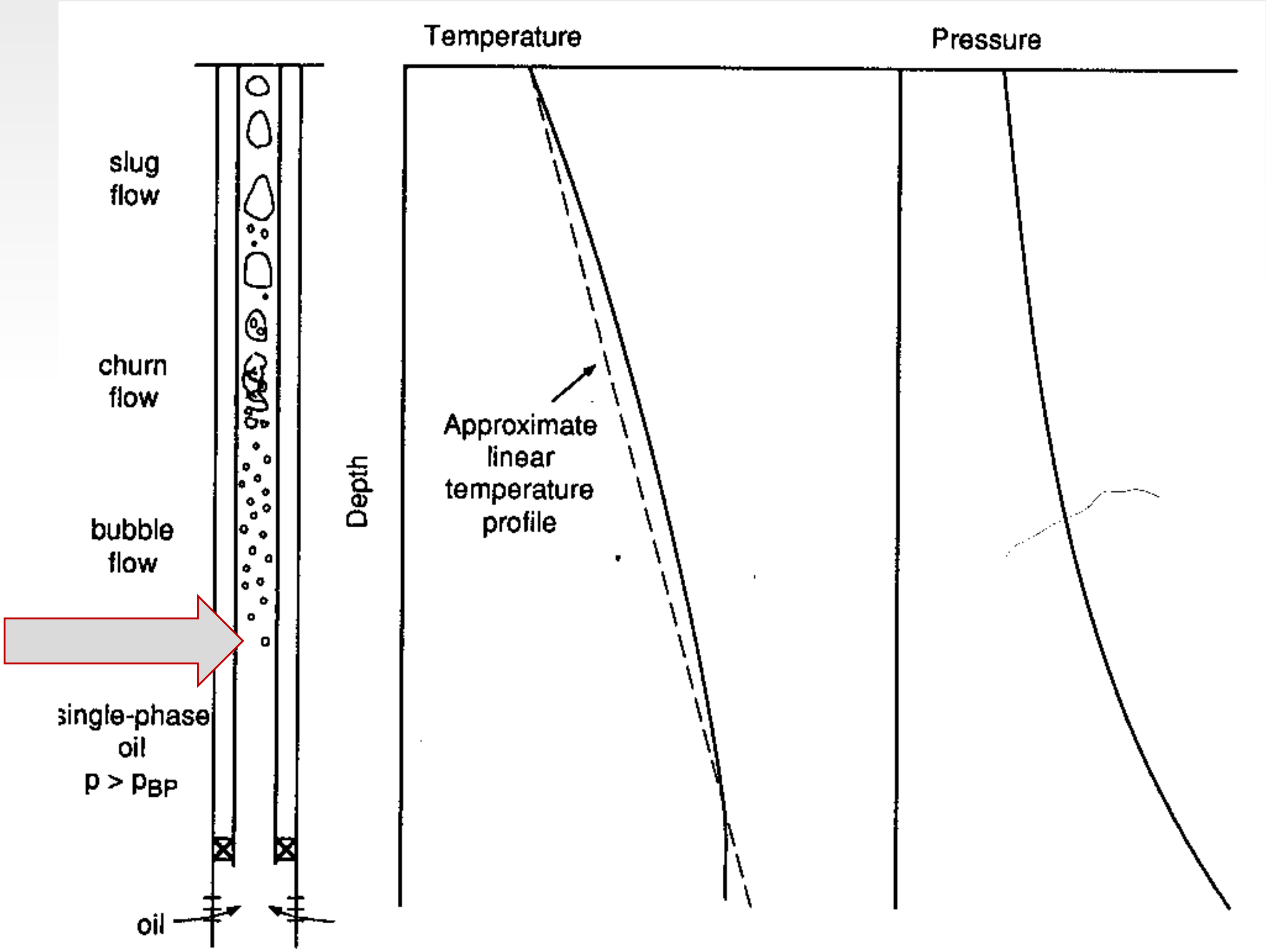
BOEM, 2015, Worst Case Discharge Program Overview, Office of Resource Evaluation Reserves Section, presentation slides

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

Correlation	Fluid	Pipe ID (in)	Pipe length (ft)	liquid rate (bbl/d)	Gas rate (Mscf/d)	Fluid properties	Degree From horizon
Poetmann and Carpenter (1952)	Oil/gas, gas/oil/water	2, 2 ½, 3	1,100-11,000	5 - 1,400 (oil)	18 -1,630	30°-54° API; 0.6-1.15 Gas SG 0.2<GOR<41 Mscf/bbl	90
Baxendell and Thomas (1961)	Gas/oil	2 7/8 , 3 ½	6,250	200-5,100 (oil)	N/A	Oil: 34° API, 2.58 cp at 160° F 120<GOR< 160 vol/vol	90
		1 5/8, 3 ½				Oil: 20°-40° API 1 – 300 cp	
Mukherjee and Brill (1985)	Air/oil	1, 1 ½	2 x 56	0-2,300	0-35	100<GLR<1320 scf/bbl	any angle
Asheim (1986) (Mona)	Tested with Forties field, Ekofisk field, and Prudhoe Bay flow line data points						0 to 90
Yao and Sylvester (1987)	Gas/water, oil/gas	compared with field data from Camacho (1970) and Reinicke and et al. (1984), Govier and Fogarasi (1975)					90
Ansari (1994)	Developed with data from TUFFP Databank						90
Petalas and Aziz (1996)	Verified against Stanford Multiphase Flow Database (SMFD)						any angle
Chokshi and et al.(1996)	Air/water	3 ½	1333	79-4250	42-2800	16<GLR<12685	90
	Evaluated with TUFFP						
Gomez et al. (2000)	Validated against TUFFP						any angle
OLGA-S 2000 S.S.	Used over 10000 data from SINTEF multiphase flow loop						N/A
LedaFlow	Used over 10000 data from SINTEF multiphase flow loop						N/A

Duns and Ros (1963)	1, 5/8, 3 ½, 6 in ID Vertical Pipe
Asheim (1986) (Mona)	Tested with Forties field, Ekofisk field, and Prudhoe Bay flow line data
Ansari (1994)	Developed with data from TUFFP Databank
Gomez et al. (2000)	Validated against TUFFP Databank
OLGA-S 2000 S.S.	Used over 10000 data from SINTEF multiphase flow loop

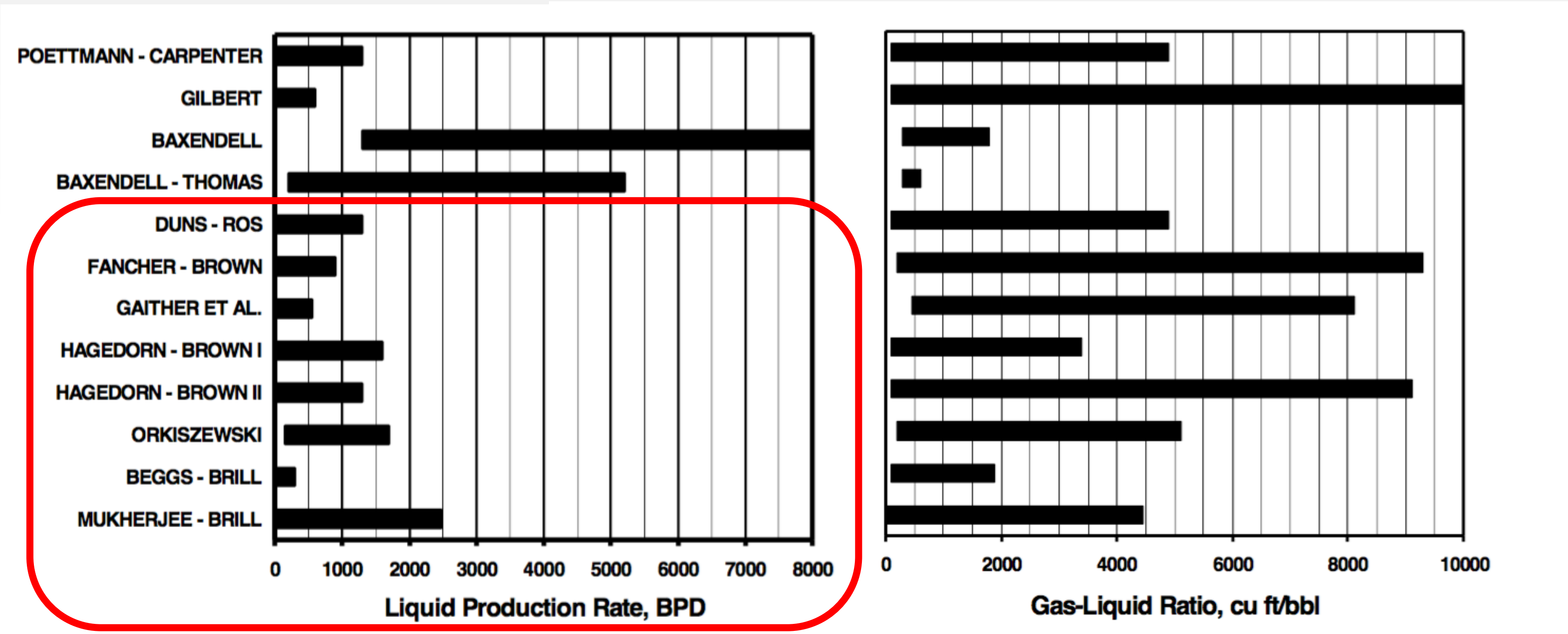
SOURCES OF ERRORS ON FLOW MODELS [3]

Review of Databases Used to Develop Flow Models

SINTEF multiphase flow loop (OLGA-S 2000 S.S.)	Nitrogen, Naphtha/ diesel, lube oil	8 in ID
TUFFP databank	Oil/gas/water	1-8 in ID
Forties field	Oil/gas	3.958, 6.185 in ID

Sources of Errors on Flow Models [4]

Review of Flow Rates Used to Develop Flow Models



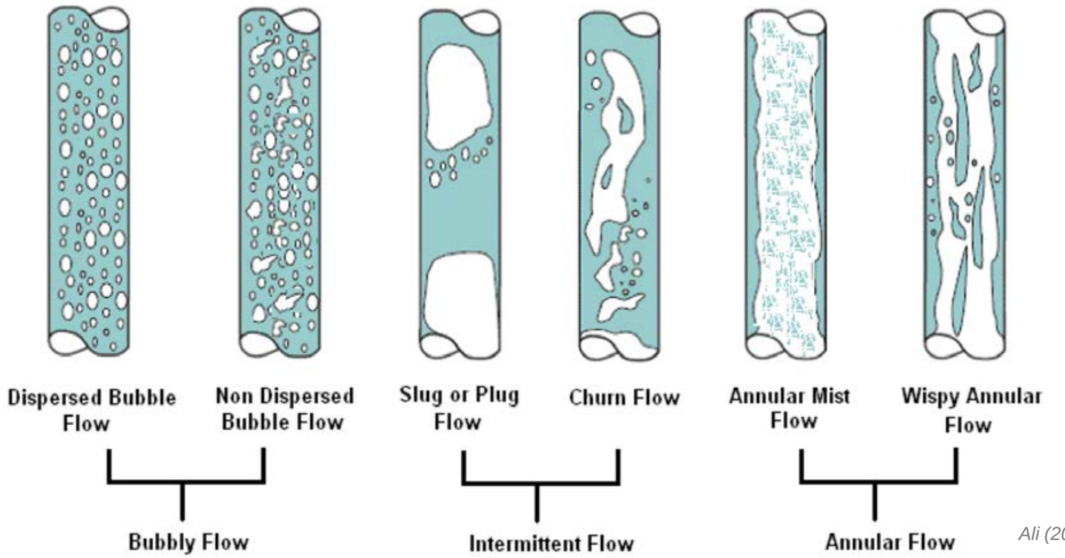
Q_l < 2,500 STB/D

Takacs (2001)

Sources of Errors on Flow Models [5]

Why Flow Regime Predictions are Important for WCD calculations?

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

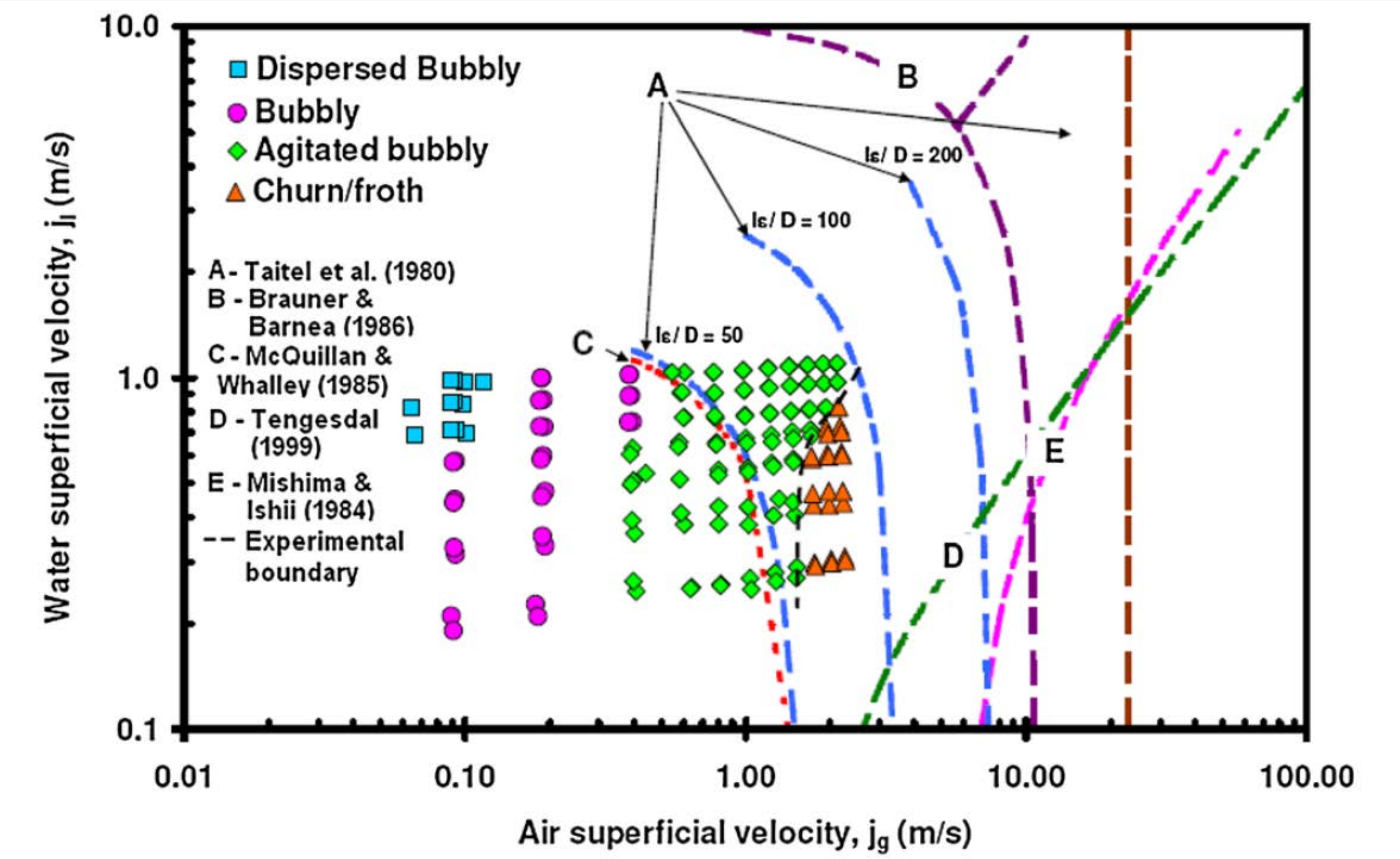


Ali (2009)

Flow Regime Maps for Large-Diameter Pipes

Ali (2009) - Experimental conditions tested

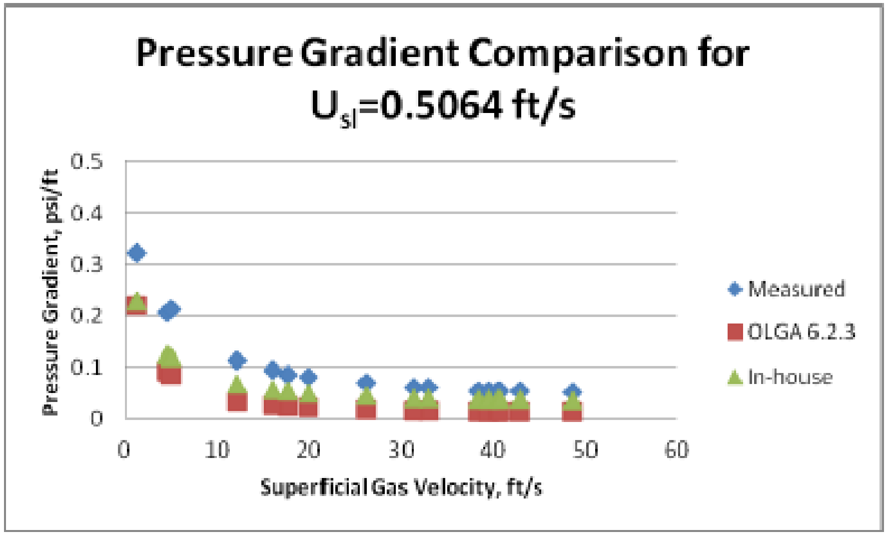
Study	Qo, BBL/D	Ql, GPM	ID, in	Usl, m/s	GLR, SCF/STB	Qg, MMSCF/D	Qg, SCFM	Usg, m/s
Ali	30,300	883	10	1.1	41	0.350	243	2.3

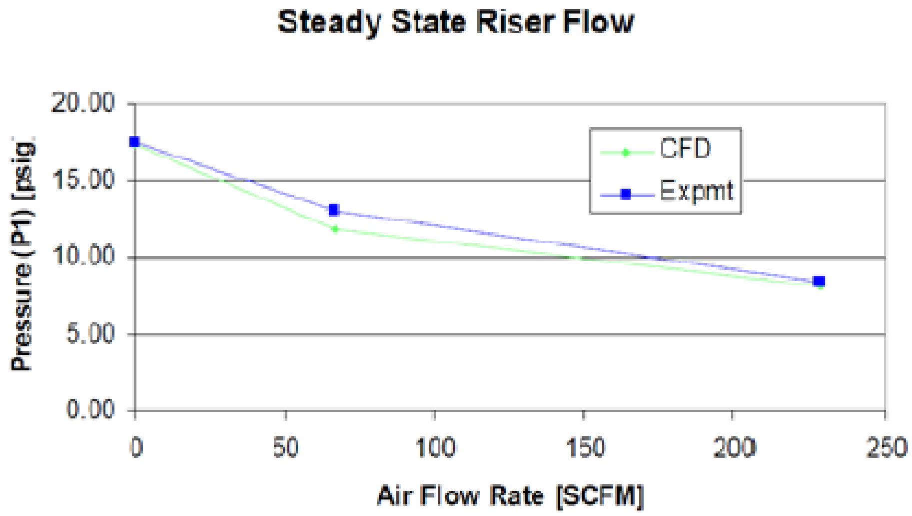


Evaluation of Using CFD models for Multiphase flow in Large Pipe Diameters

Zabaras (2013) - Experimental conditions tested

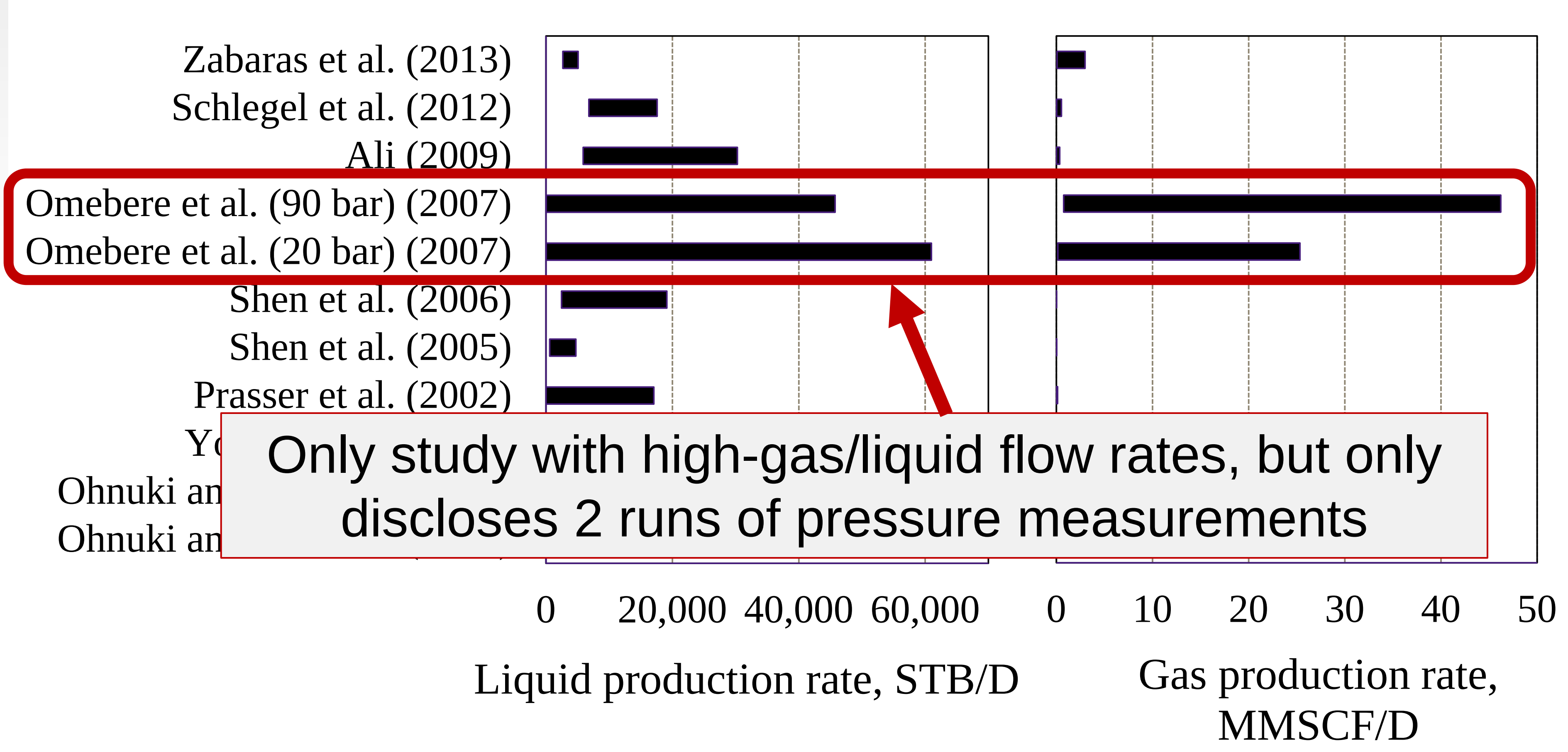
Study	Qo, BBL/D	Ql, GPM	ID, in	Usl, m/s	GLR, SCF/STB	Qg, MMSCF/D	Qg, SCFM	Usg, m/s
Zabaras	5140	150	11	0.15	2640	2.97	2063	15.9



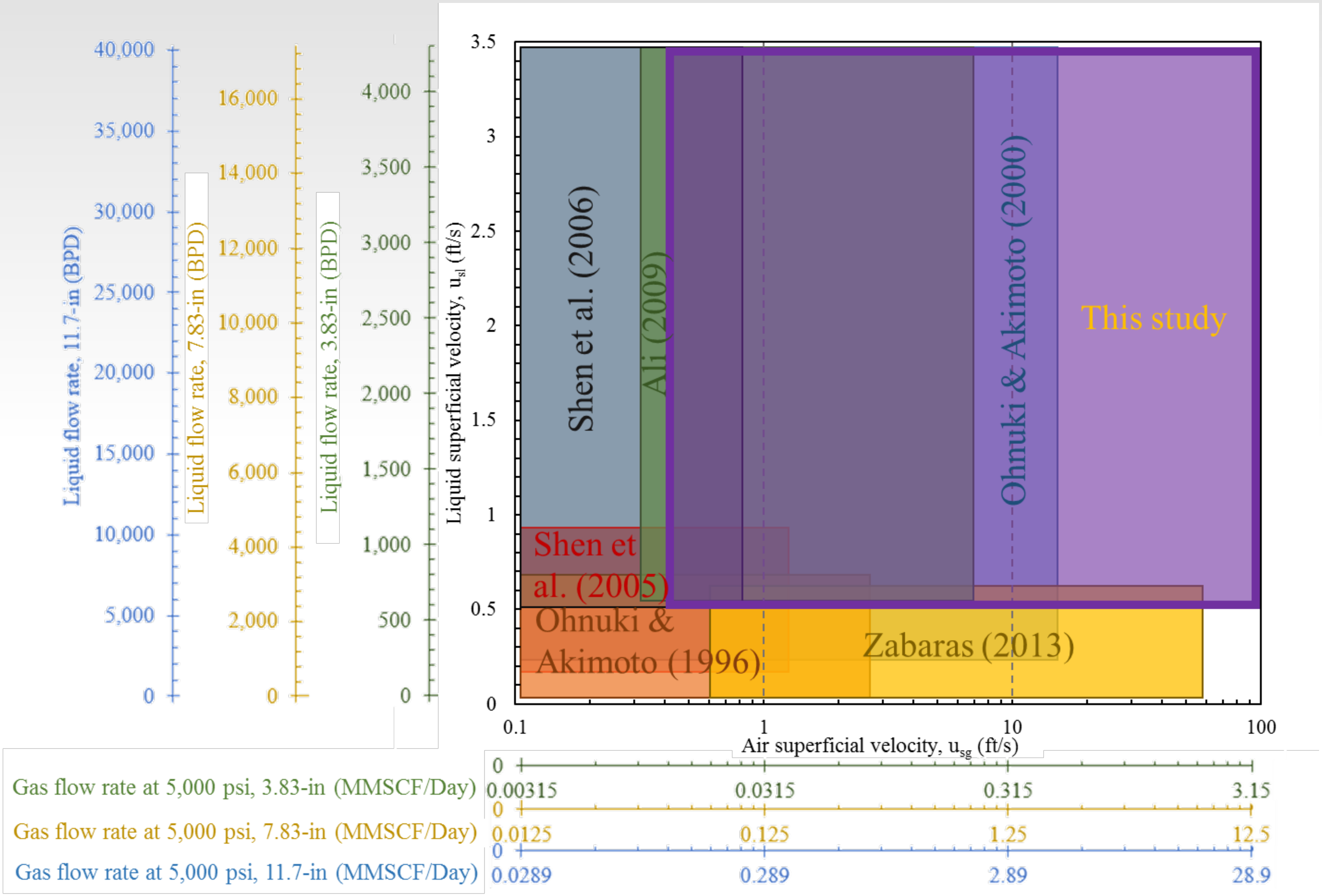


Gaps in Studies for Large-Diameter Pipes [1]

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



Gap in Studies for Large-Diameter Pipes [2]



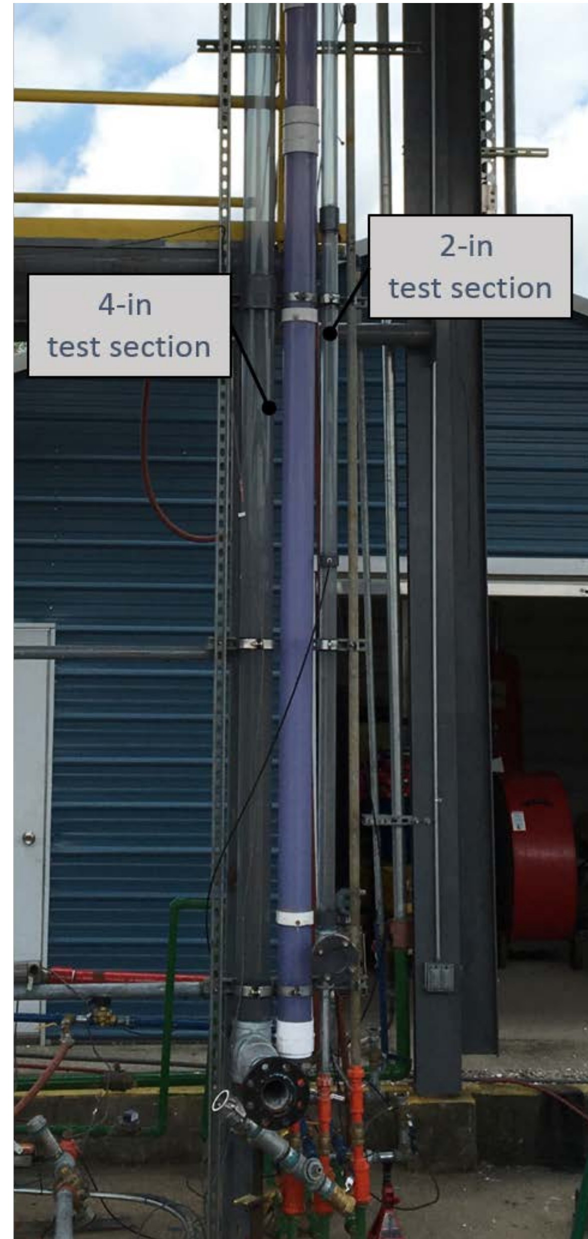
Conclusions from Literature Review

- **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

Thermocouple
Ball valve
Gate valve
Control valve
Check valve



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Pressure
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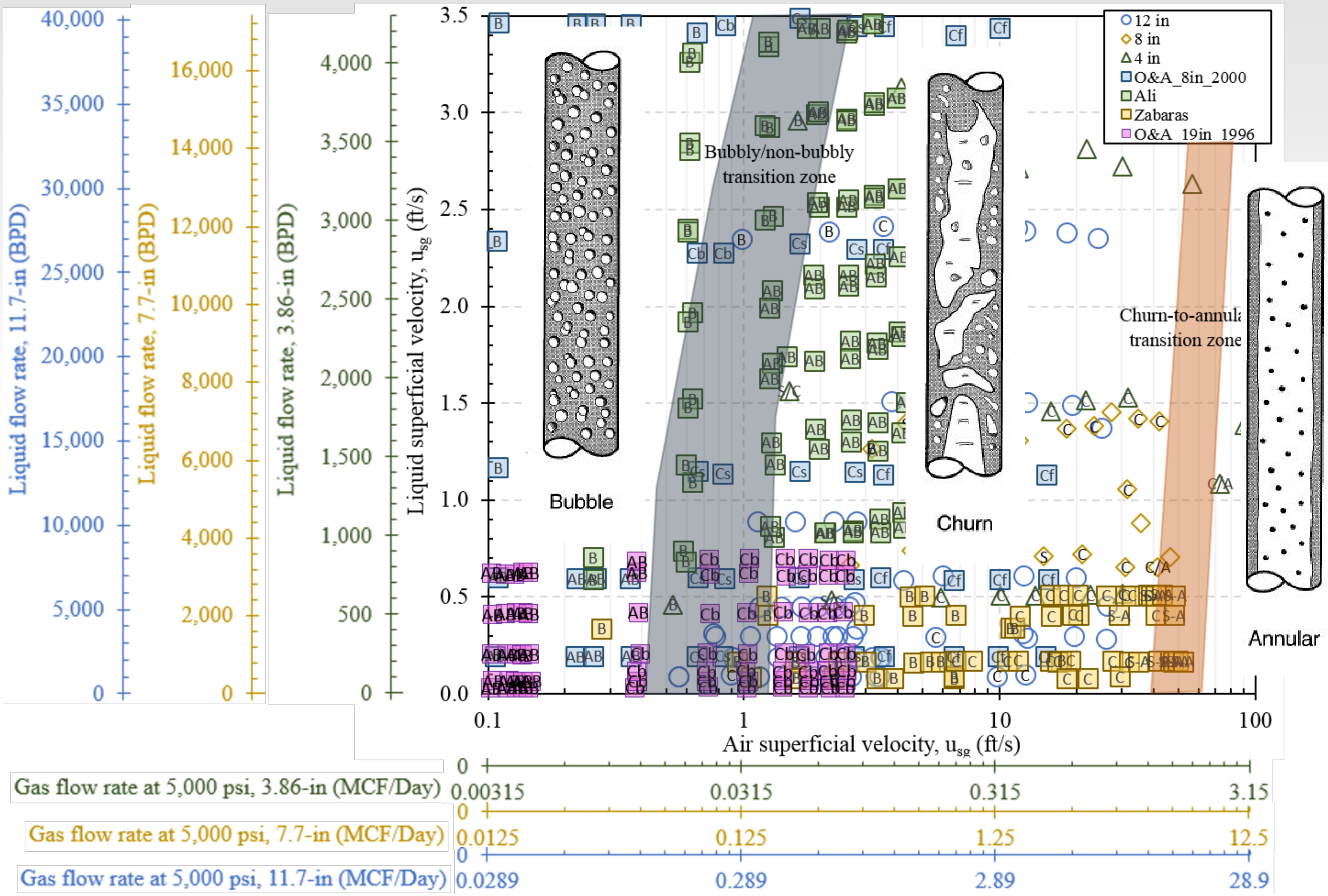
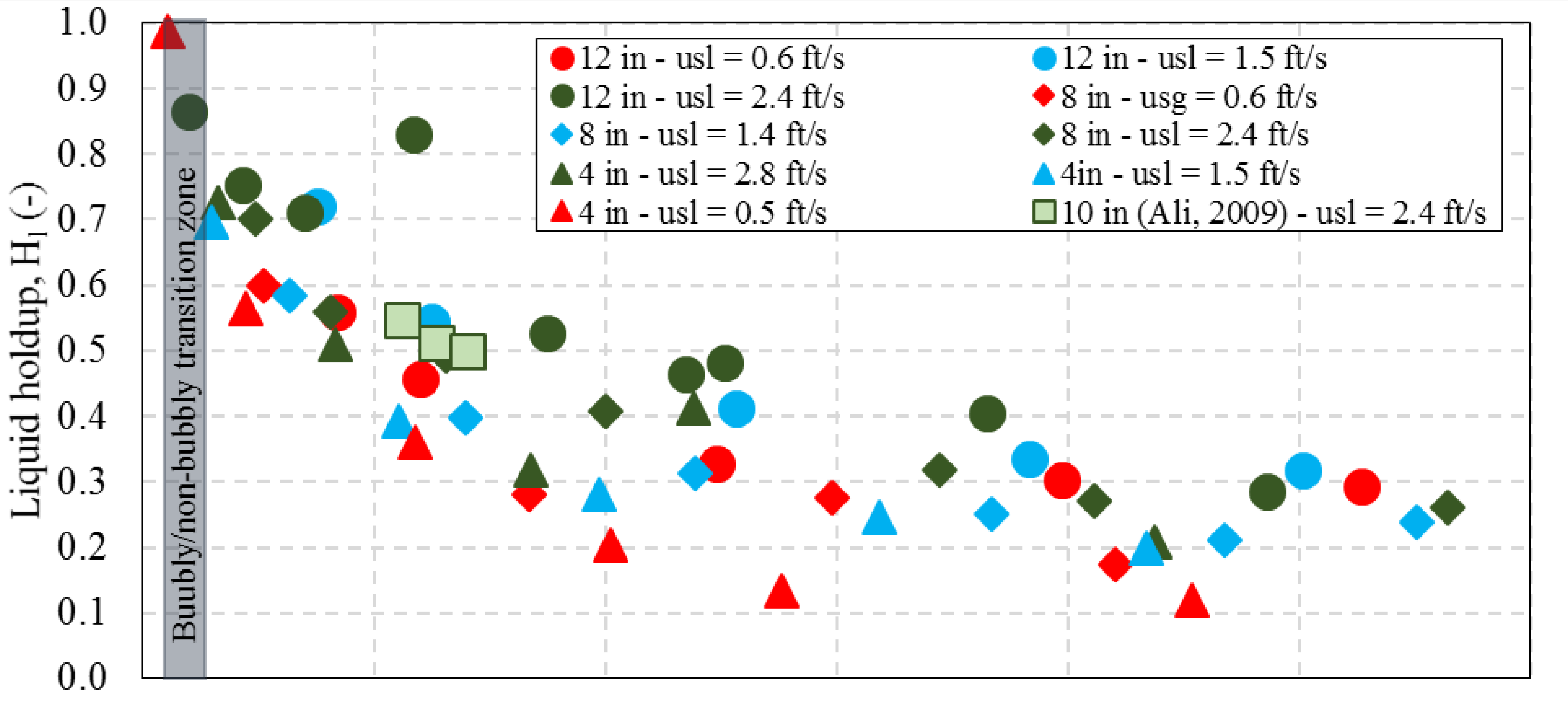
Flow Regime Observations [2]

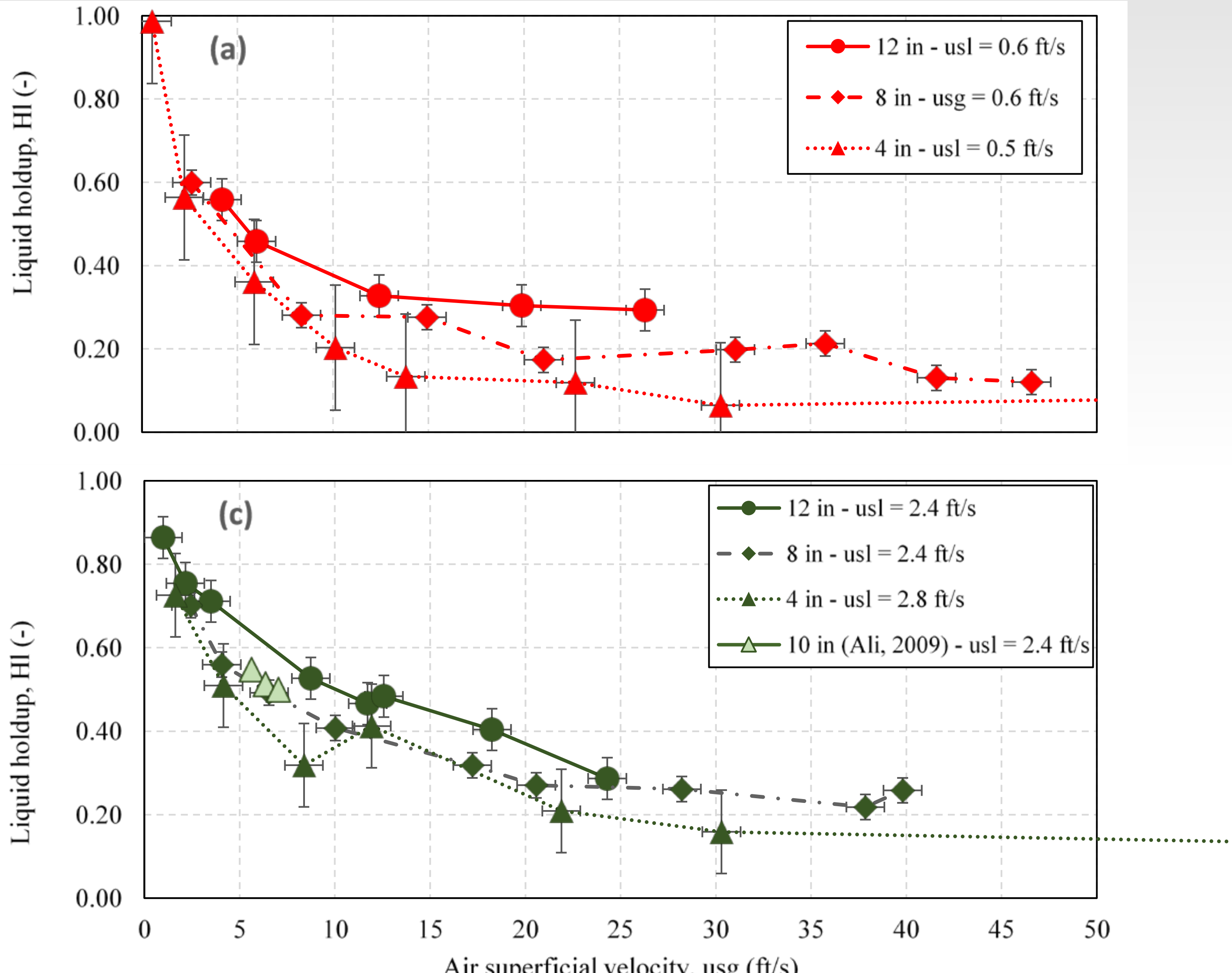


Liquid Holdup Measurements [1]

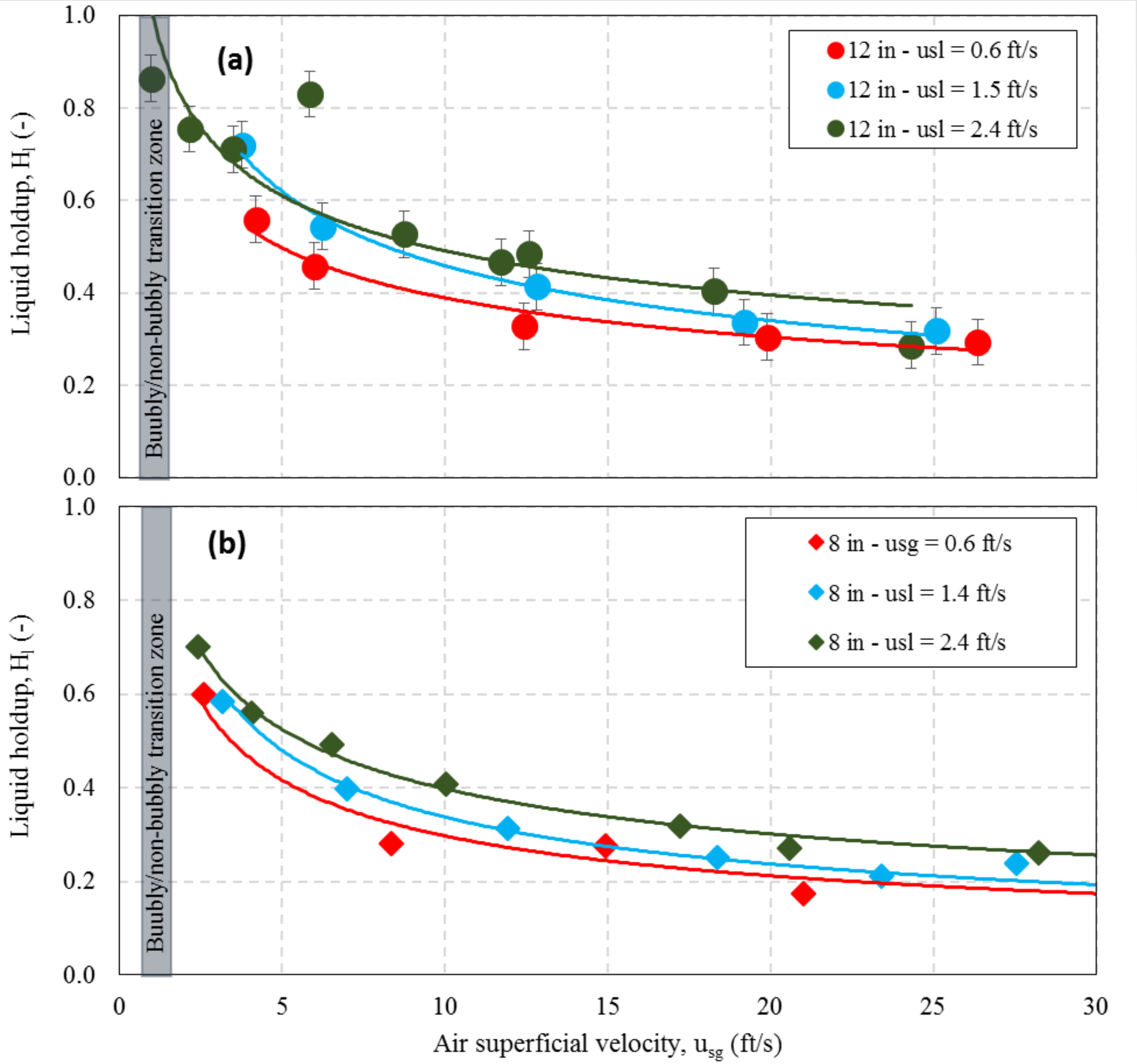


$$1.53\left[\frac{g(\rho_L-\rho_g)\sigma}{\rho_L^2}\right]^{0.25}(1-\alpha)^{0.5}sin(\theta)=\frac{u_{sg}}{\alpha}-1.2(u_{sl}+u_{sg})$$

Liquid Holdup Measurements [2]



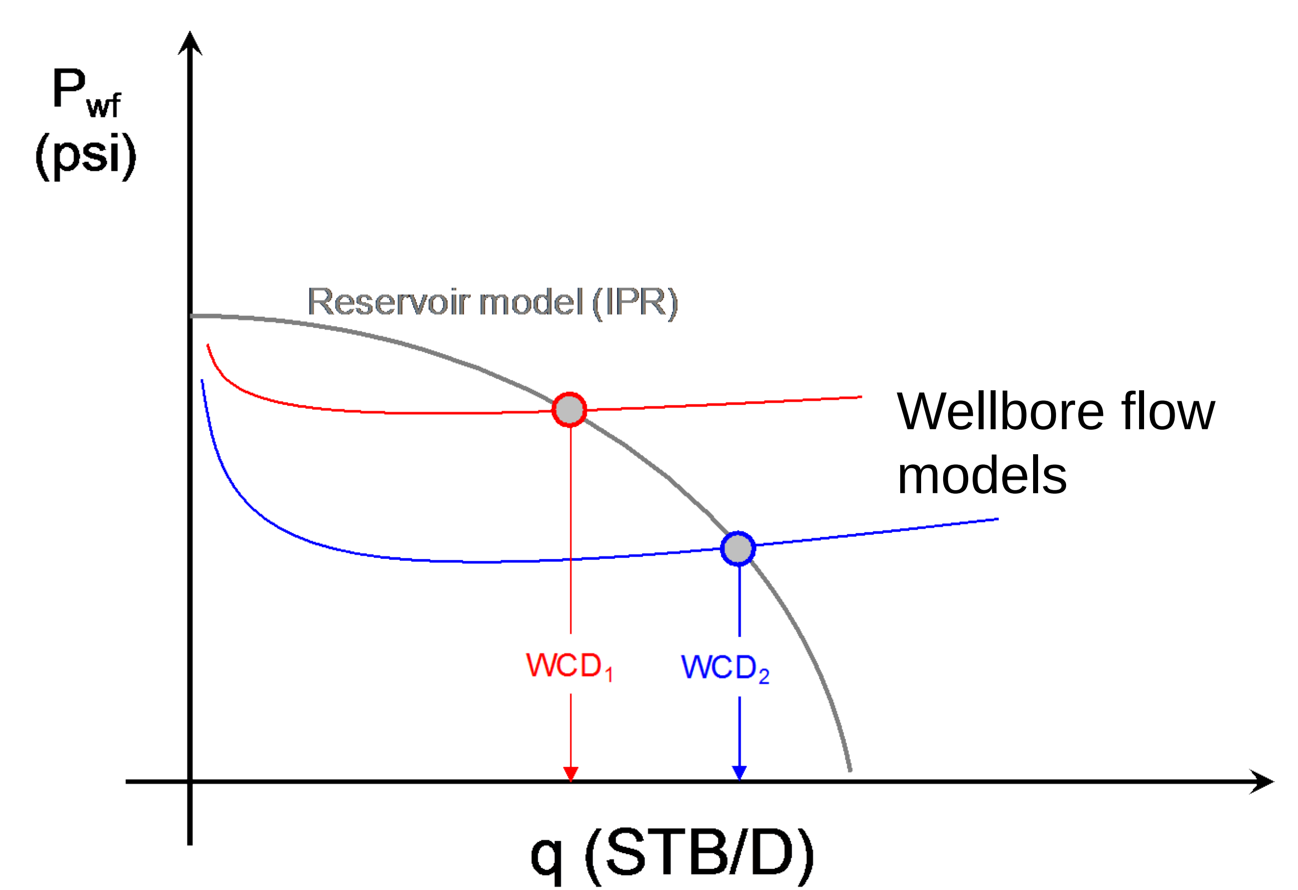
Liquid Holdup Measurements [3]



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

Δp/Δz Measurements [1]

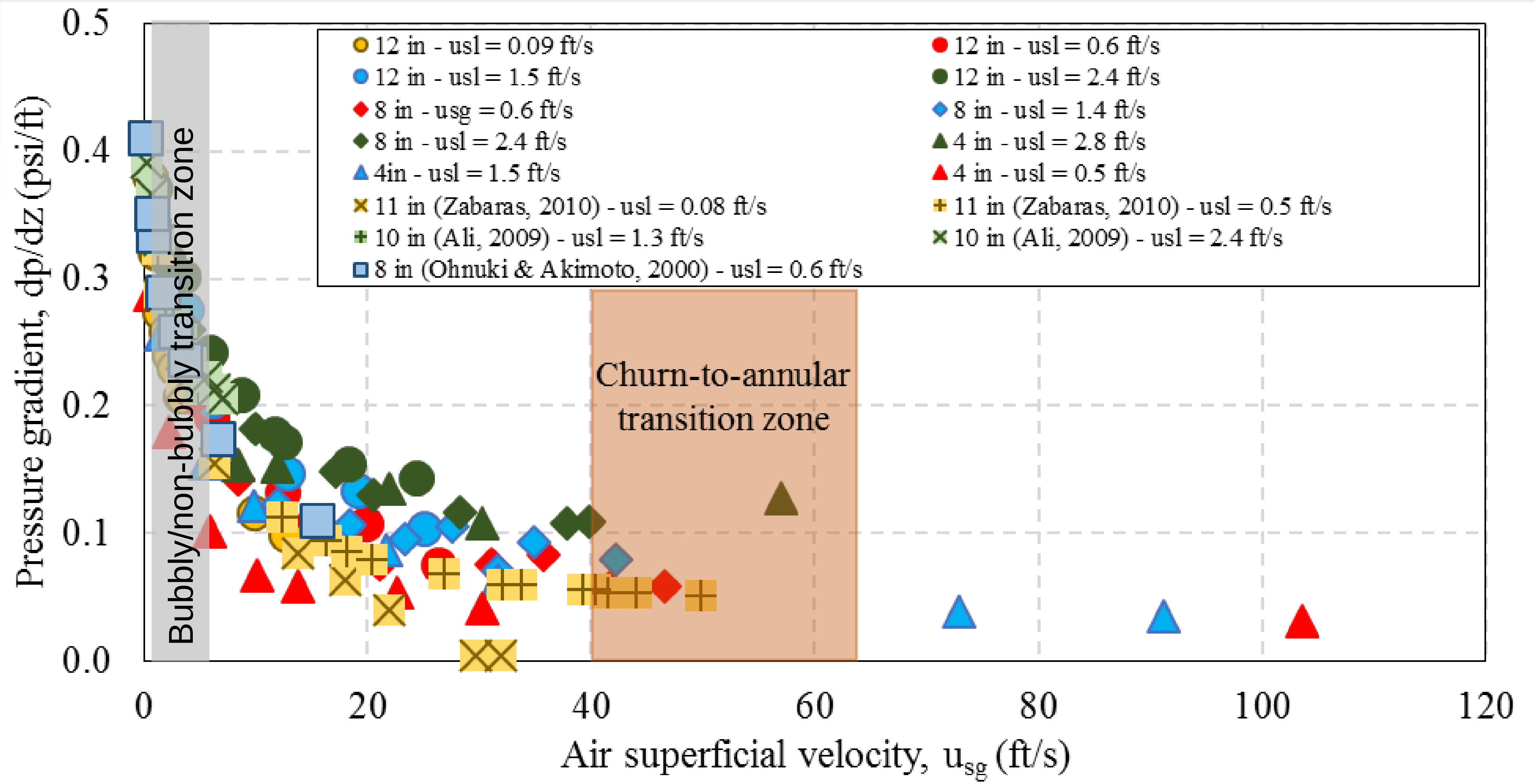
$$\frac{dp}{dz} = \underbrace{\frac{g}{g_c}\bar{\rho}}_{gravitational} + \underbrace{\frac{2 f \bar{\rho} u_m^2}{g_c D}}_{friction} + \underbrace{\bar{\rho}\frac{\Delta(u_m^2 / 2g_c)}{\Delta z}}_{acceleration}$$



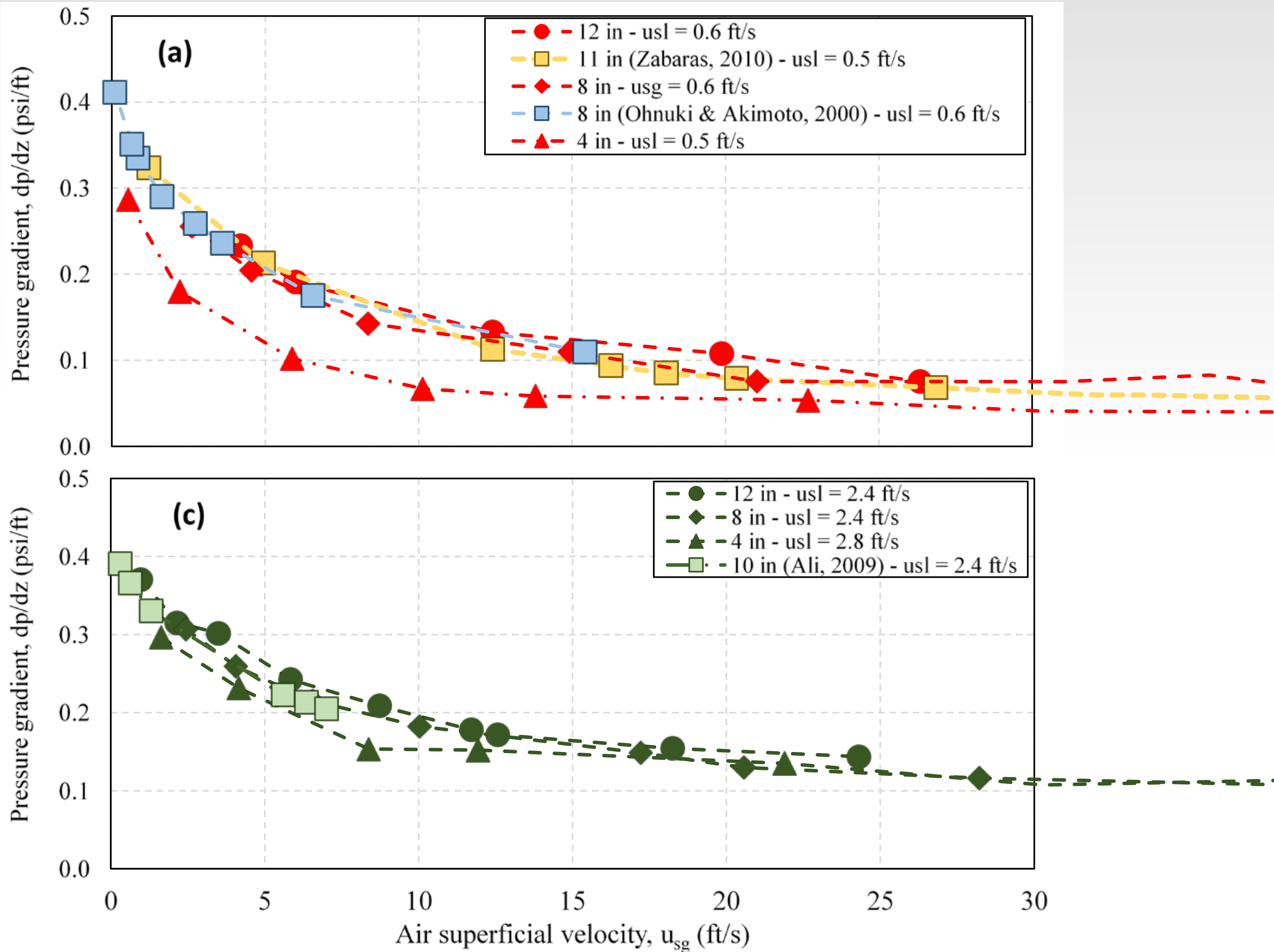
Δp/Δz Measurements [2]

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

$$\frac{dp}{dz} = \underbrace{\frac{g}{g_c}\bar{\rho}}_{gravitational} + \underbrace{\frac{2 f \bar{\rho} u_m^2}{g_c D}}_{friction} + \underbrace{\bar{\rho}\frac{\Delta(u_m^2/2g_c)}{\Delta z}}_{acceleration}$$



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, H_l 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**)

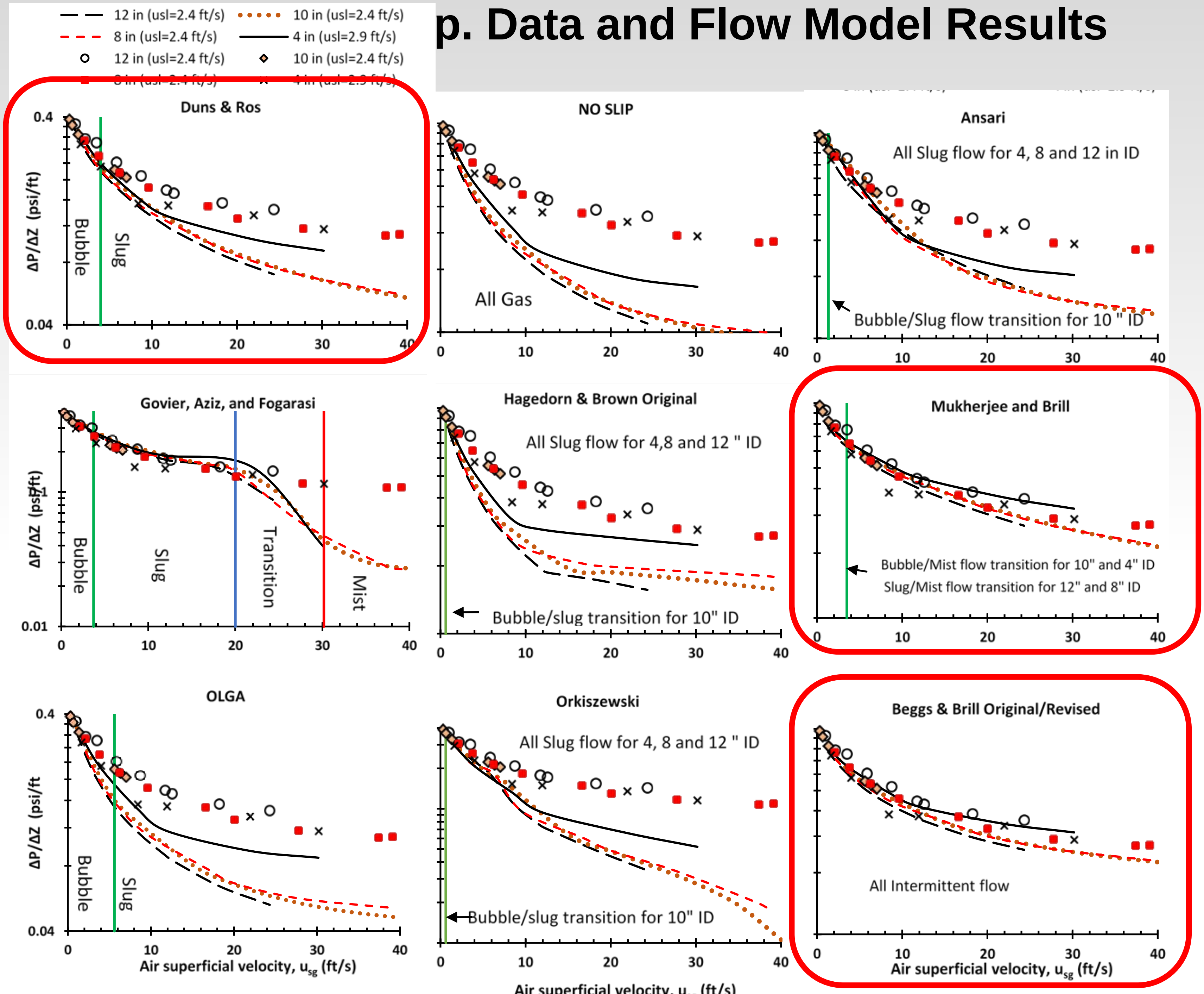
Evaluation of Flow Models with Experimental Data *(Task 6)*

Methodology for Comparison of Flow Models

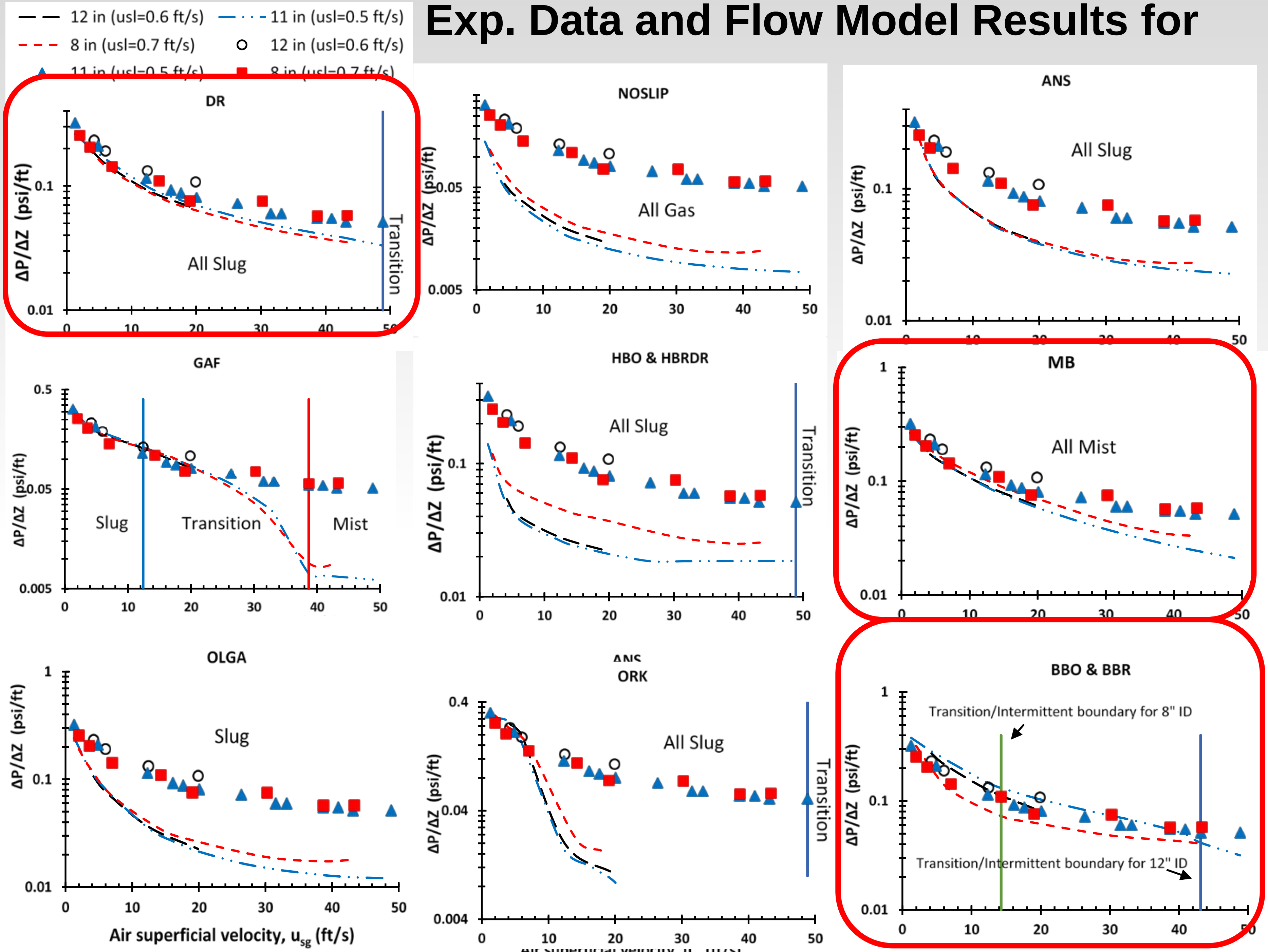
Wellbore flow model	Nomenclature
Ansari (1994)	ANS
Beggs and Brill (1973)	BB
Beggs and Brill Revised (1979)	BBR
Duns and Ross (1963)	DR
Govier, Aziz, and Fogarasi (1972)	GA
Gray Original (1974)	GO
Gray modified (PipeSim 2011)	GM
Hagedorn and Brown (1964)	HB
Hagedorn and Brown with Duns and Ross map (PipeSim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

- Common models available in commercial packages
- Models available in PIPESIM at LSU
- Include different model approaches (empirical, mechanistic, CFD)

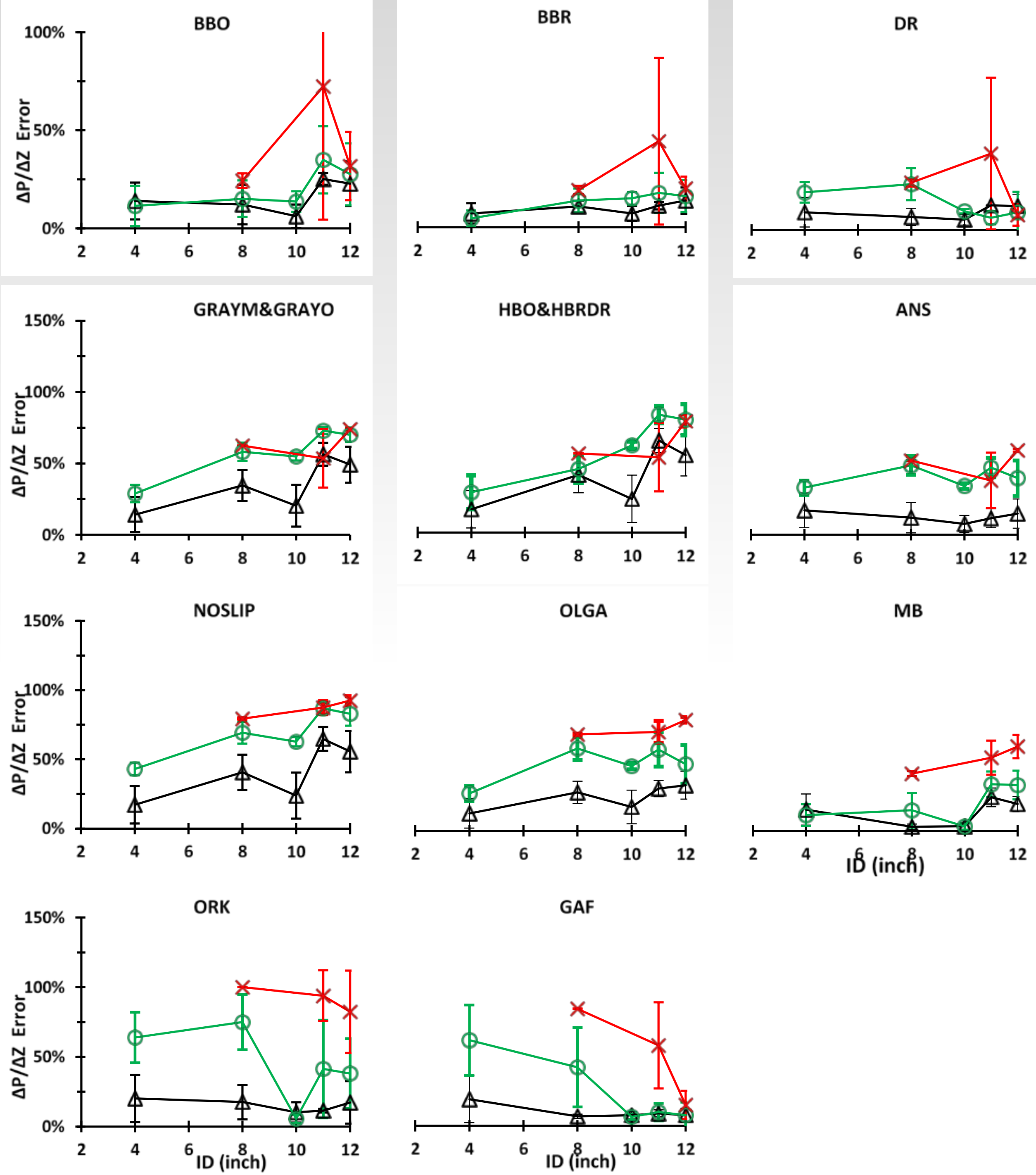
p. Data and Flow Model Results



Exp. Data and Flow Model Results for



Data points from:
LSU (2016), Ali (2009),
Zabaras et al. (2013)



$0 < \frac{u_{sg}}{u_{sl}} < 5$

$5 < \frac{u_{sg}}{u_{sl}} < 50$

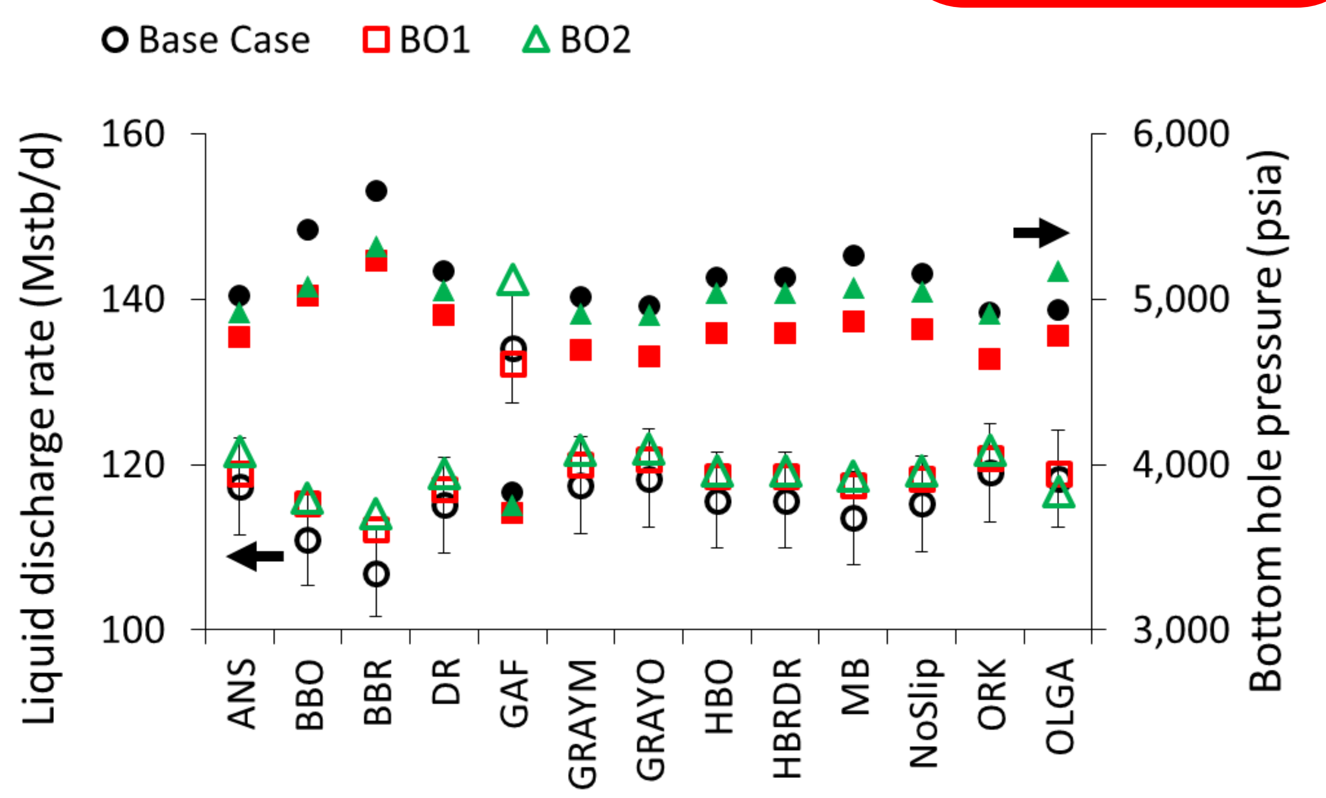
$50 < \frac{u_{sg}}{u_{sl}} < 500$


Oh My God
I NEED A BREAK ....
HEBA PHOTO 2008 WWW.HEBAPHOTO.COM

Comparison of Flow Models Applied to WCD *(Task 2)*

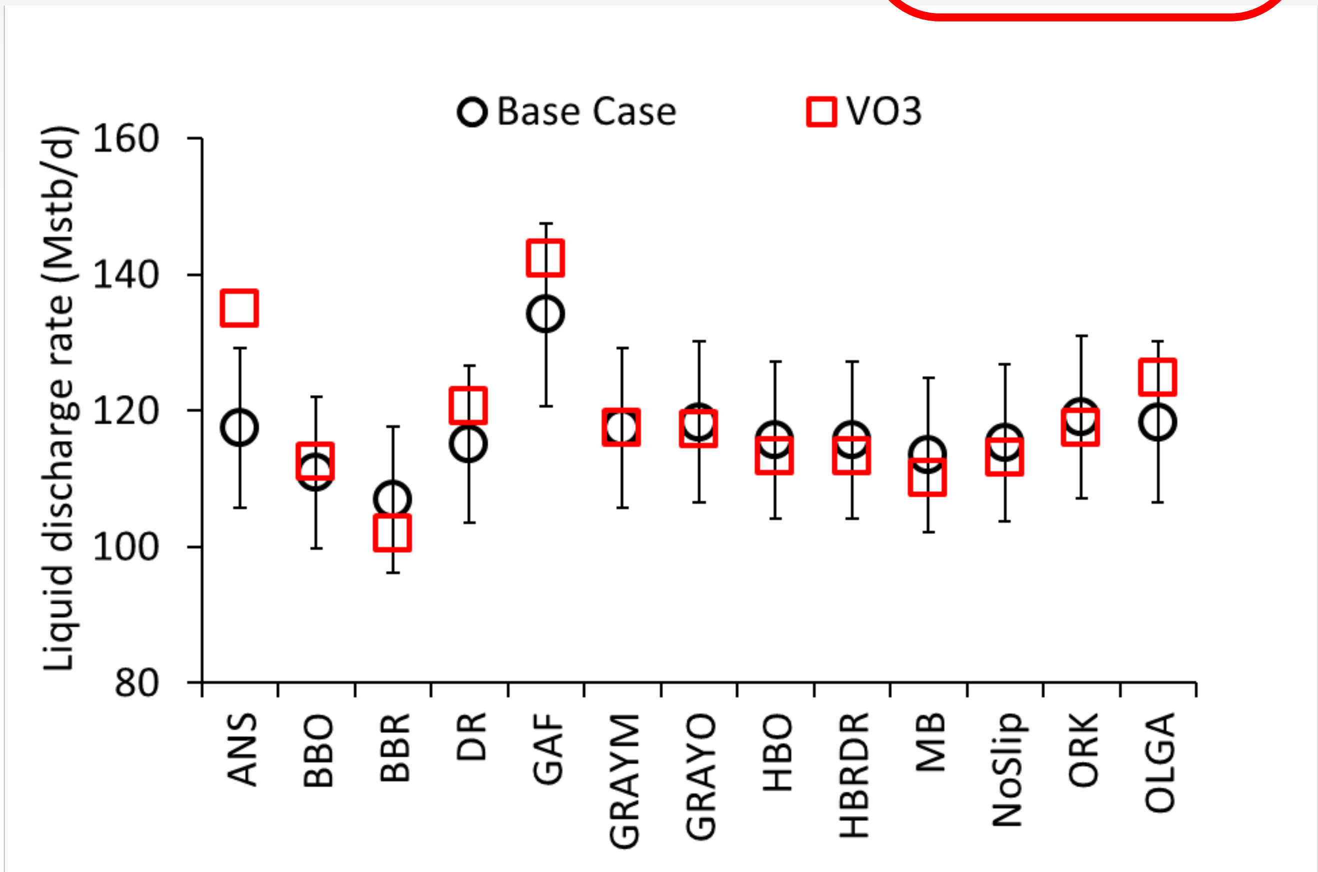
Results for WCD Calculations for Different Wellbore Flow Models

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

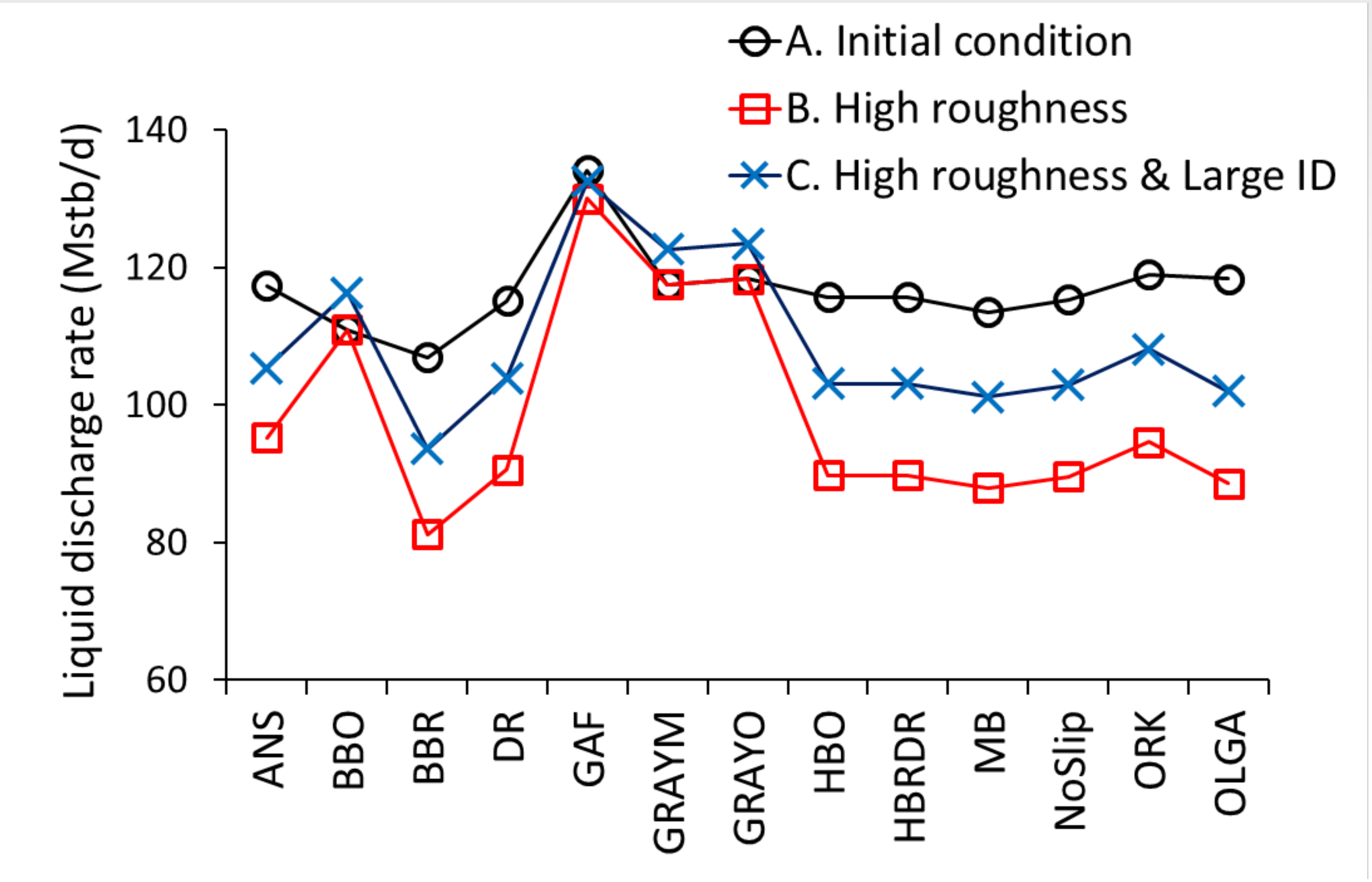


Effect of Fluid Type

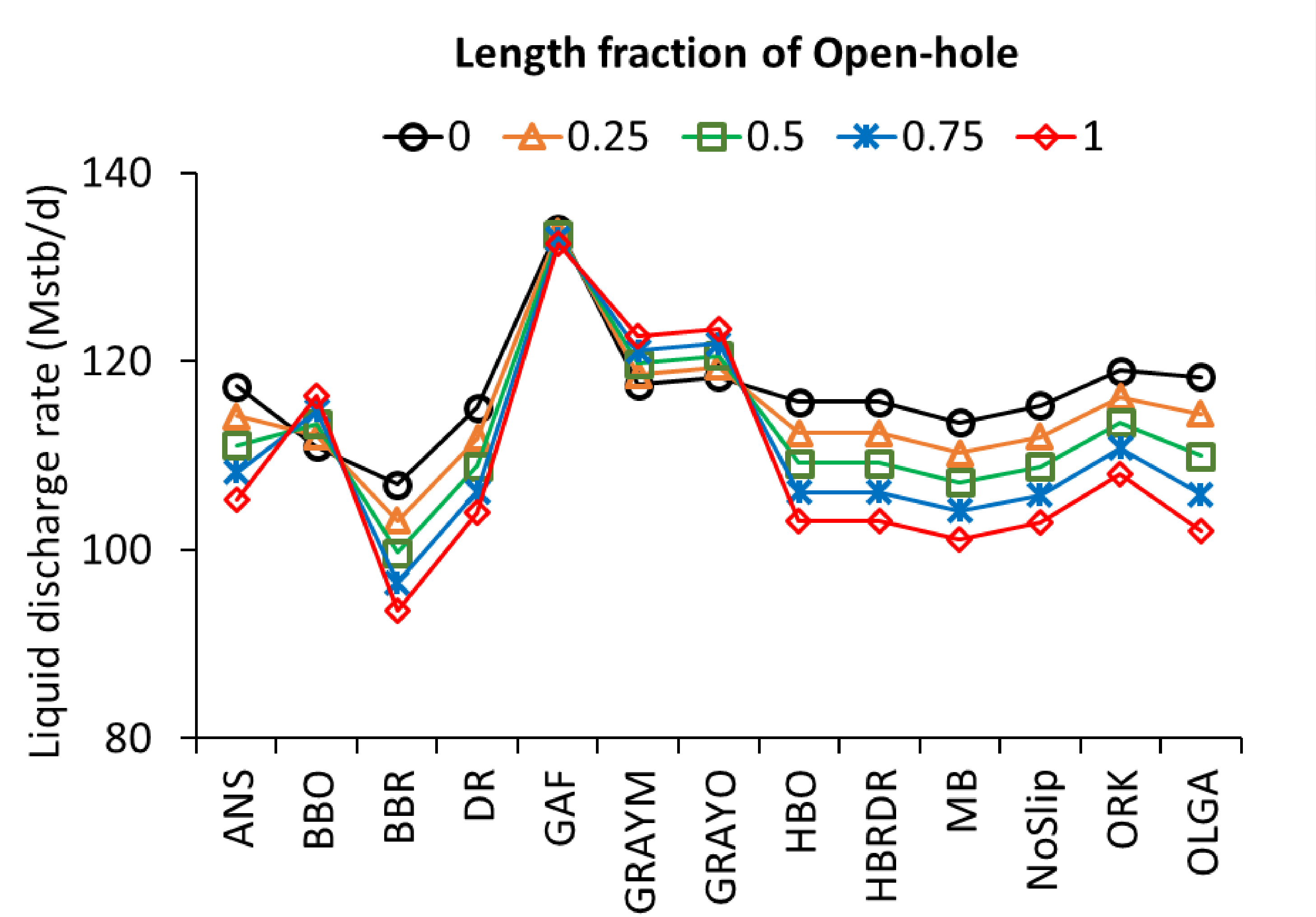
Fluid Sample	Reservoir measured depth (ft)	Reservoir pressure (psi)	Reservoir Temperature (°F)	GOR (scf/stb)	Oil gravity (API)	PI (STB/D/psi)
Base Case	16,726	11,305	210	1,700	28	19.05
VO3	14,374	11,009	261	3,803	42.1	19.05



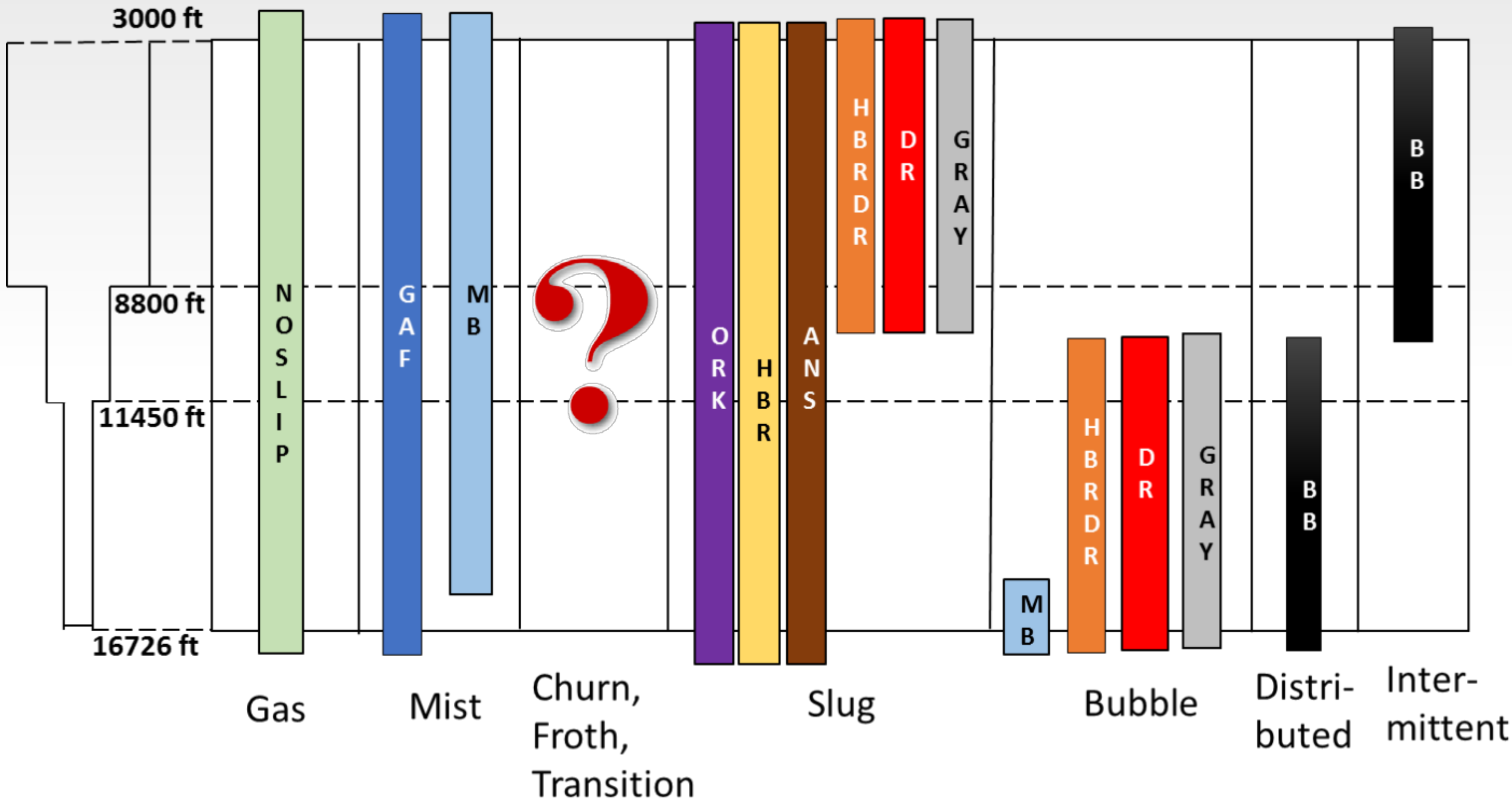
Effect of Roughness [1]



Effect of Roughness [2]



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, ρ_o, μ_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**

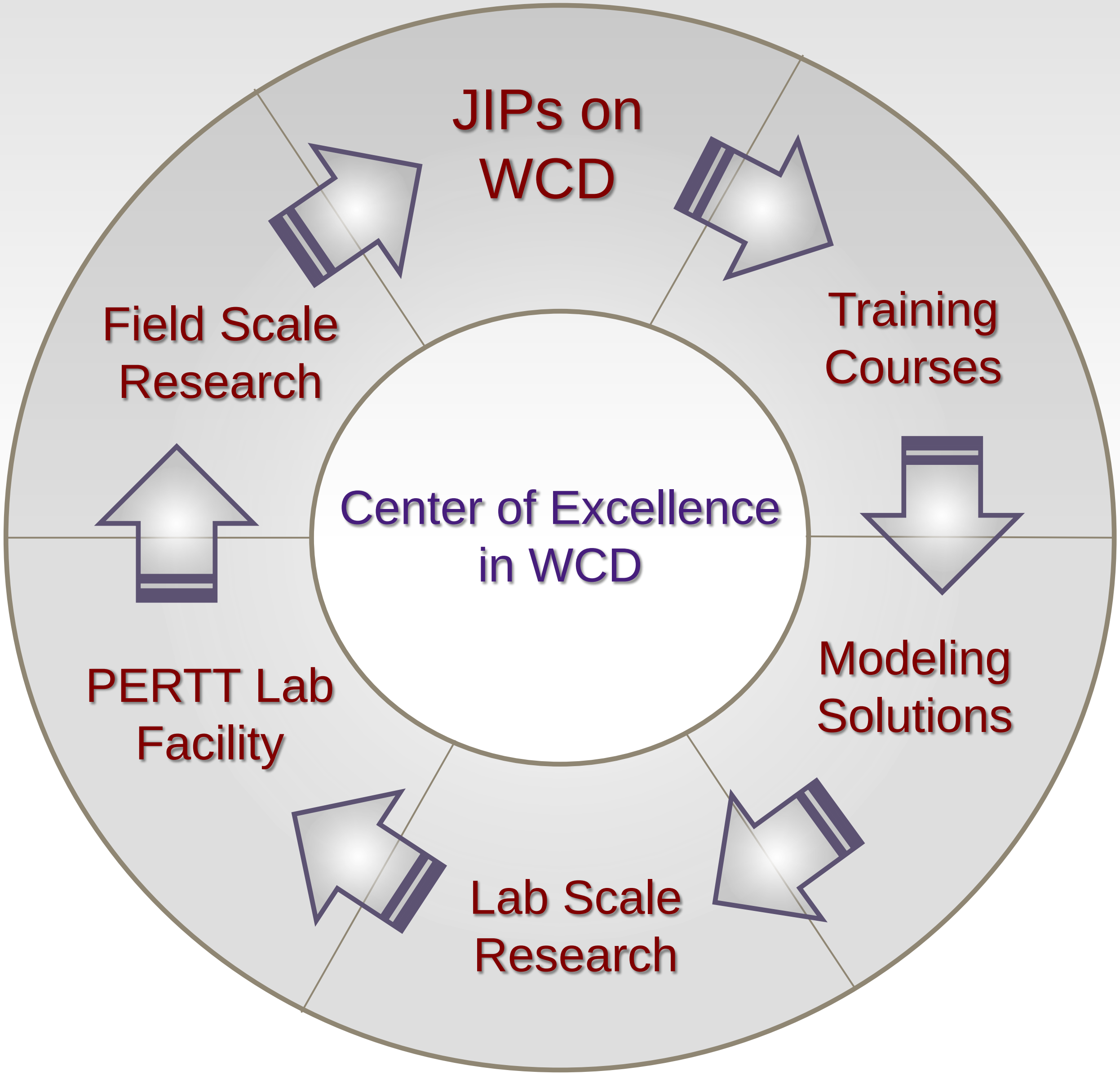
Suggestion for Future Projects

❑ 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

LSU WCD Research Center



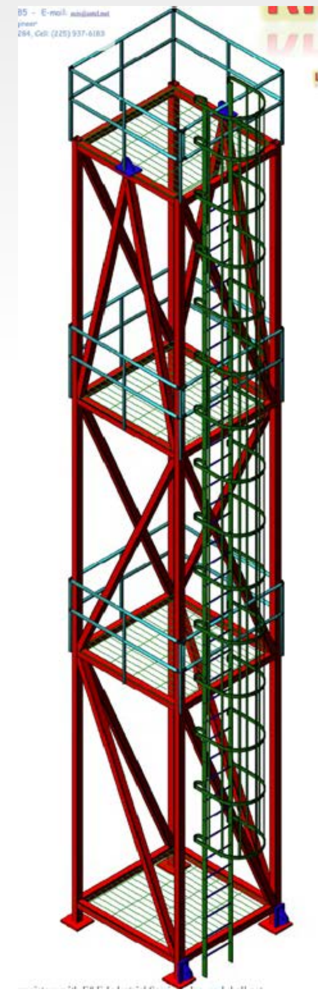
Preliminary Priority List of Topics [1]

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

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

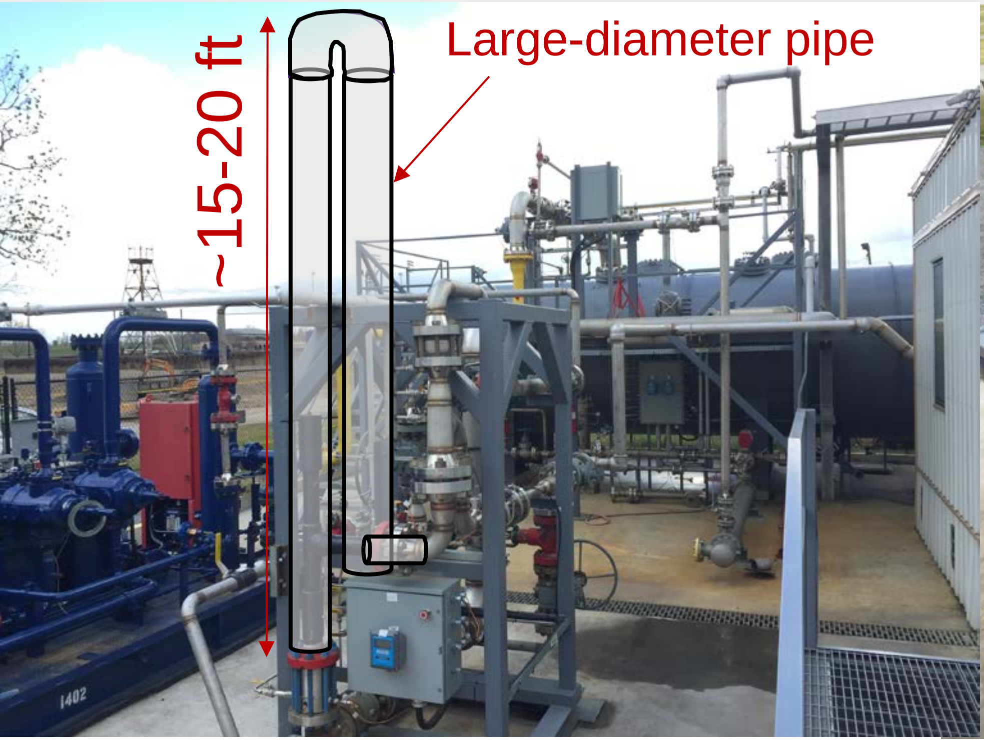
Old Inclinable flow loop

40-60 ft



Preliminary Priority List of Topics [2]

- ❑ Flow tests for different **pressures and fluid types** (fluids other than water and air)

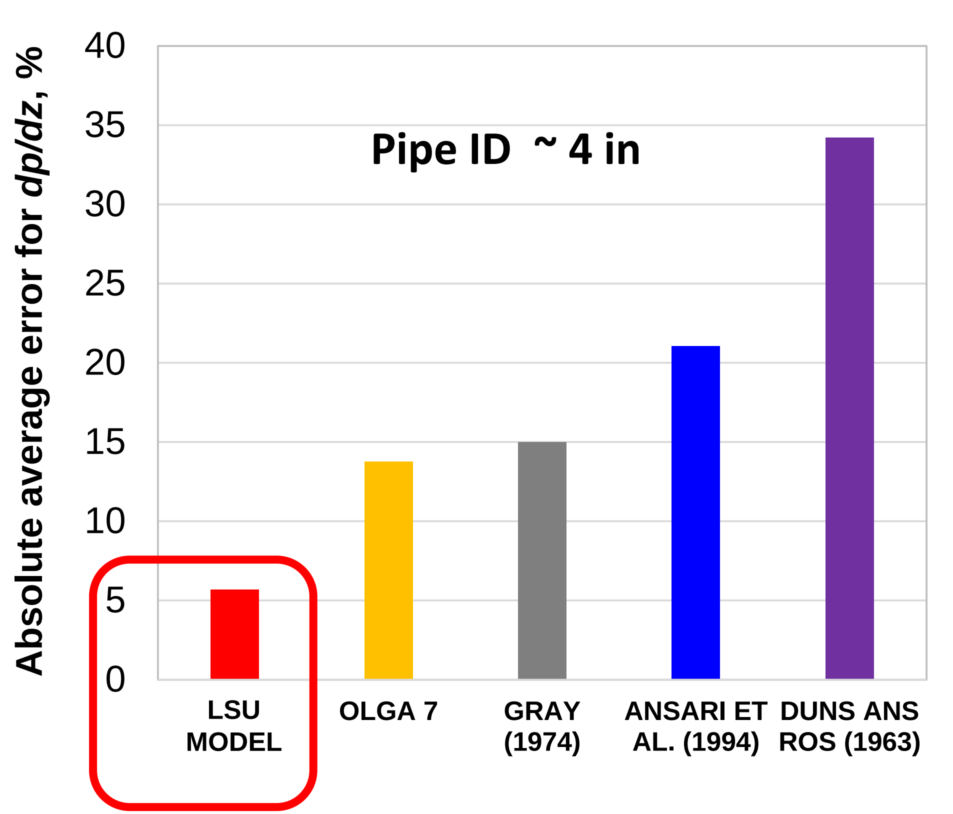


- ✓ Industry investment already made of about ~$ 2,000,000
- ✓ Closed-loop that allow use of different fluid types (oil, gas, water, nitrogen...)
- ✓ Allow use of pressures up to 1,200 psi
- ✓ Allow tests with high-liquid rates (15,000 BBL/D) and high-gas rates (4 MMSCFD)

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)