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

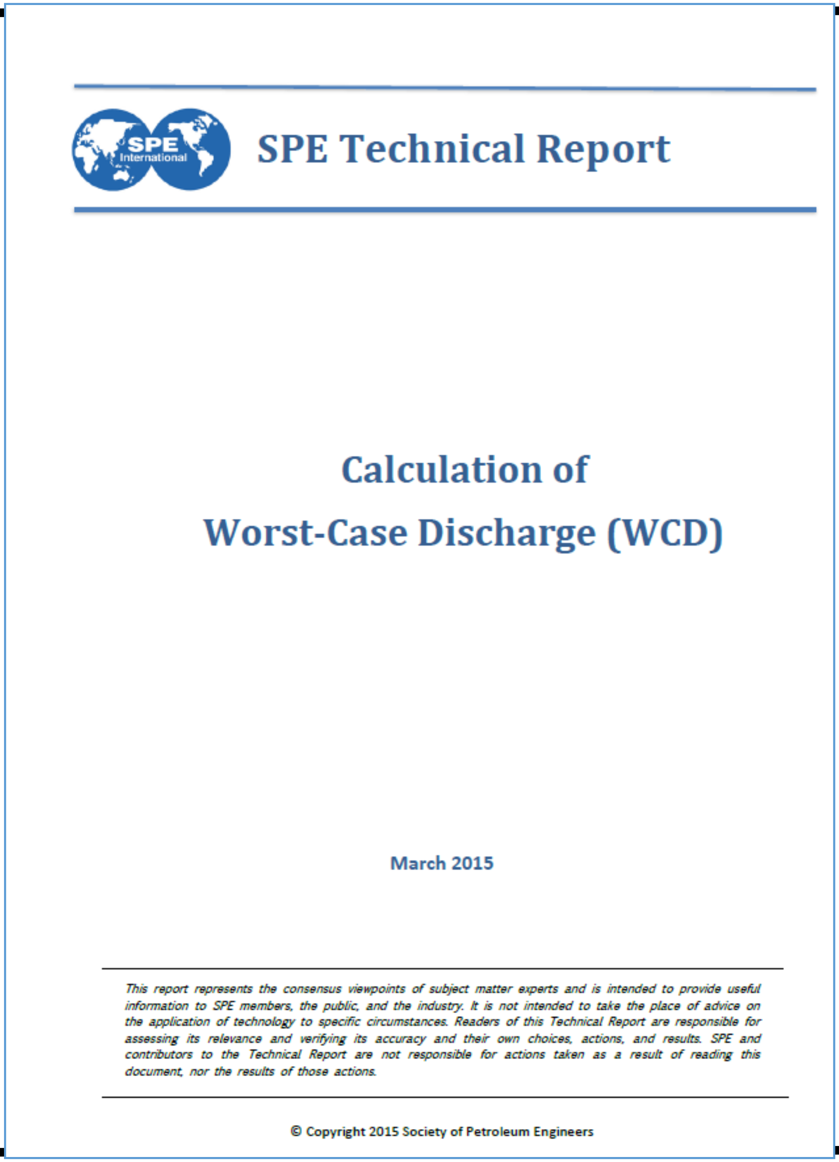
The UNIVERSITY of OKLAHOMA
Mewbourne School of Petroleum and Geological Engineering

BOEM
Bureau of Ocean Energy Management

Introduction

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: M15PC00007. 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.


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.

sonic velocity flow limitations

2.5.9 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.

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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.

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.

Objectives

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

Ramadan Ahmed, Co-PI

Rida Elgaddafi
Post-Doc Associate

Olawale Taye
Post-Doc Associate

Raj Kiran
PhD Candidate

Jeff McCaskill
Technician and Equipment Specialist

Deliverable Milestone

Deliverable(s) / Milestone (s)
Completion of Technical Report for Literature Study and Theoretical Studies
Completion of Technical Report for Models CFD Simulations/WCD Model
Completion of Technical Report for Laboratory Results
Completion and Development of WCD Model and Computational Tool
Completion of Draft Reports

Progress

Deliverables	Due
Literature Review and Theoretical Studies Report	January 5th, 2018
CFD Simulation/WCD Model Technical Reports	March 24th, 2018
Technical Report for Laboratory Results	April 24th, 2018
Completion of WCD Model and Computational Tool	October 12, 2018
Final Report	October 3, 2018

- **Kick off meeting, October 24th , 2017**

Methodology and Scope

Literature Review

Review preceding experimental and theoretical studies

Computational Fluid Dynamics

Develop a simulation model for predicting TP characteristics

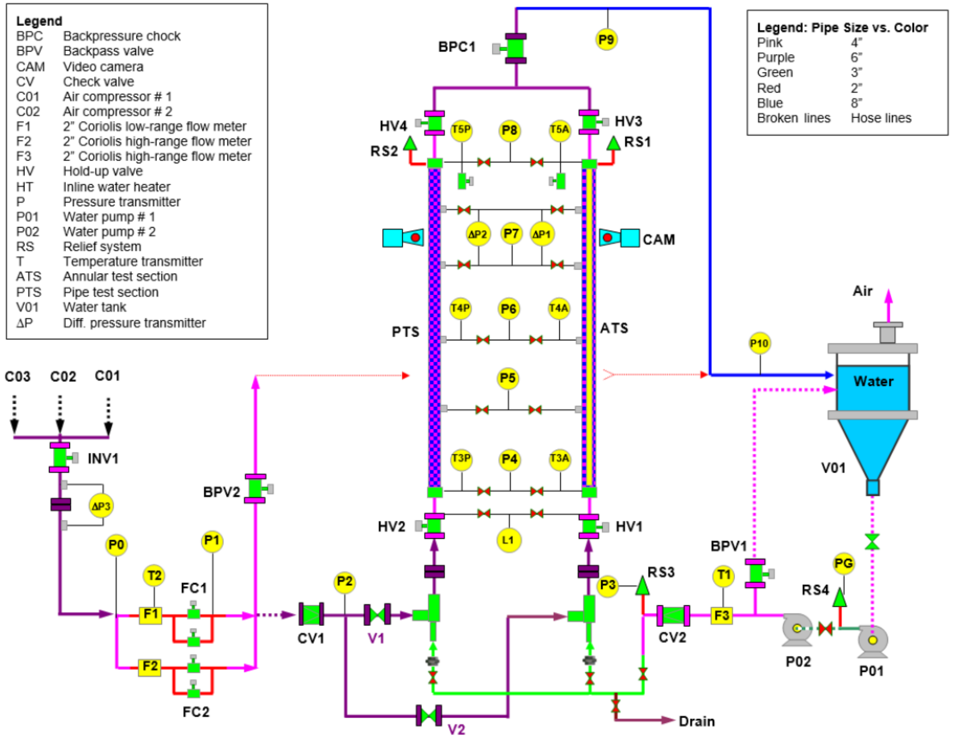
Experimental study

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

WCD Computational Tool

Two-phase flow mechanistic model, PVT model and Nodal Analysis

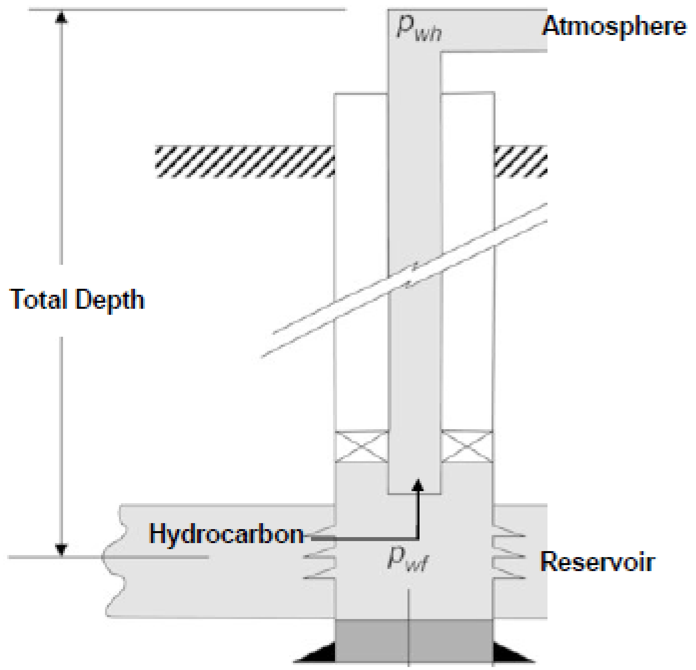
University of Oklahoma (OU) : High Velocity Experimental Setup



- 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 WCD rate displayed



Simplified schematic of well production system (Mach et al. 1979)

Input data
- Reservoir properties
- Wellbore properties

→ Interface → Output

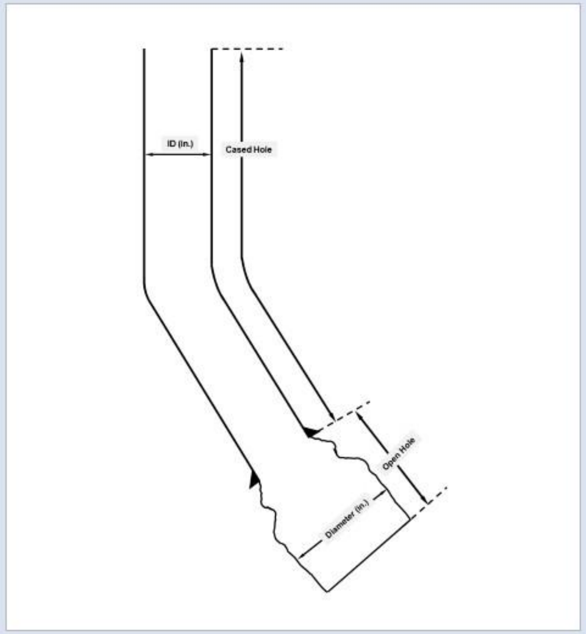
University of Oklahoma (OU) : WCD Computational Tool

WCD SOFTWARE

File | Open Hole Input | Output | Plots | Plots

Casing Inner Diameter, Dc (inch)	6	(2-100)
Casing Roughness, epsilonc (inch)	0.008	(>0)
Hole Diameter, Dh (inch)	5	(>Dc)
Cased Hole Diameter, Dch (inch)	7	(>Dc)
Hole Roughness, epsilonh (inch)	0.039	(>0)
Measured Depth, MD (ft)	8000	(>0)
Wellhead Pressure, Pw (psia)	100	(>Pr)
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 behing liner, Dlh (inch)	6	(0>Dlh>Dl)
Liner Inner Diameter, Dl (inch)	5.5	(0<Dl<Dc)
Liner Roughness, epsilonl (inch)	0.008	(>0)
Casing Shoe Depth, Lcs (ft)	2000	(>0)
Kickoff Point, KOP (ft)	500	(>0)
Well Inclination from Vertical, theta (deg.)	45	(0-45)
Well Type	Inclined Well	

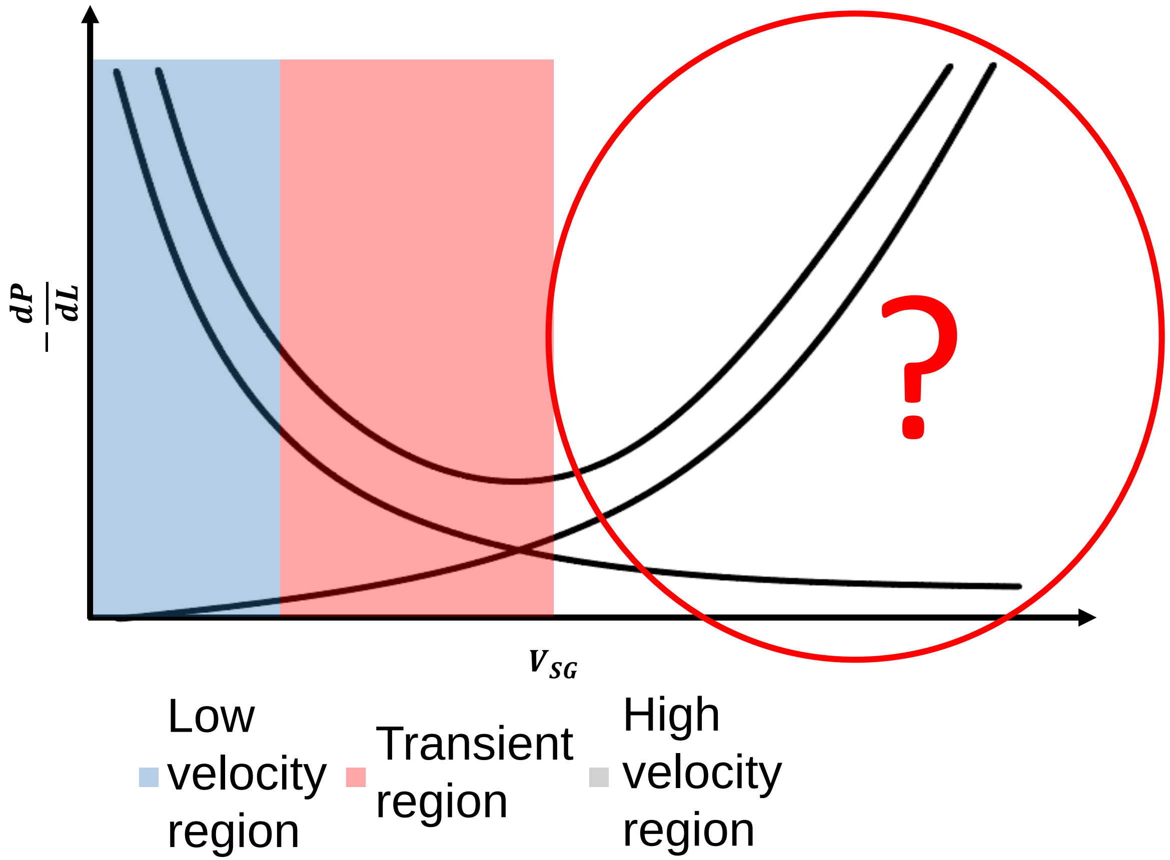
Well Profile



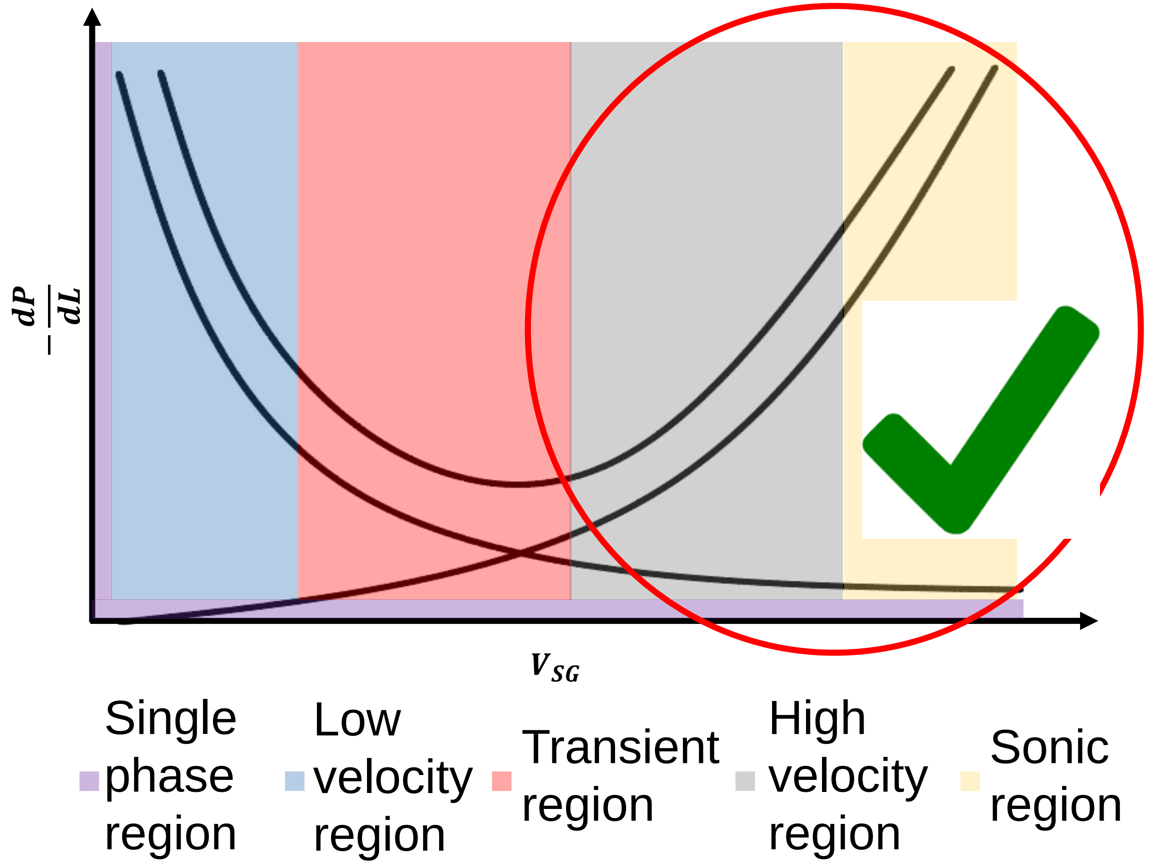
Update Input File | Run Program | Read Output File

OU WCD Computational Tool-Contributions

Other Available Tools for WCD



OU WCD Computational Tool



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 Setup and Procedure

Ramadan Ahmed, Co-Principal Investigator

Oct, 12th 2018

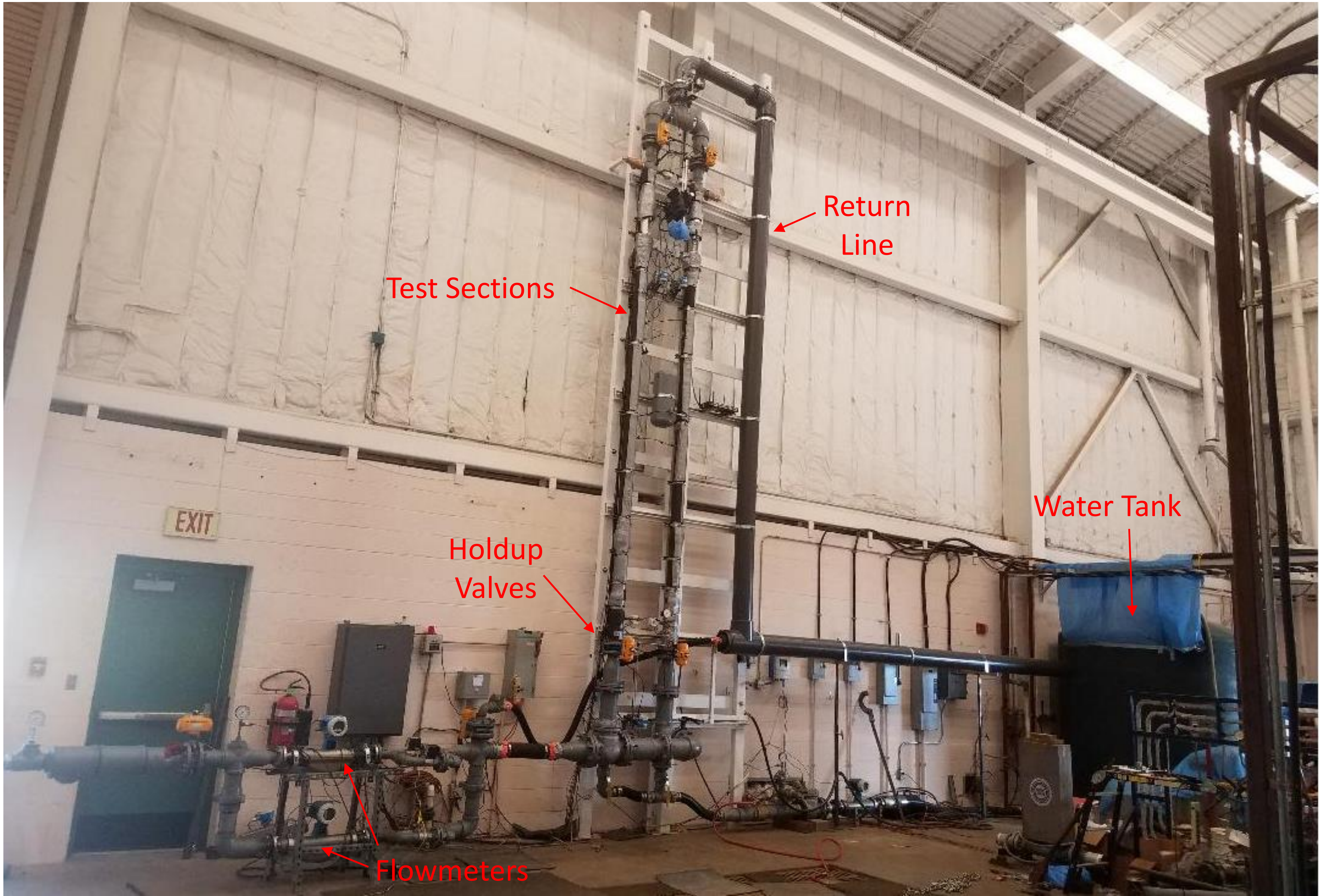
Outline

- Introduction
- Flow Loop Components
- Problems and Challenges
- Measuring Techniques
- Test Type and Procedure

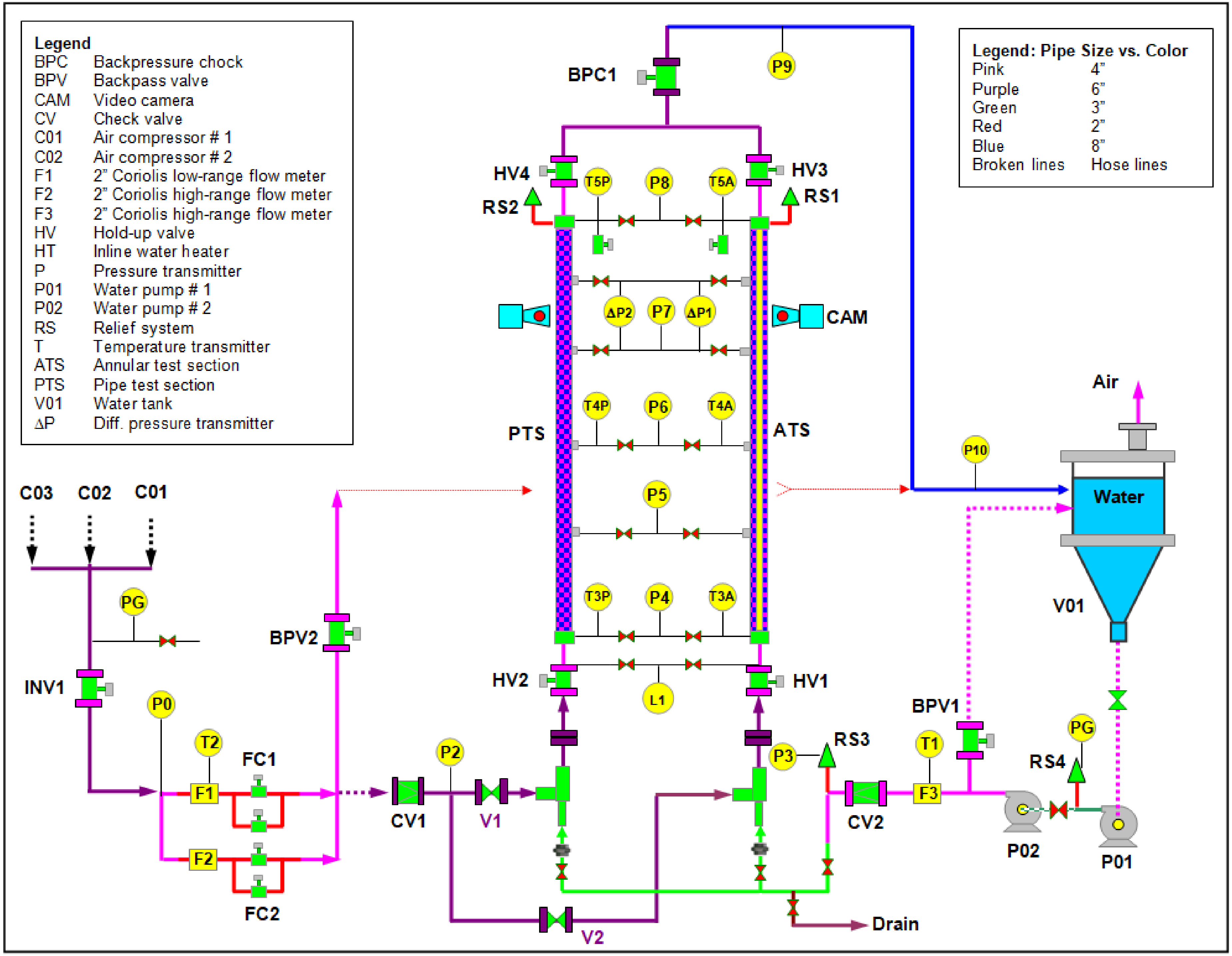
Introduction

- 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



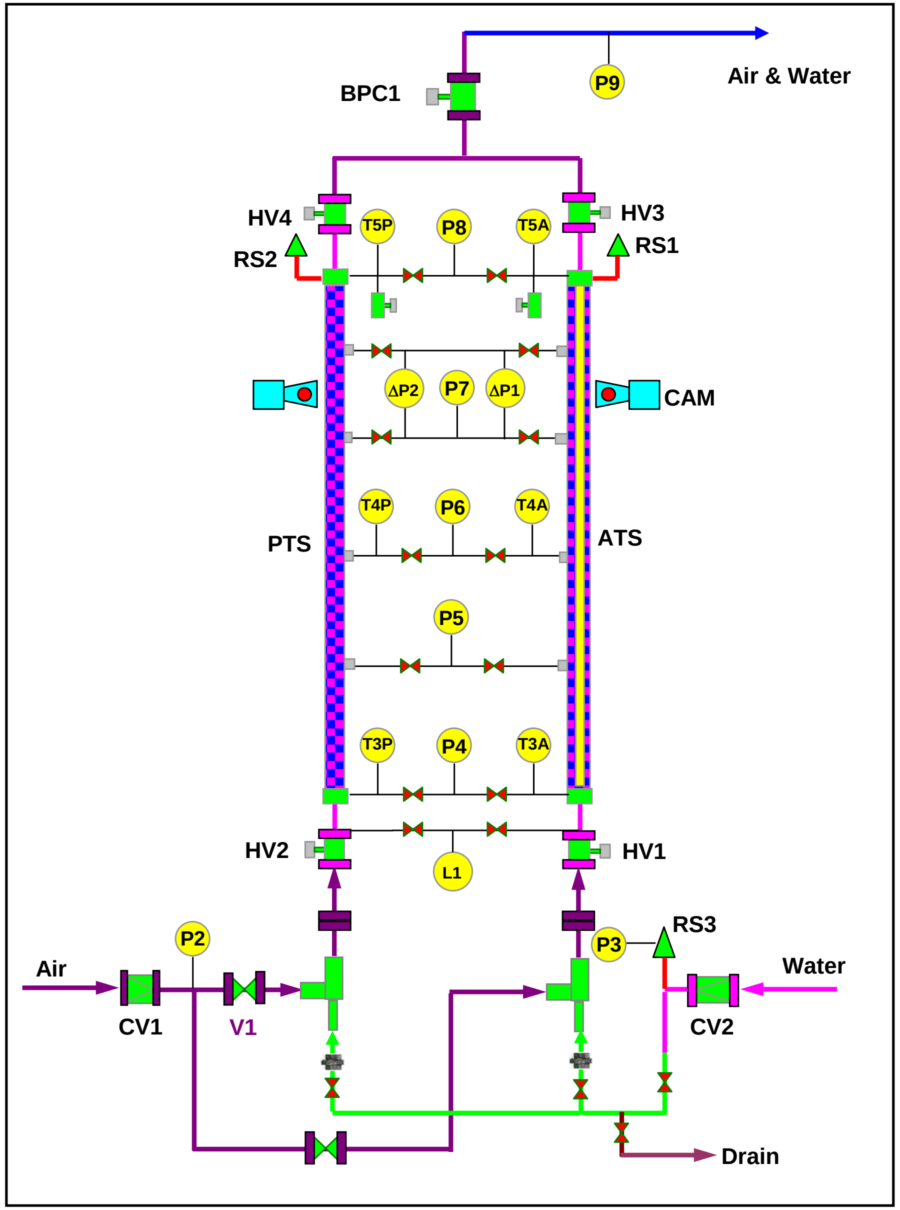
Schematic


Legend
BPC Backpressure chock
BPV Backpass valve
CAM Video camera
CV Check valve
C01 Air compressor # 1
C02 Air compressor # 2
F1 2" Coriolis low-range flow meter
F2 2" Coriolis high-range flow meter
F3 2" Coriolis high-range 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 Size vs. Color
Pink 4"
Purple 6"
Green 3"
Red 2"
Blue 8"
Broken lines Hose lines
BPC1
P9
HV4
HV3
T5P
P8
T5A
RS2
RS1
ΔP2
P7
ΔP1
CAM
T4P
P6
T4A
PTS
ATS
Air
P10
P5
Water
C03
C02
C01
T3P
P4
T3A
V01
PG
BPV2
HV2
HV1
L1
INV1
BPV1
P0
T2
FC1
P2
P3
RS3
T1
PG
RS4
F1
CV1
V1
CV2
F3
P02
P01
F2
FC2
V2
Drain

Flow Loop Components

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

Test Sections



Sensors

- Differential pressure
- Static Pressure
- Temperature

Valves

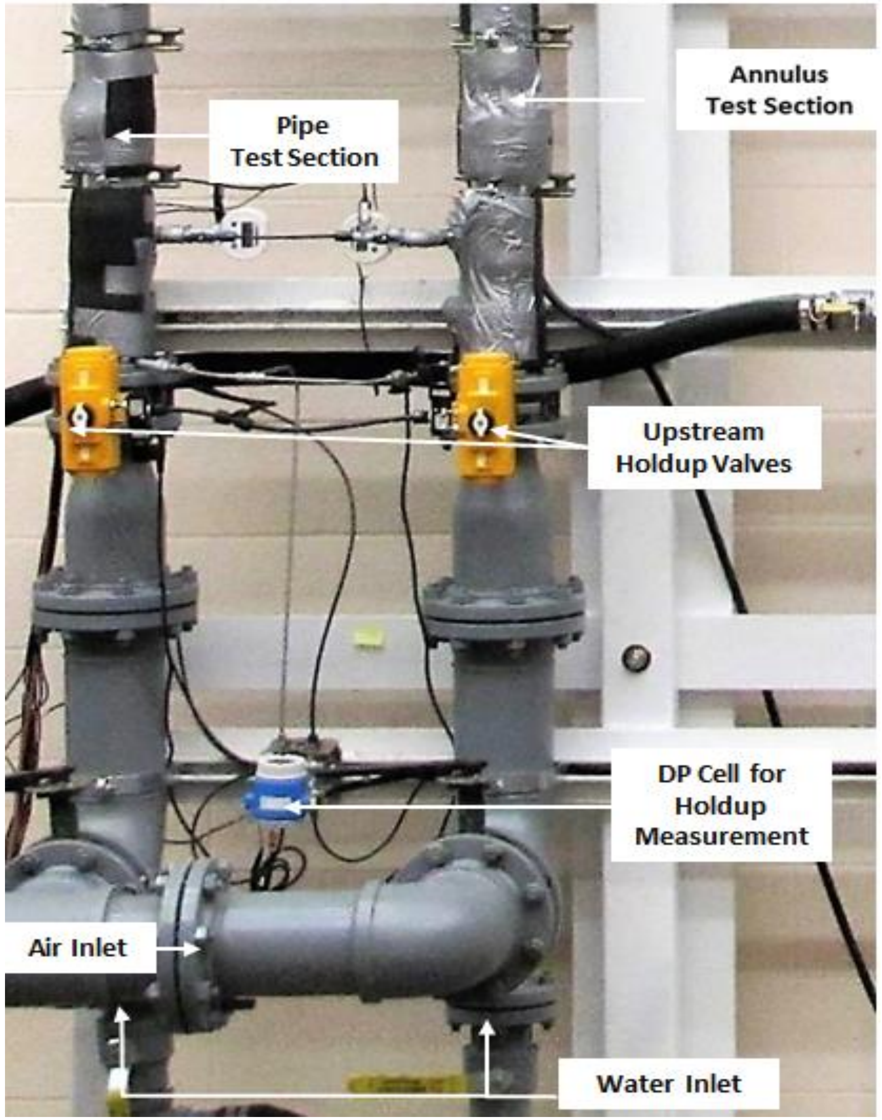
- Holdup
- Safety
- Check

Others

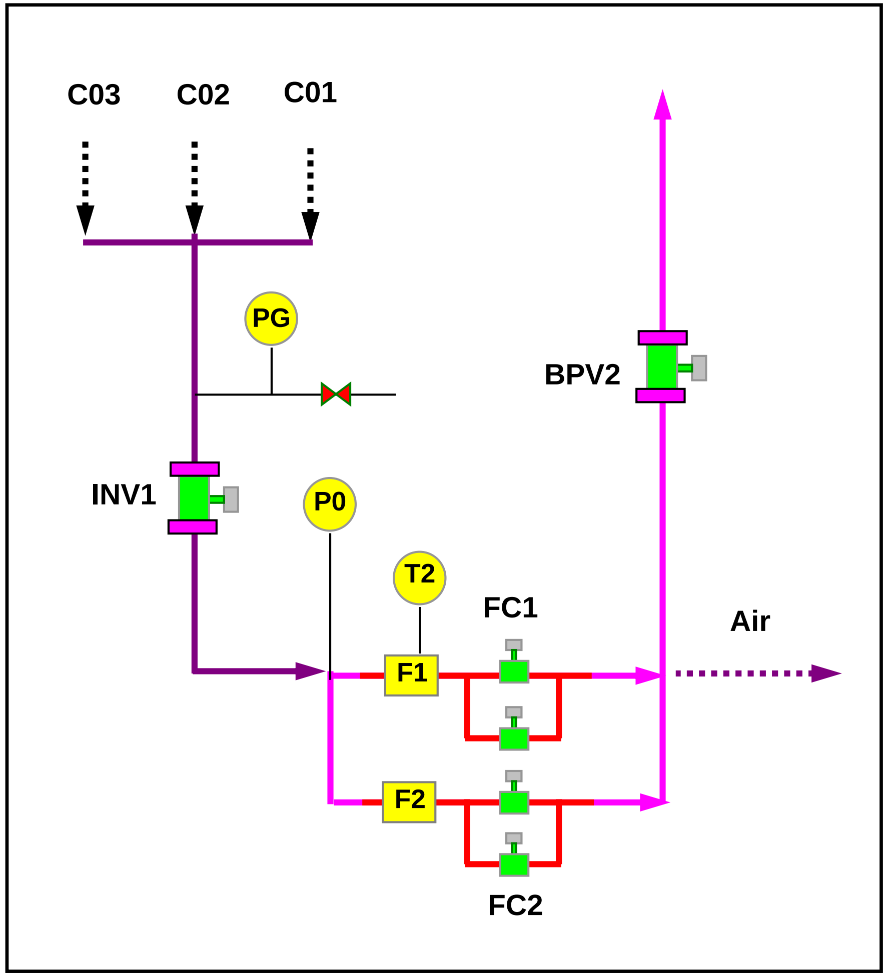
- Visualization system
- Air accumulators
- Perforated disks

Inlet Section

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



Air Supply System



Compressors

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

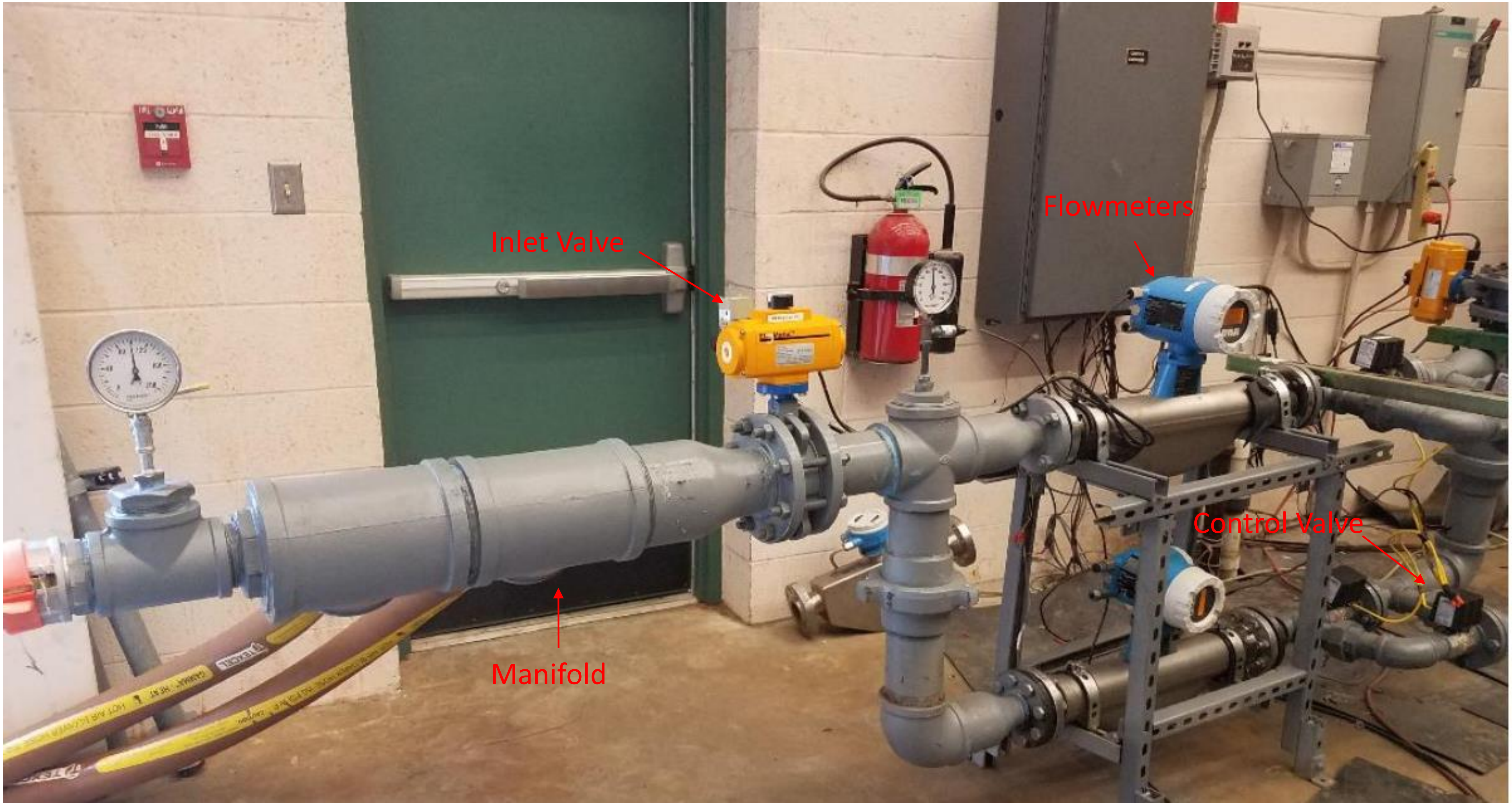
Valves

- Inlet
- Bypass (not used)
- Flow regulating

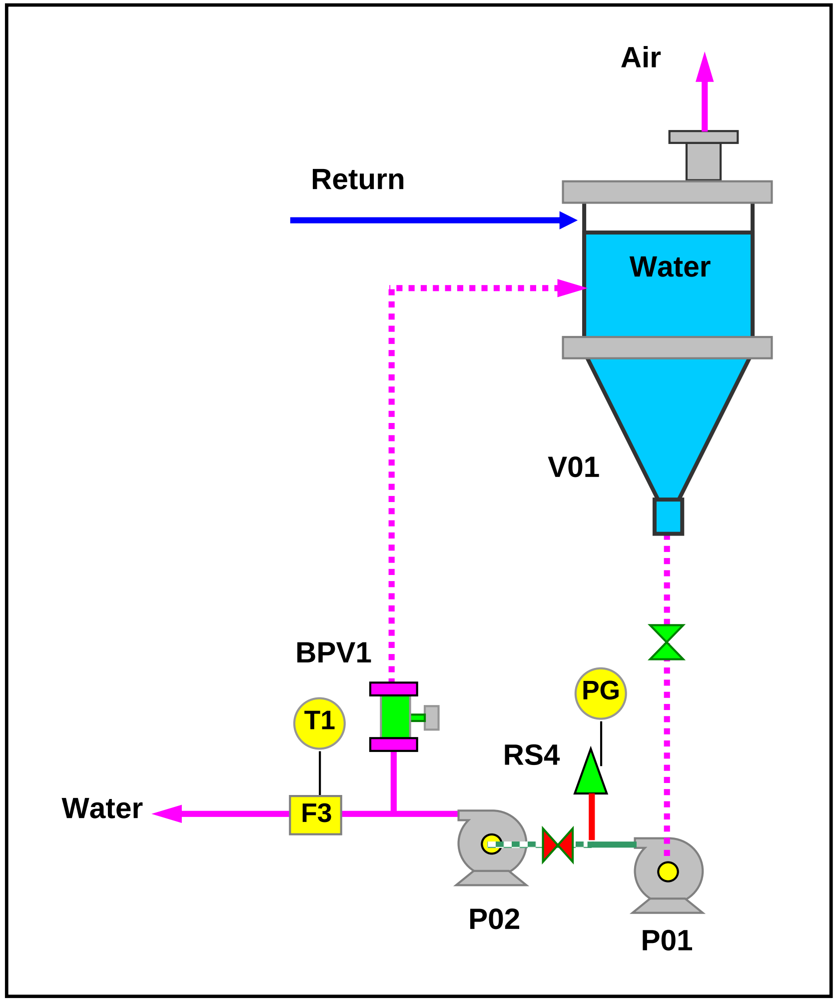
Sensors

- Flow meters (F1 and F2)
- Pressure
- Temperature

Air Supply System - Photo



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 H_2O

- Flow Rate: Coriolis flow meters

  Accuracy 0.35%

  Accuracy 0.05%, Measuring Range 550 and 2564 lb/min

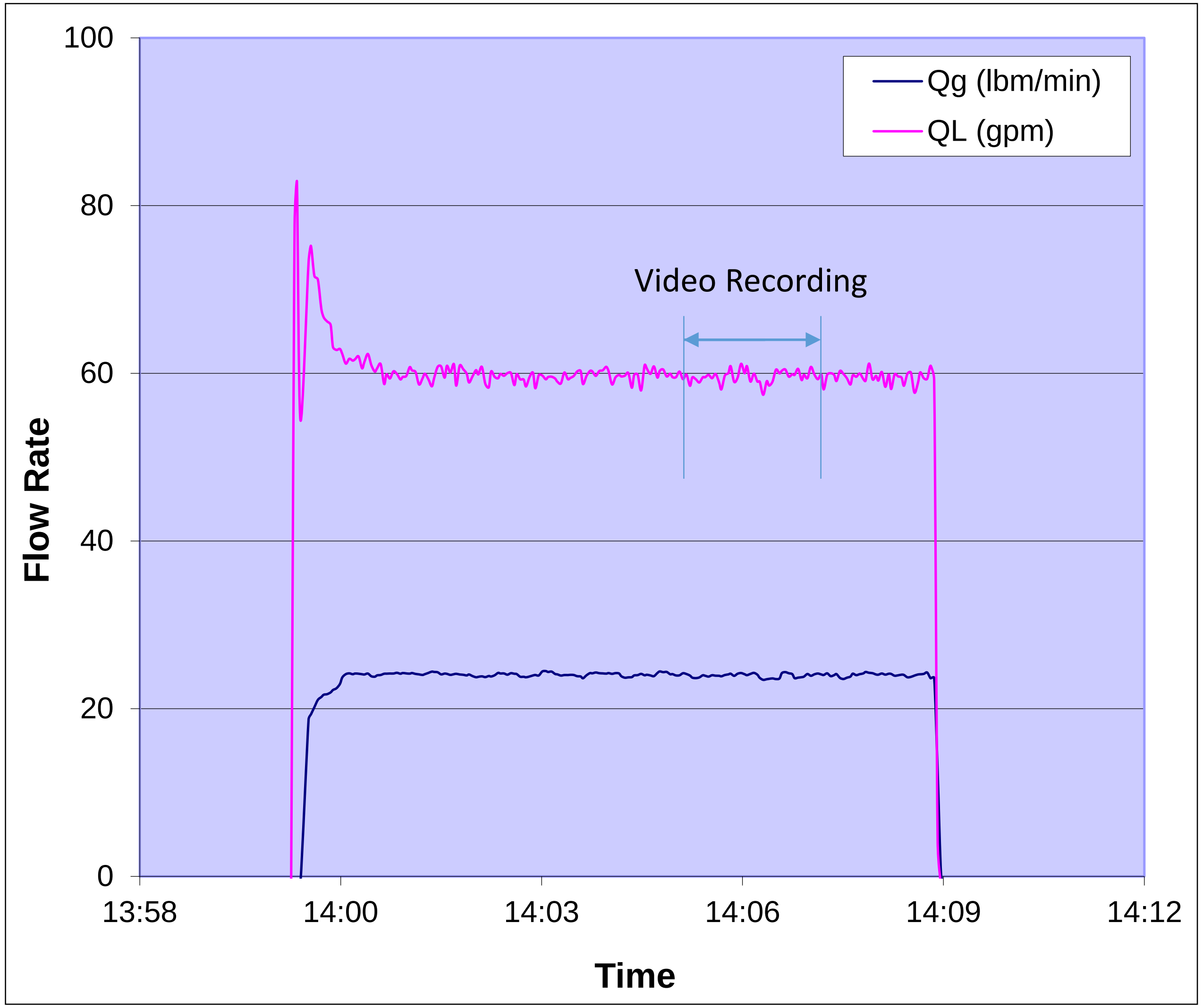
- Liquid Holdup: Differential pressure sensor

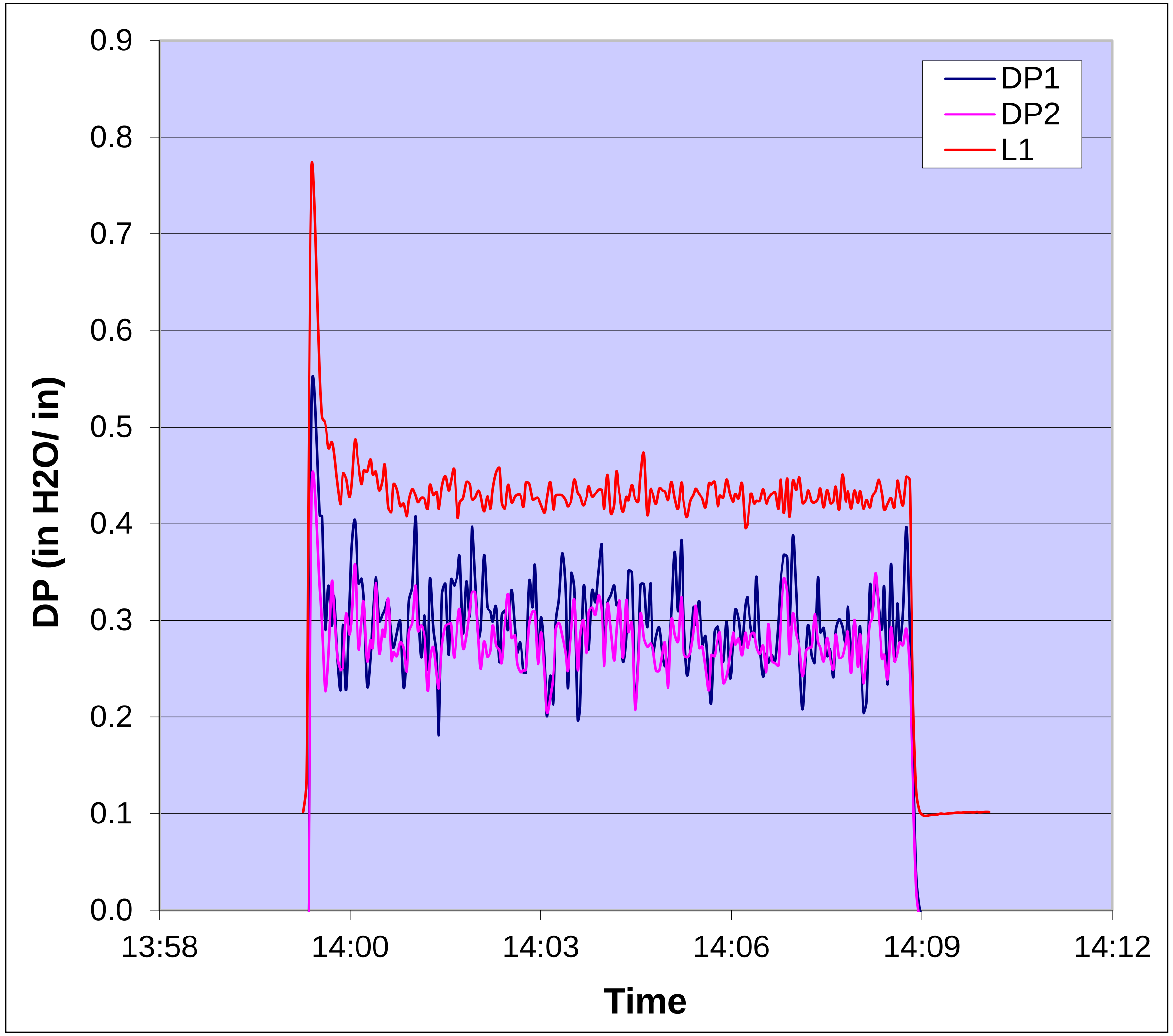
  Accuracy 0.05%, Measuring Range ± 200 in H_2O

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

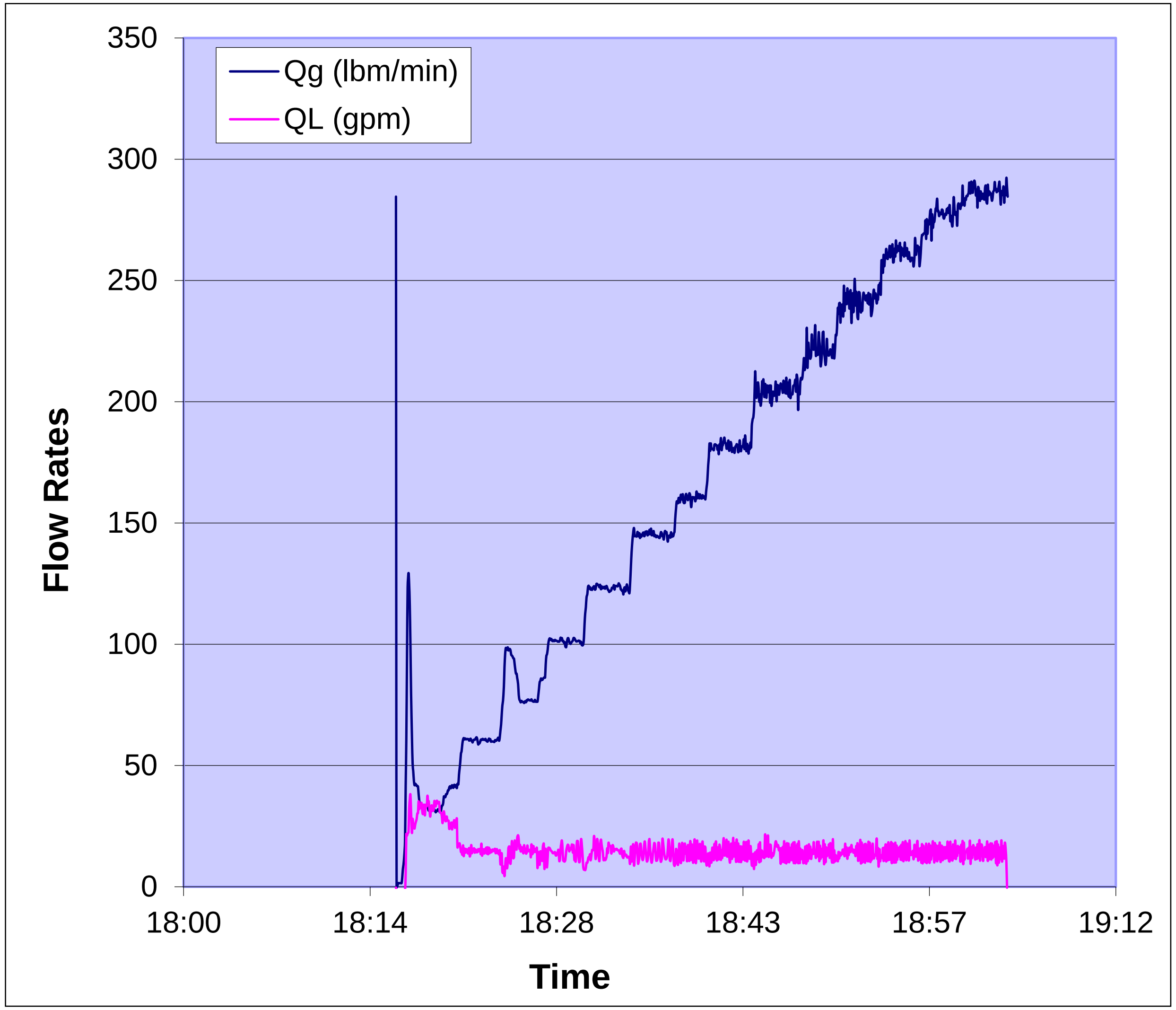


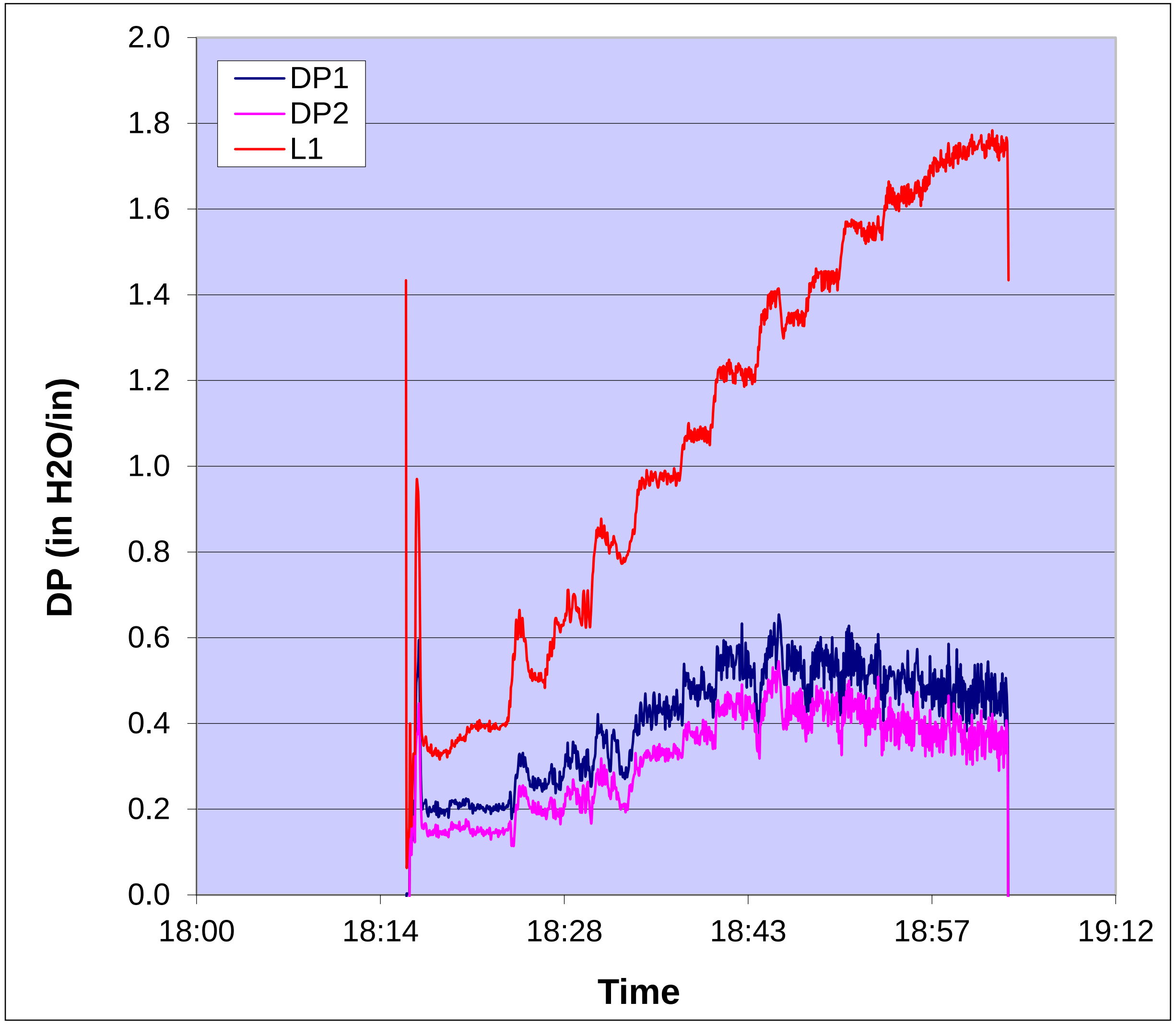


Test Procedure – Variable Rate Experiment

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





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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

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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.

June 3, 1979 (GOM) Oil flows from the blown Ixtoc wellhead. (National Oceanic and Atmospheric Administration)

Statement of problem

- Blowout incidents of oil and gas offshore wells can cause a 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

Literature Review – Key Findings

- 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.

Literature Review – Key Findings

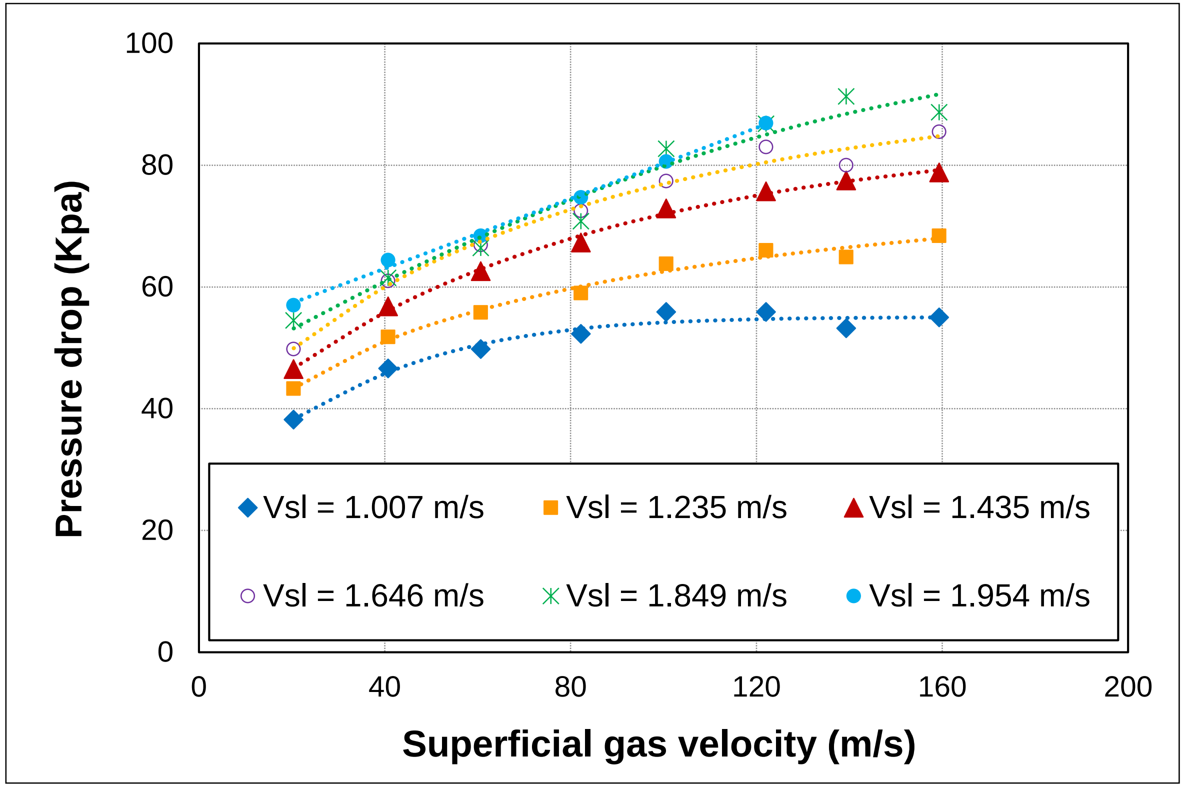
- Very limited theoretical and experimental studies were carried out to investigate two-phase flow phenomena in annuli.
- Post CFD simulation model of two-phase flow in the wellbore are limited to relatively low gas and liquid superficial velocities.
- Existing CFD simulations of sonic and supersonic 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.

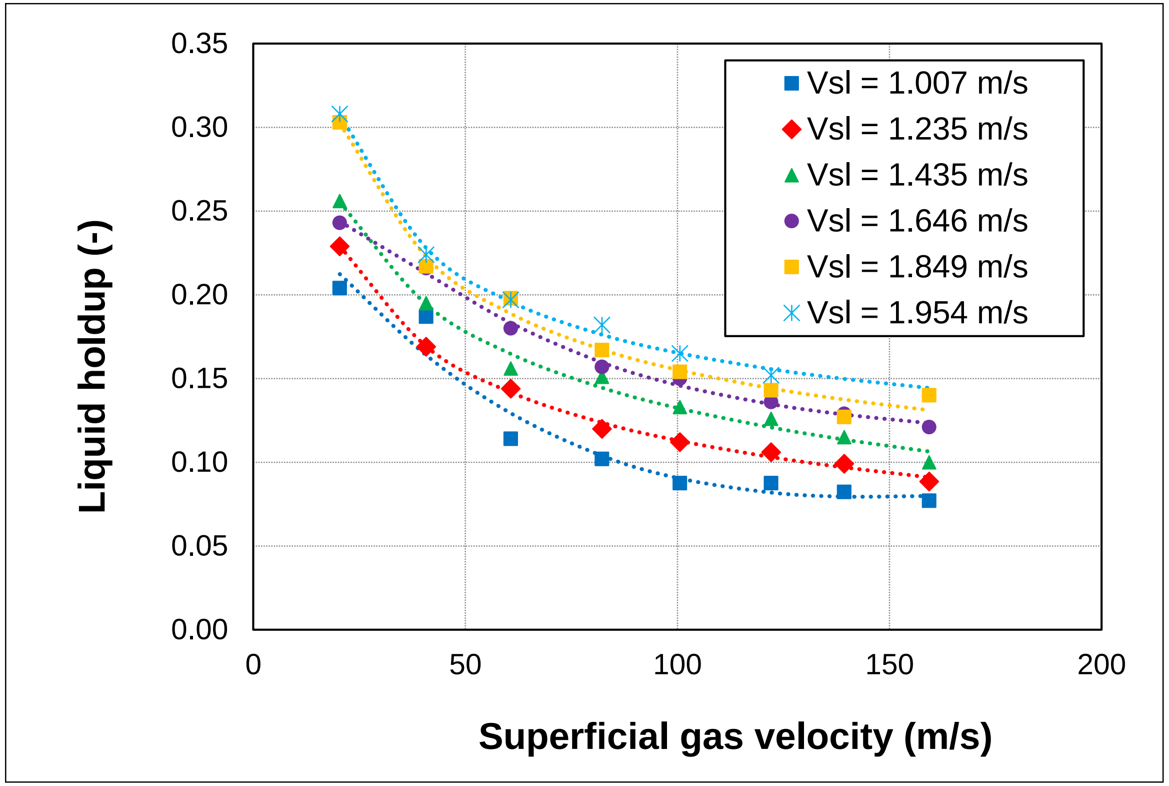
Literature Review - Con.

- **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

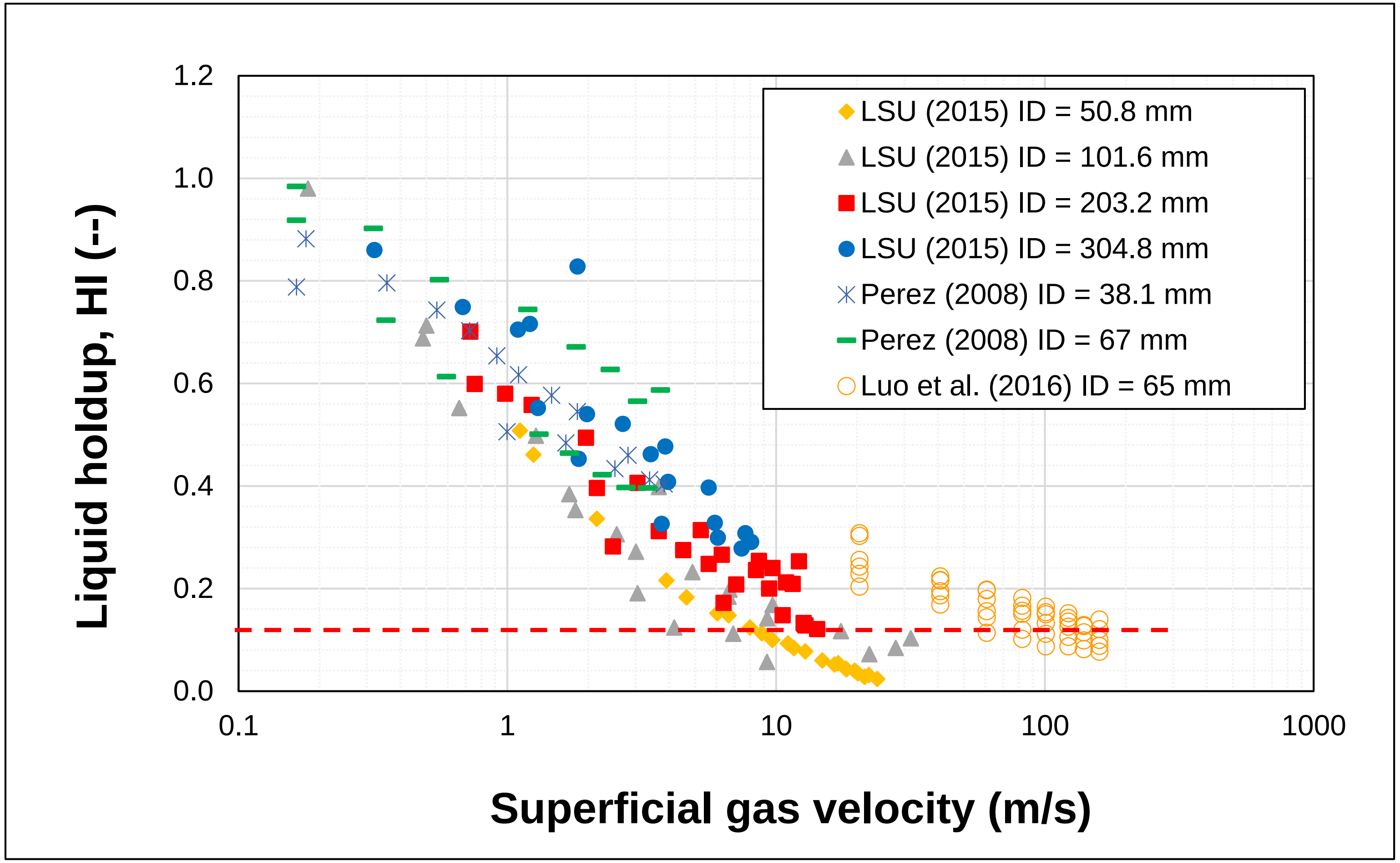




Literature Review - Comparative Analysis

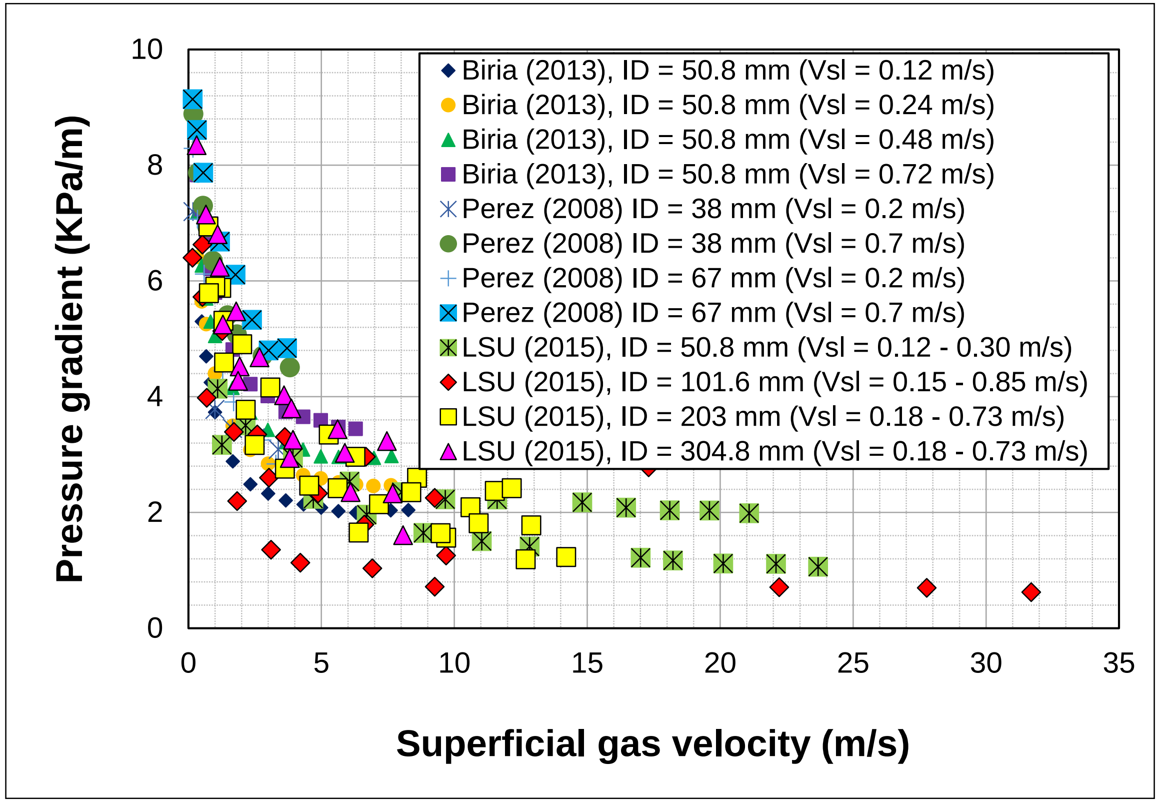
❖ Experimental Studies

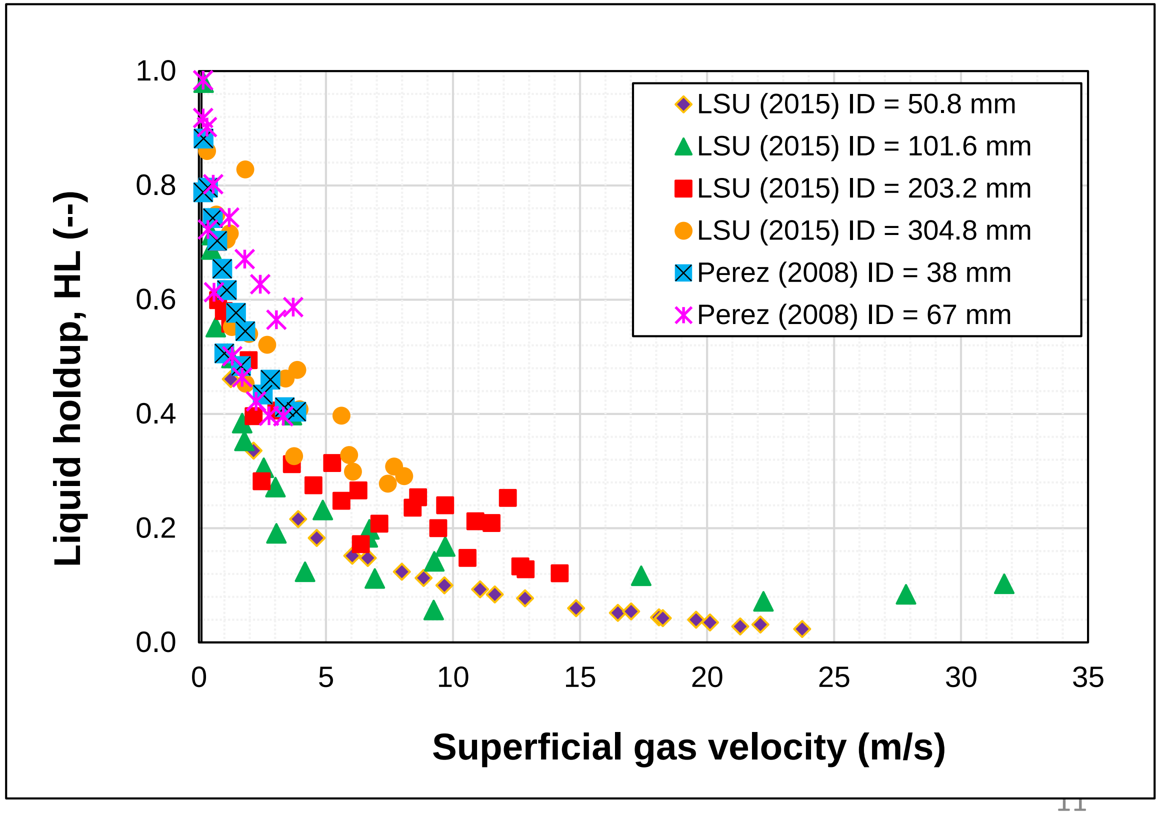
- **Luo et al. (2016)**
- **Perez (2008)**
- **Waltrich et al. (2015)**



Literature Review - Comparative Analysis

Reference	Test section ID (mm)	V_{sl} (m/s)	V_{sg} (m/s)	Flow pattern
Biria (2013)	50.8	0.12 – 0.72	0.33 – 8.27	Bubbly and Slug
Perez (2008)	38 - 67	0.2 – 0.7	0.16 – 3.83	Bubble, slug and churn
Waltrich et al. (2015)	50.8 – 305	0.12 – 0.73	0.31 – 31.0	Bubbly, slug, churn and annular flow





Literature Review - Factors Affecting WCD

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

Wellbore conditions

+

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

Reservoir Parameters

→ WCD rate

Computational Fluid Dynamic – CFD Model

❖ Fundamentals of CFD Model (ANSYS Fluent)

- **Conservation of mass (continuity equation)**

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = S_m$$

- **Conservation of momentum**

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.(\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F}$$

❖ Modelling Multiphase Flow

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

❖ Turbulence Model

- ✓ K – ε model
- ✓ K – Omega model

CFD Model – Solver setup

▪Flow Geometry → Mesh Generation → Model setup → Solution

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

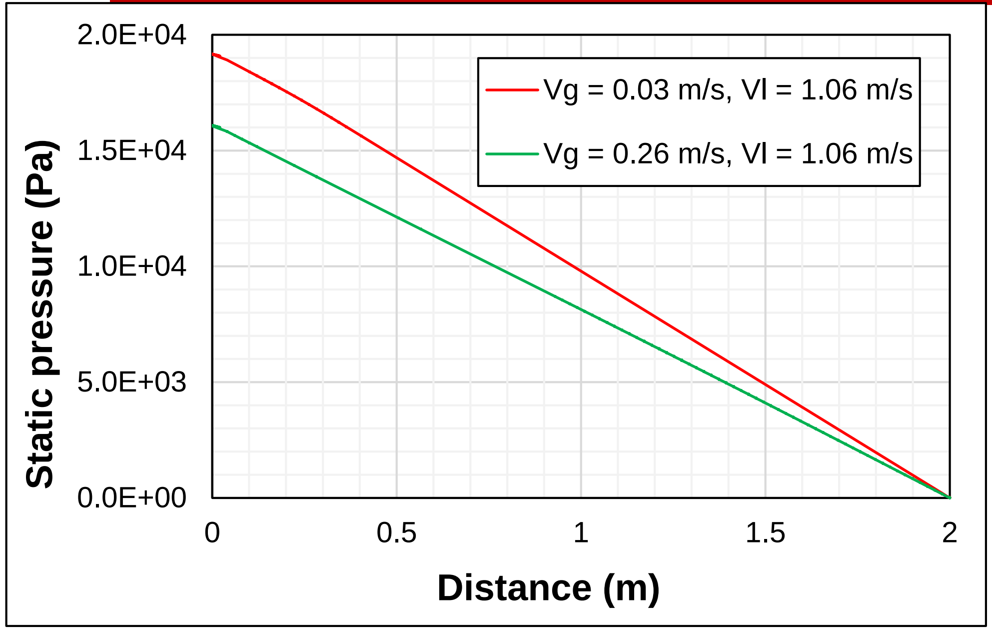
CFD Model – Validation

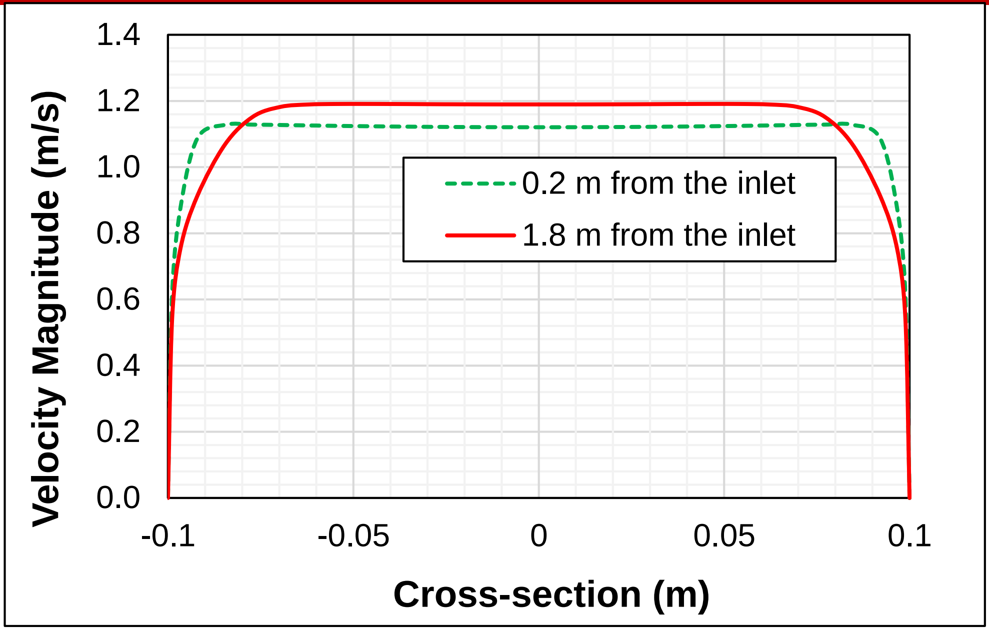
Experimental Data [Ohnuki and Akimoto (2000)]

Case	Flow pattern	Pipe diameter (in)	V_{SG} (m/s)	V_{SL} (m/s)	CFD (DP/DL) (KPa/m)	Exp. (DP/DL) (KPa/m)	Existing model (DP/DL) (KPa/m)	Error (%)
1	bubble	8	0.03	0.18	9.50	9.05	9.43	5
2	bubble	8	0.03	1.06	9.65	9.7	9.5	0.5
3	bubble	8	0.26	1.06	8.05	8.5	8.9	-5

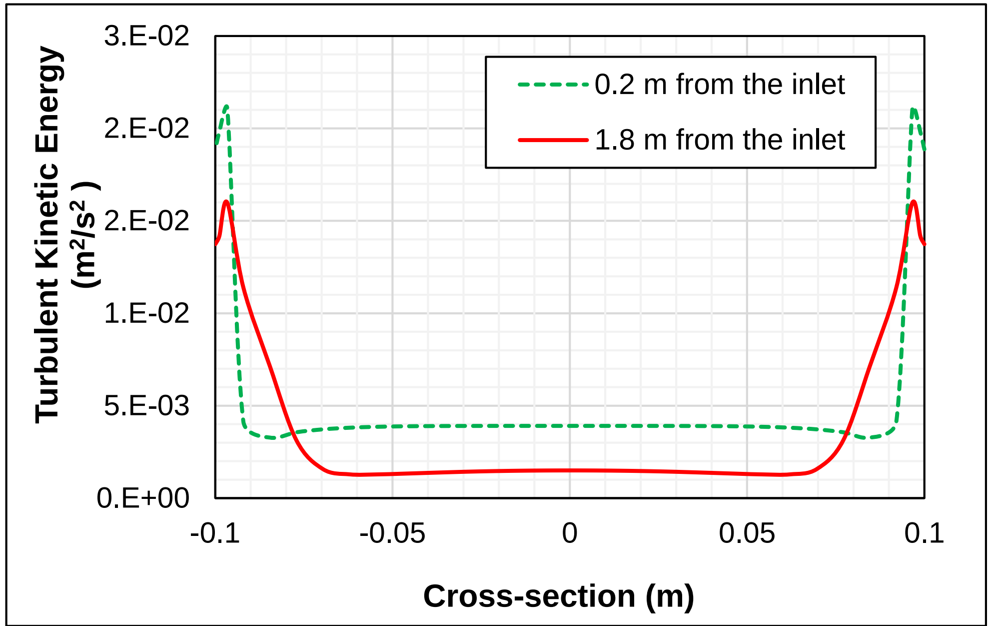
CFD Model – Results

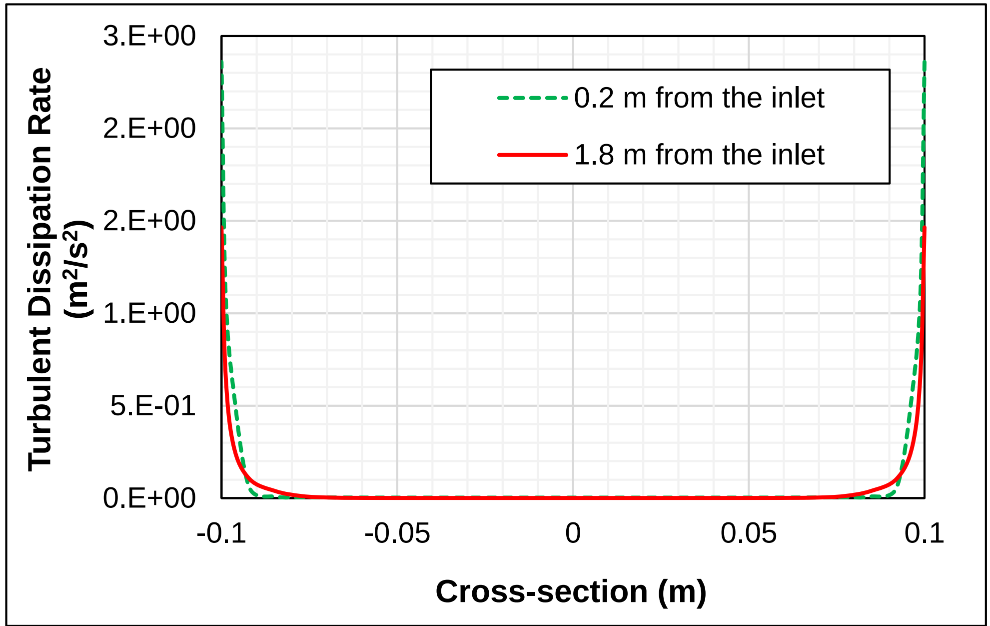
- **Pressure & Velocity Profile**





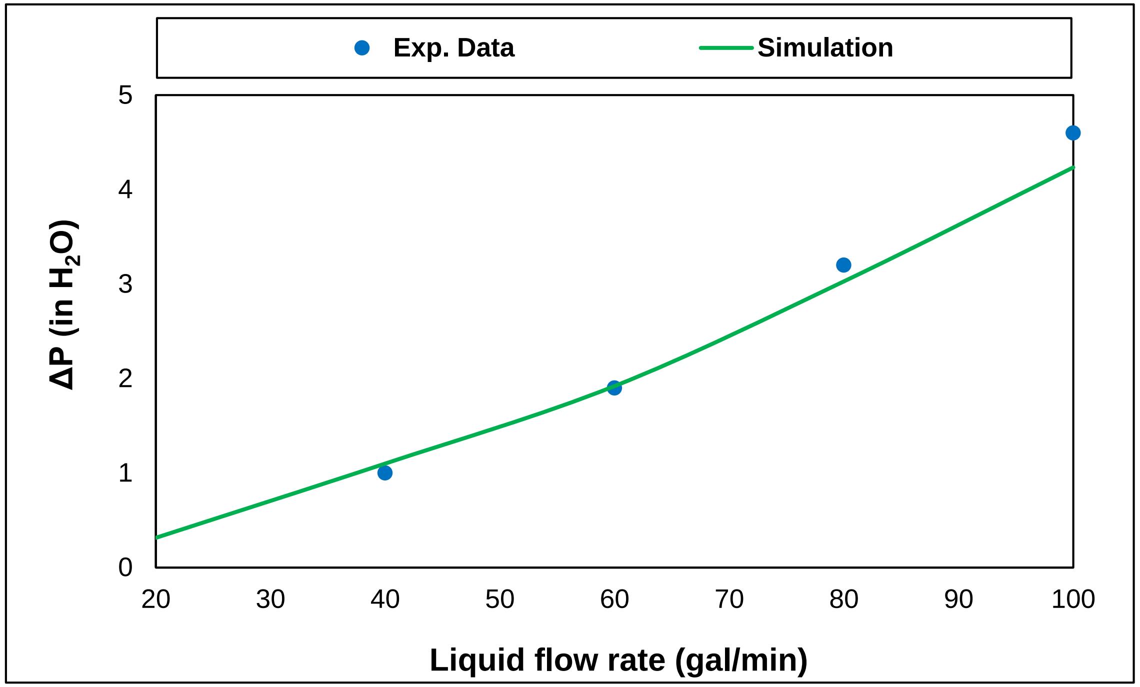
- **Turbulence Flow Characteristics**



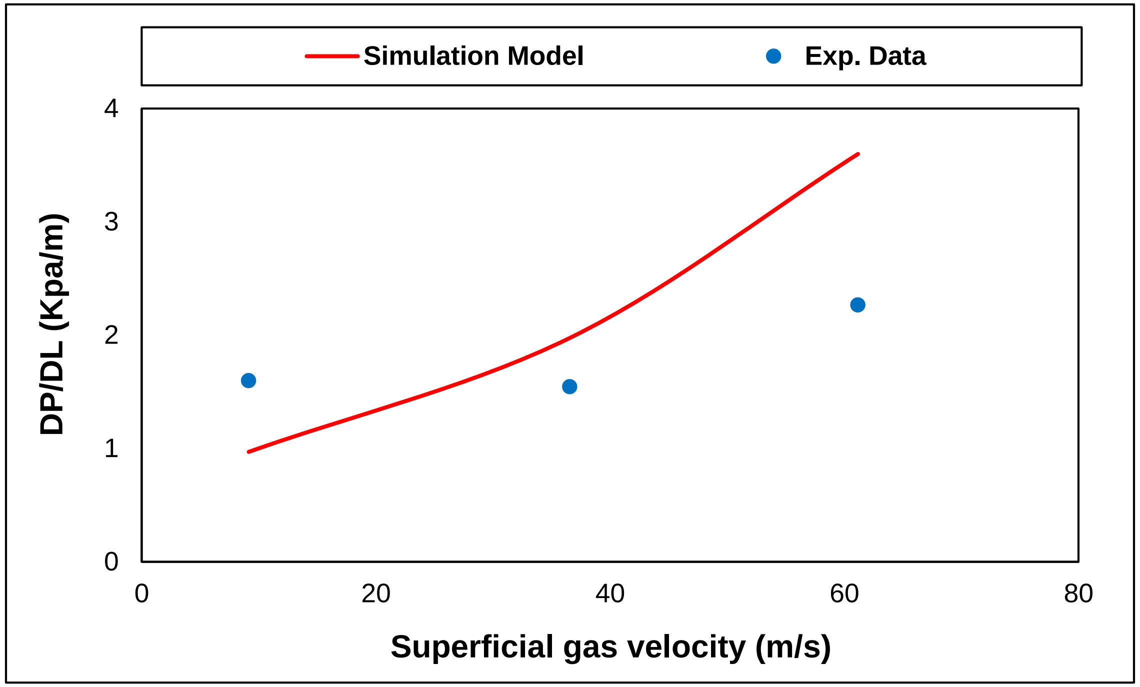


CFD Model – Validation (OU Data)

Single phase flow simulation



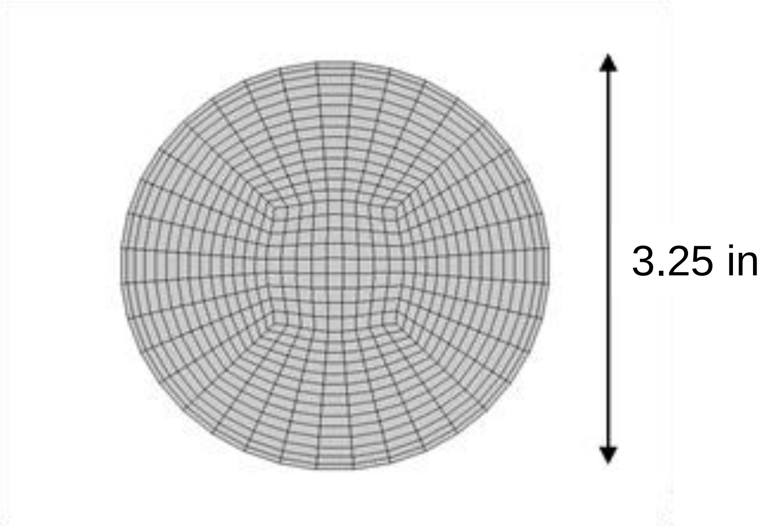
Two phase flow simulation

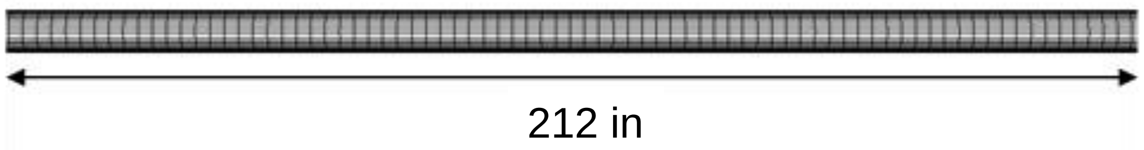


CFD Model – High Velocity

CFD Model for OU Lab-Setup

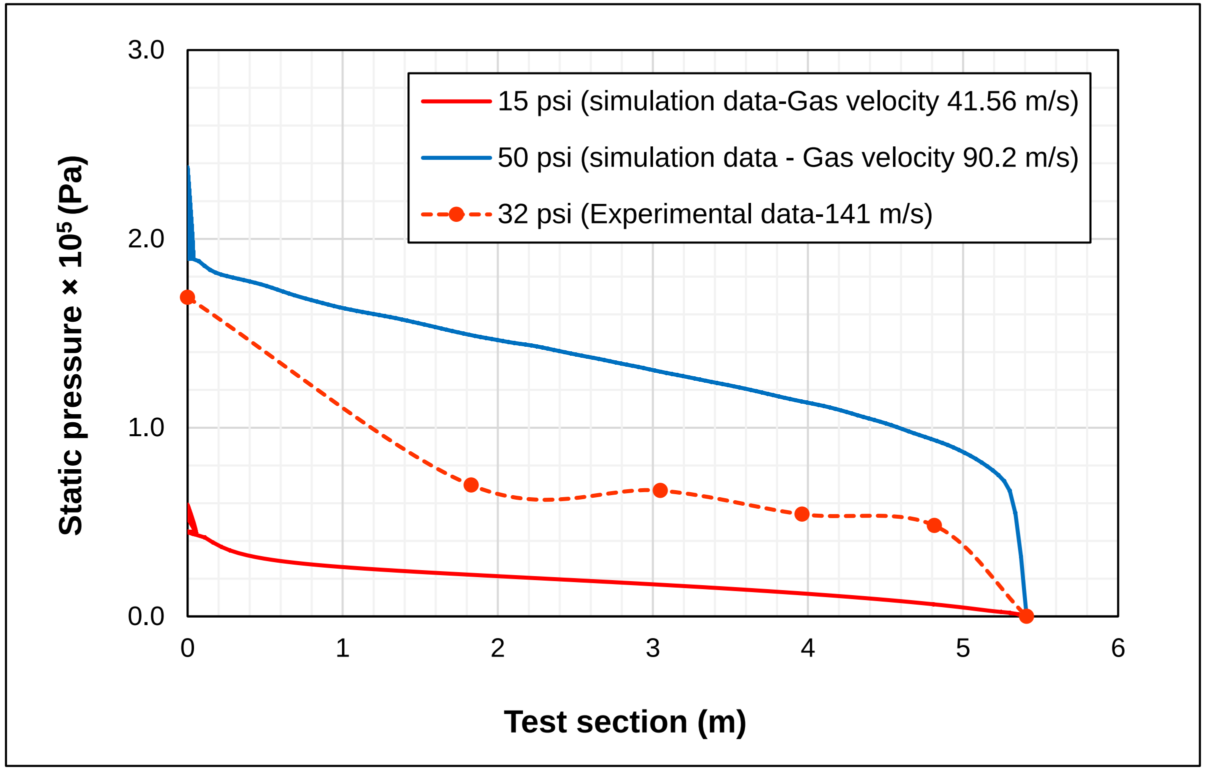
- ✓ Pressure based solver
- ✓ Specify fluid test (air compressibility)
- ✓ Active energy equation
- ✓ Multiphase model (hybrid model)
- ✓ Turbulence model (SST k-ω model)
- ✓ Boundary condition (pressure inlet boundary)
- ✓ Solution method
- ✓ Solution control

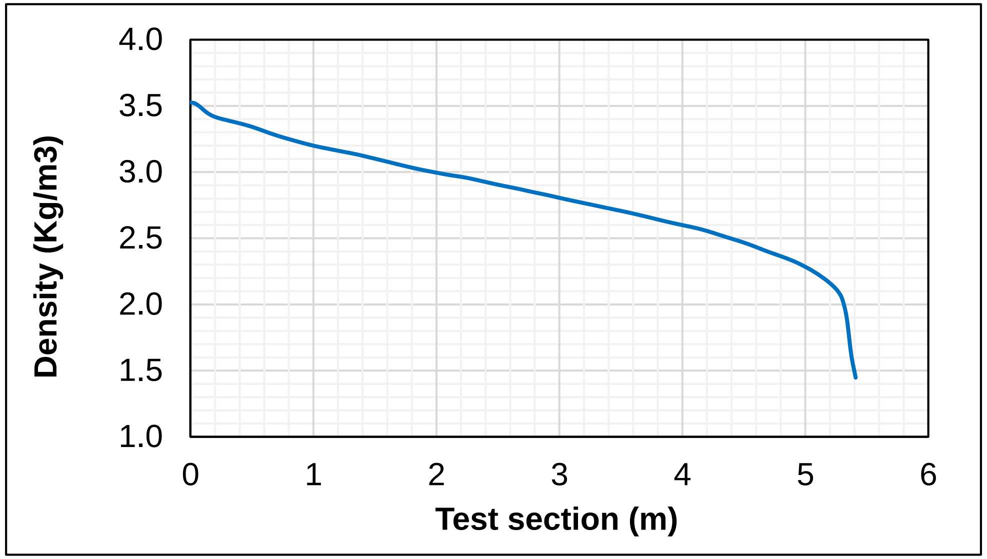


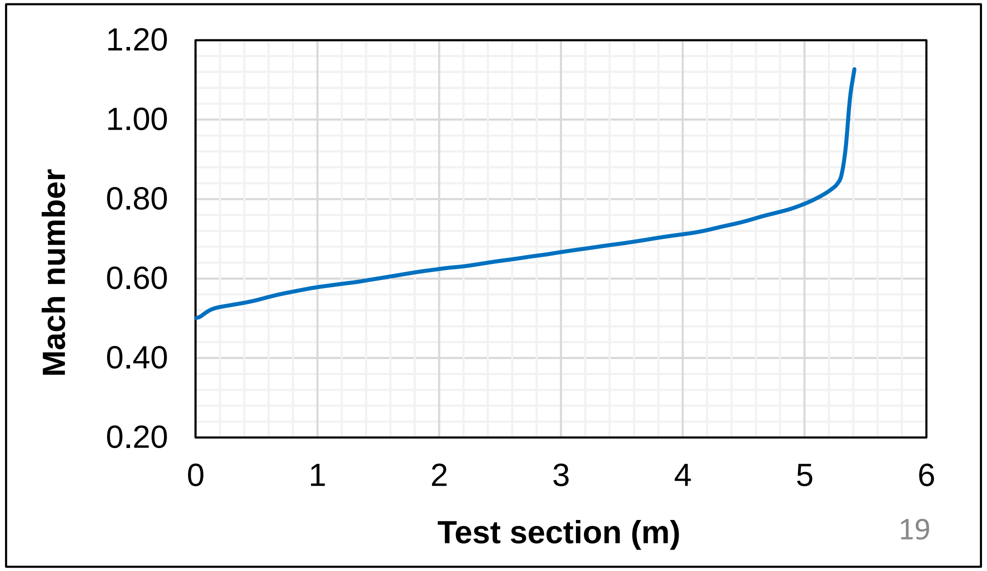


CFD Model – Results

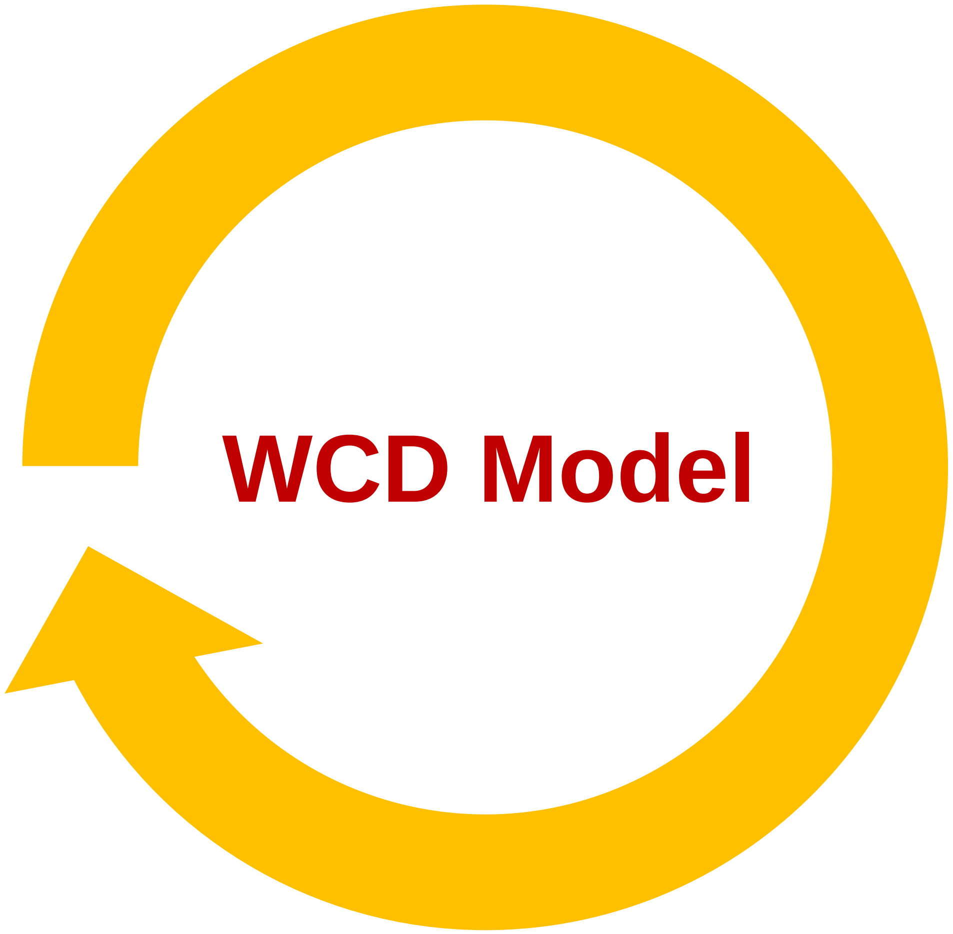
❖ Pressure, Density & Mach number Profile





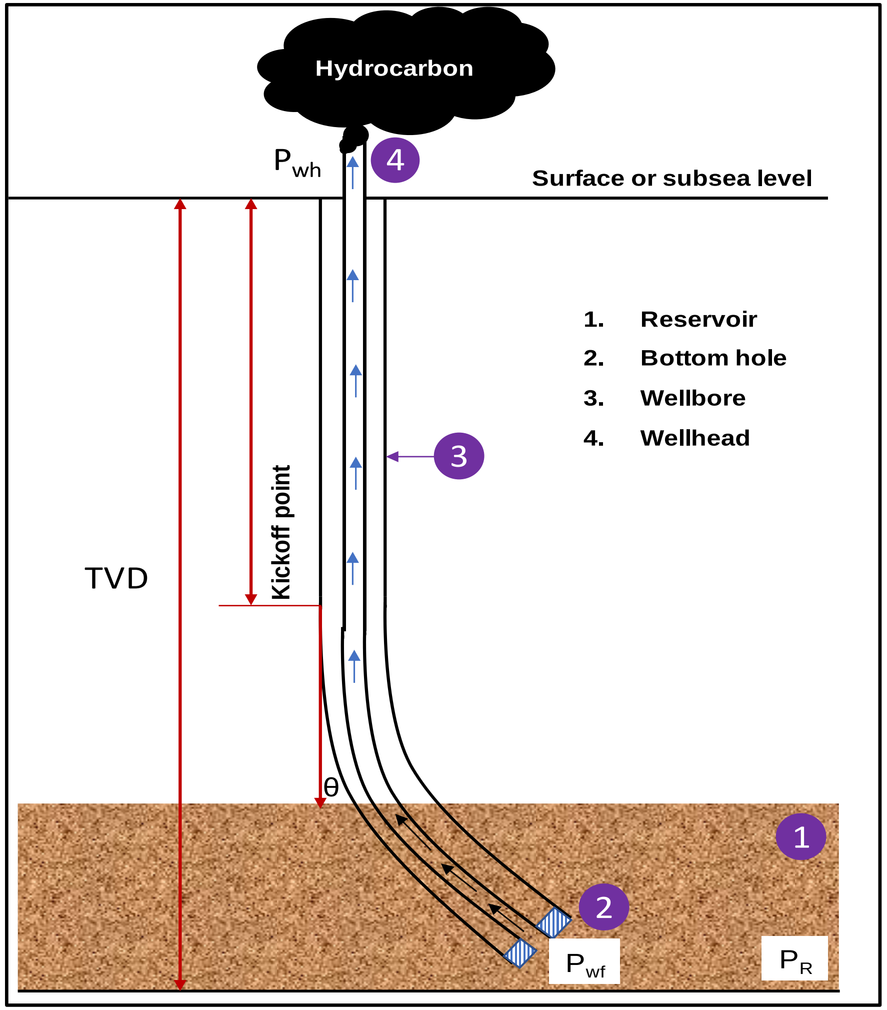


WCD - Computational Tool



- **Nodal Analysis Technique**
- **PVT Model**
- **Production Model**
- **Reservoir Model**
- **Hydrodynamic Flow Model**

WCD CT- Nodal Analysis



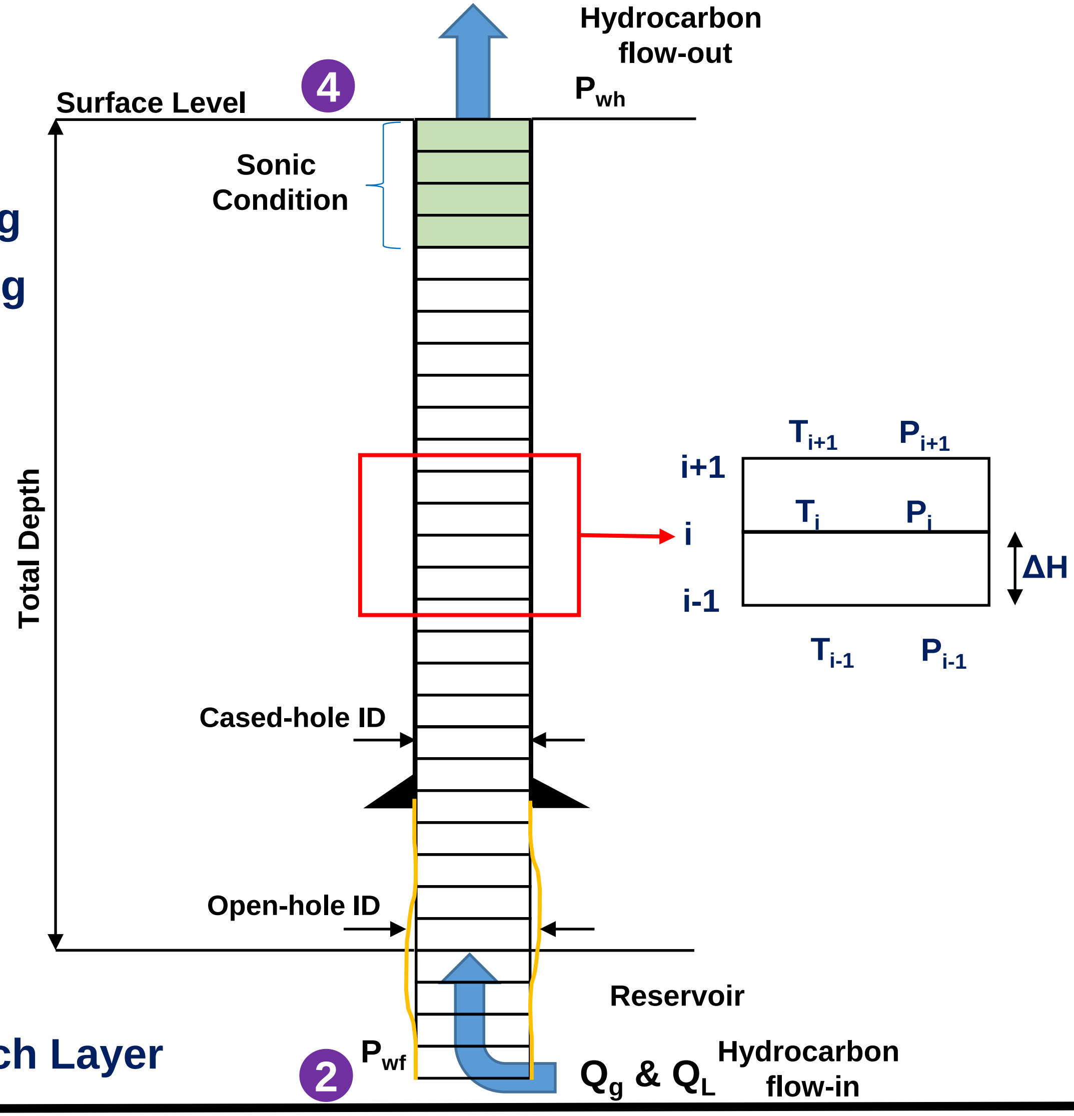
Schematic of WCD scenario

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



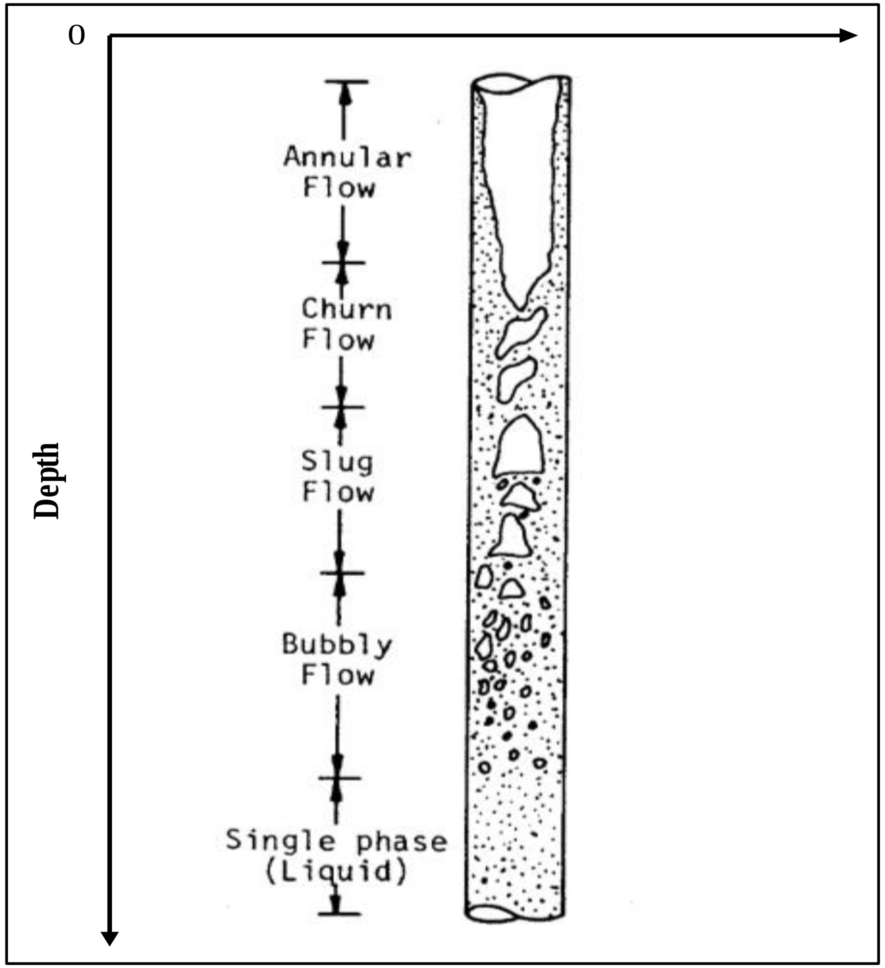
Fluid flow in the Wellbore

❖ Single phase flow

- Liquid flow
- Gas flow

❖ Two-phase flow

- Bubbly flow
- Dispersed bubble flow
- Slug flow
- Churn flow
- Annular flow
- Mist flow

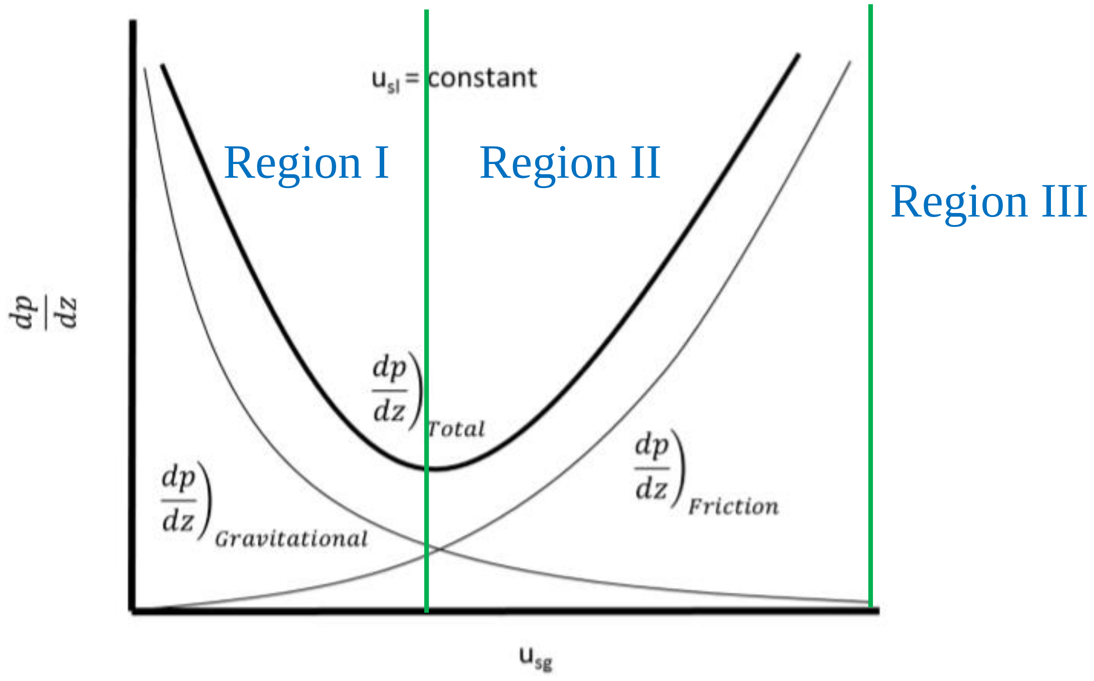


Schematic of expected two-phase flow pattern in the wellbore (Modified after Hasan and Kabir 1988)

Mechanistic Model for Two-Phase Flow in Pipe

❖ Existing Two-Phase Flow Model

REFERENCE	FLOW PATTERN
Hasan & Kabir (1984)	Bubble, Slug & Annular
Pagan et al. (2017)	Churn & Annular
Ansari et al. (1994)	Dispersed, Bubble, Slug & Annular
Tengesdal et al. (1999)	Bubble, Slug, churn & Annular
Sylvester (1987)	Slug
Yao and Sylvester (1987)	Annular – Mist

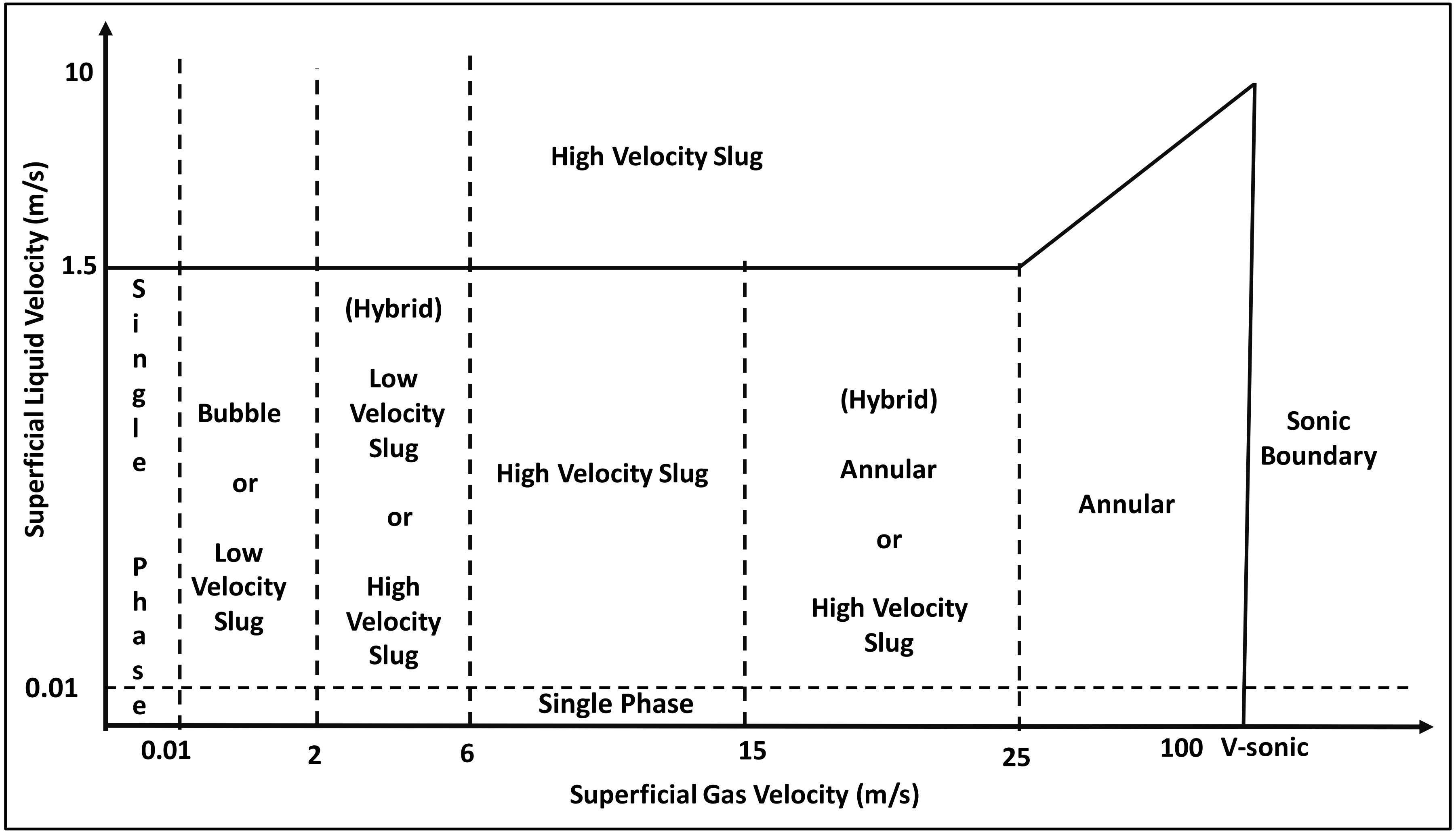


(Shoham, 2005)

Modified Flow Pattern Map for WCD – Computational Tool

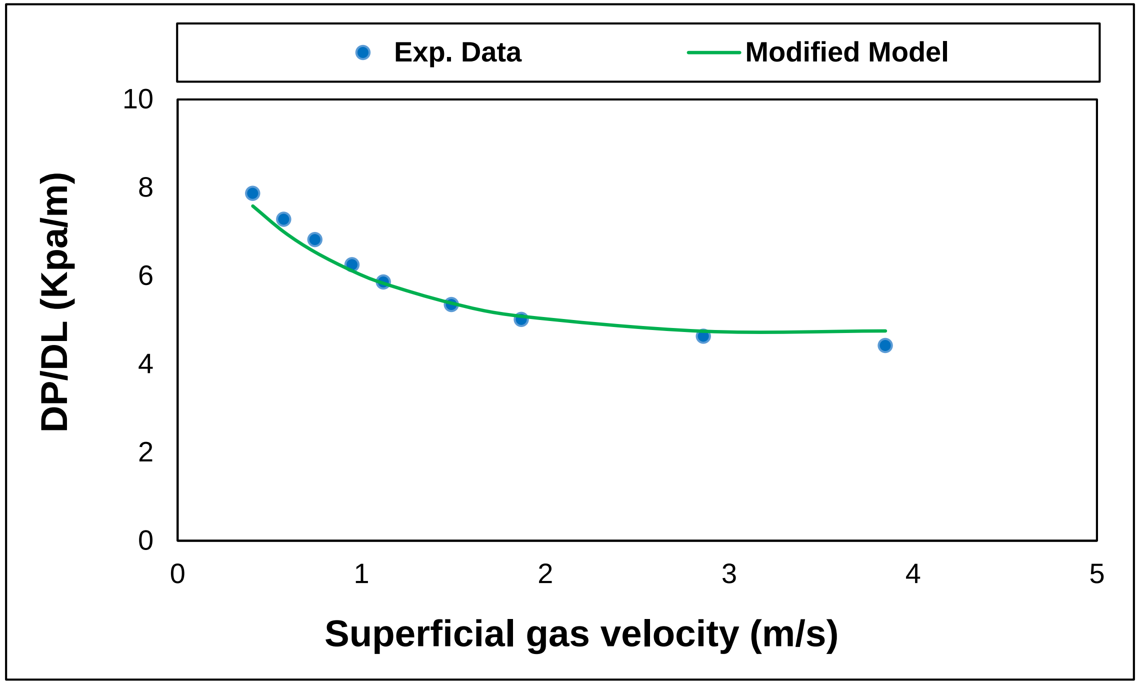
WCD Model

- Sigle Phase flow model
- Bubble flow model
- Low velocity slug model
- High velocity slug model
- Annular flow model
- Hybrid model

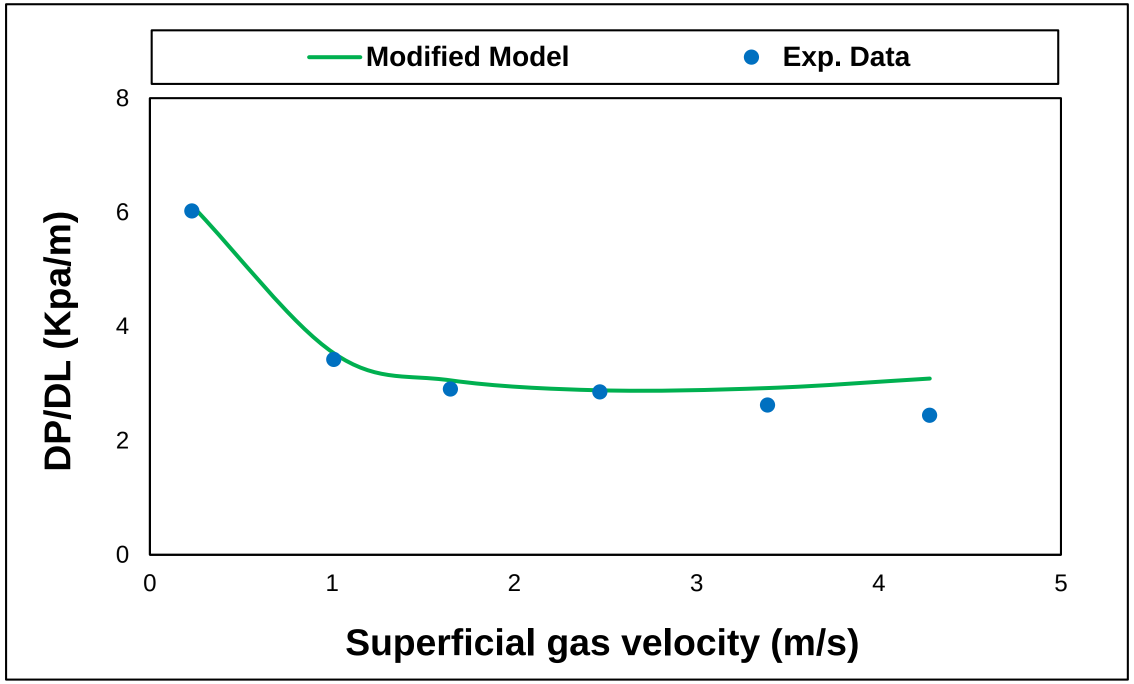


Mechanistic Model for Two-Phase Flow in Pipe – Validation

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



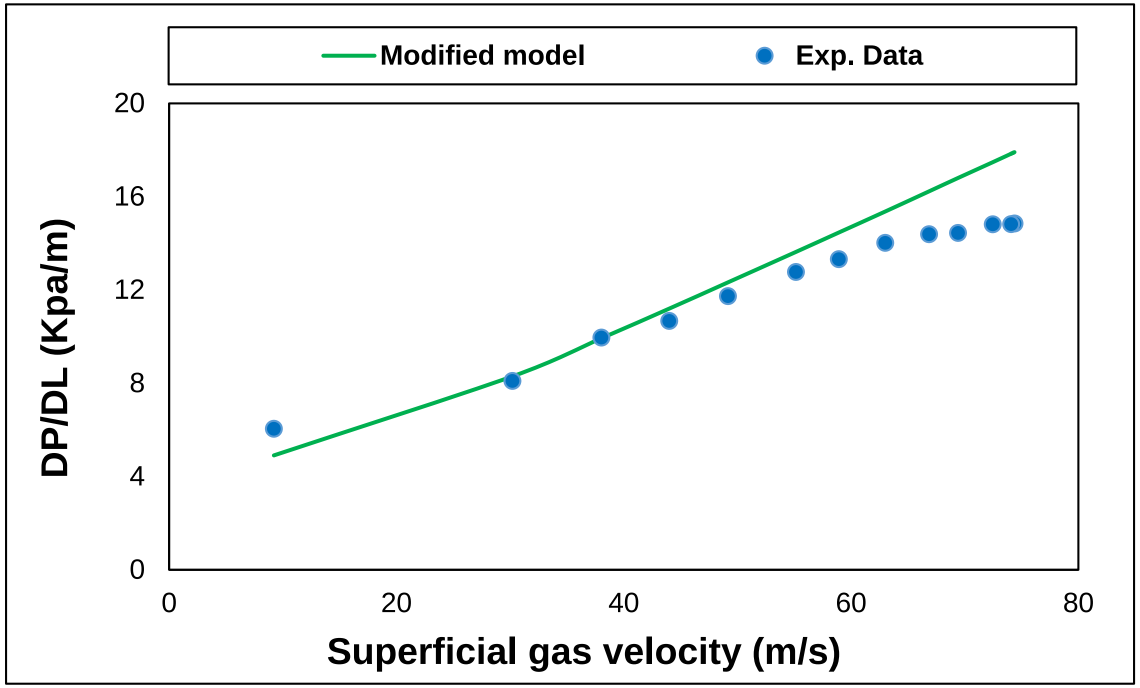
- ✓ Superficial Liquid velocity = 0.73 m/s
- ✓ Pipe ID = 1.5 in
- ✓ Superficial gas velocity = 0.40 – 3.85 m/s.
- ✓ Slug flow pattern
- ✓ Discrepancy between predicted & measured < 7%



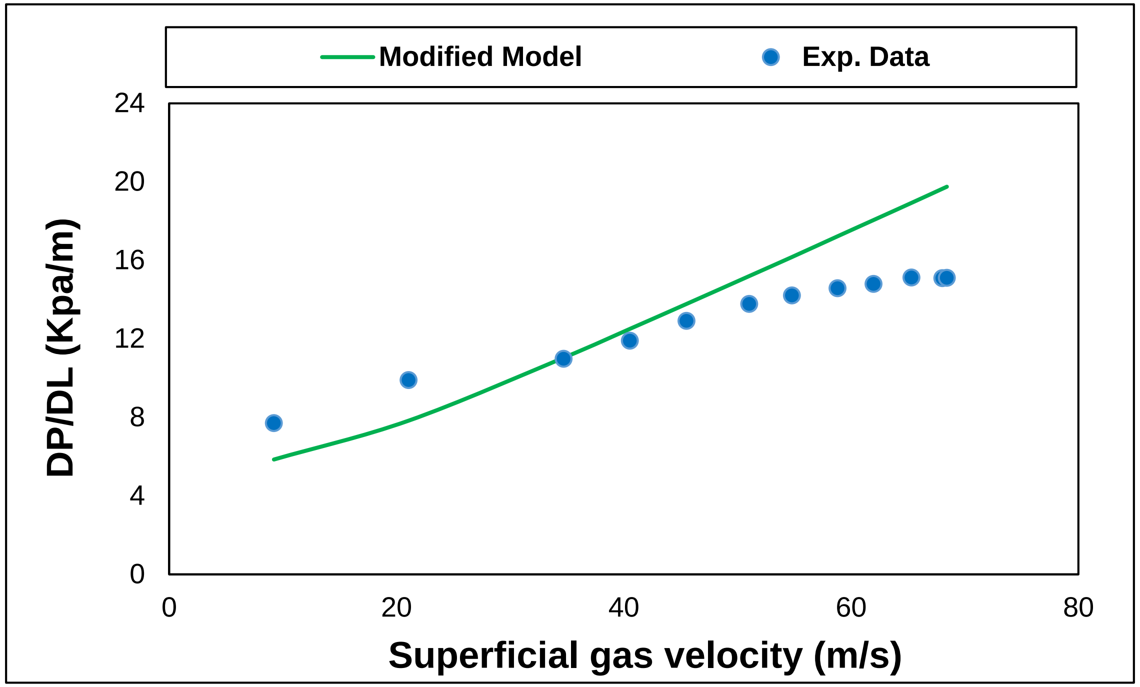
- ✓ Superficial Liquid velocity = 0.1 m/s
- ✓ Pipe ID = 1.5 in
- ✓ Superficial gas velocity = 0.23 – 4.28 m/s.
- ✓ Slug flow pattern
- ✓ Discrepancy between predicted & measured < 7%

Mechanistic Model for Two-Phase Flow in Pipe – Validation

❖ High Flow Conditions (OU – Lab Data)



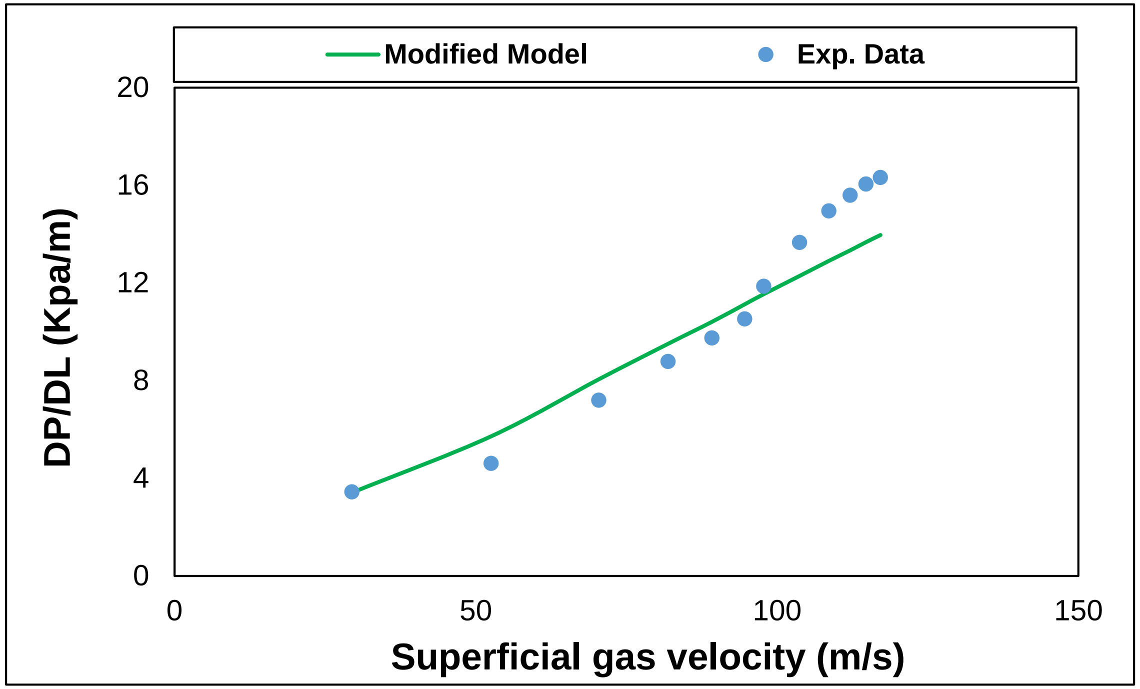
- Liquid flow rate = **200 gpm (V_{sl} = 2.41 m/s)**
- Pipe ID = 3.25 in
- Superficial gas velocity = 9.21 – 78 m/s.
- **Slug flow pattern**
- Discrepancy between predicted & measured < 20%



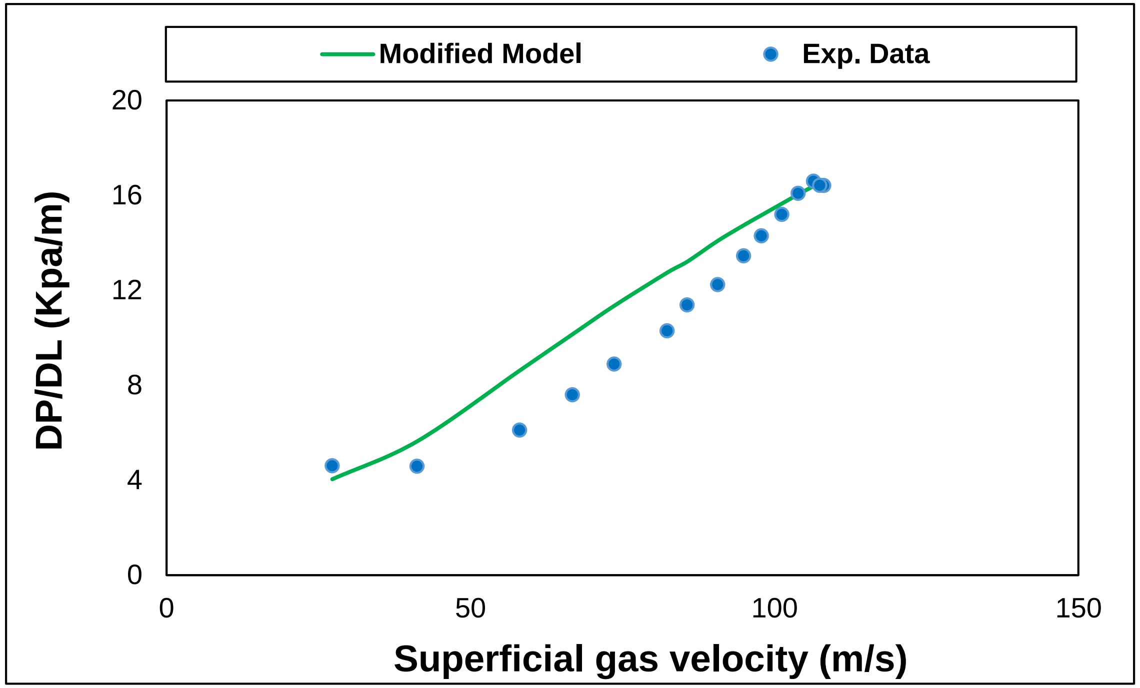
- Liquid flow rate = 240 gpm (V_{sl} = 2.86 m/s)
- Pipe ID = 3.25 in
- Superficial gas velocity = 9.22 – 68 m/s.
- Slug flow pattern
- Discrepancy between predicted & measured < 25%

Mechanistic Model for Two-Phase Flow in Pipe – Validation

❖ High Flow Conditions (OU – Lab Data)



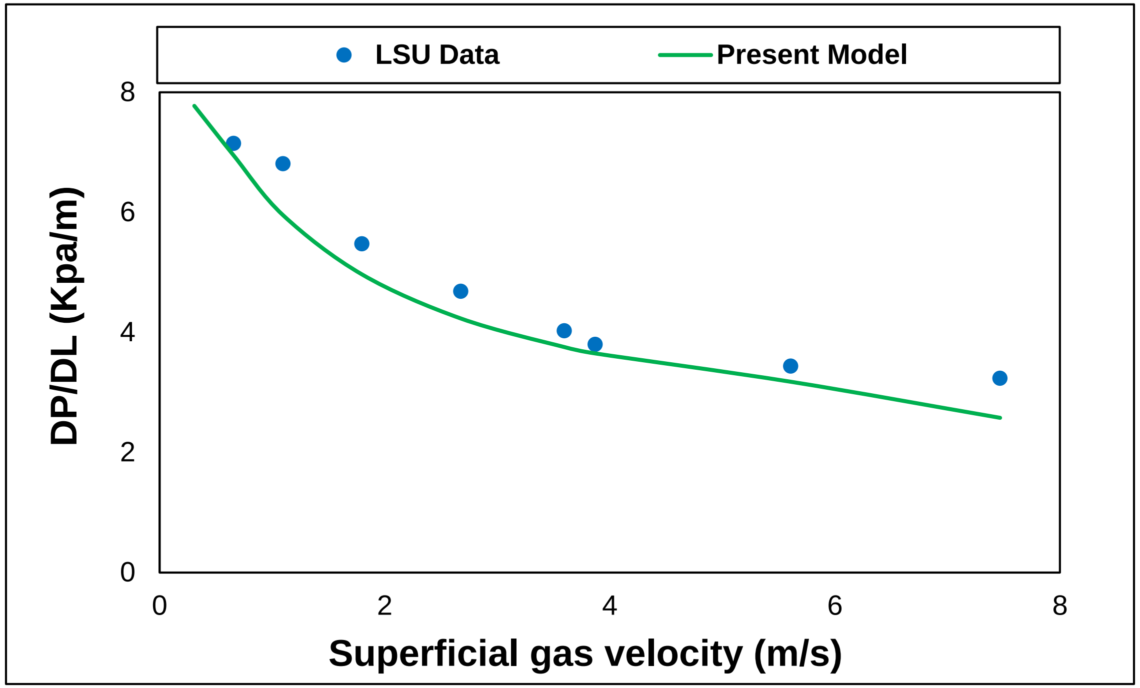
- Liquid flow rate = 60 gpm (V_{sl} = 0.72 m/s)
- Pipe ID = 3.25 in
- Superficial gas velocity = 29 – 117 m/s.
- Annular flow pattern
- Discrepancy between predicted & measured < 20%

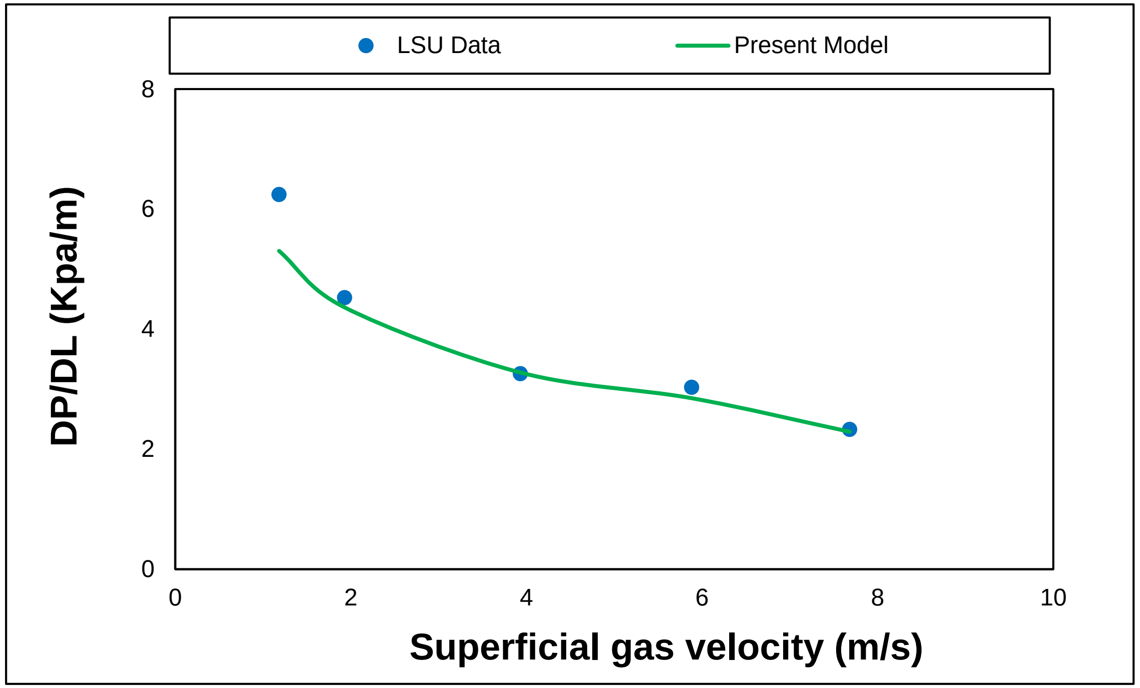


- Liquid flow rate = 80 gpm (V_{sl} = 0.93 m/s)
- Pipe ID = 3.25 in
- Superficial gas velocity = 27 – 107 m/s.
- Annular flow pattern
- Discrepancy between predicted & measured < 25%

Mechanistic Model for Two-Phase Flow in Pipe – Validation

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



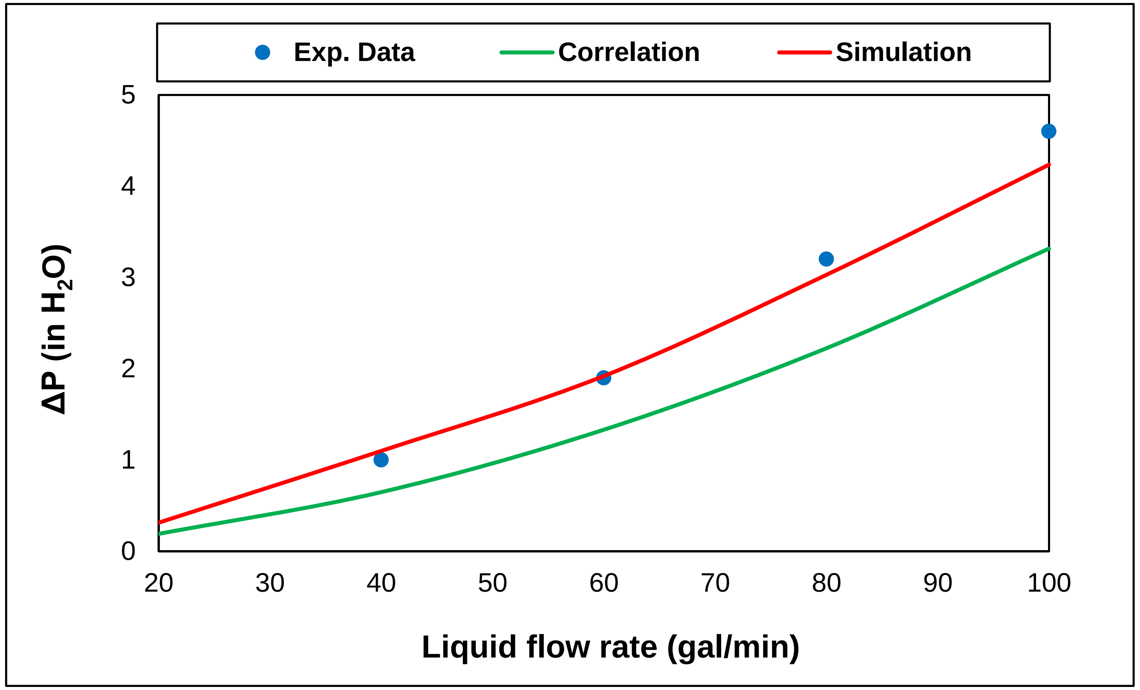


- ✓ Superficial liquid velocity V_{sl} = 0.73 m/s
- ✓ Pipe ID = 12 in
- ✓ Superficial gas velocity = 0.31 – 7.5 m/s.
- ✓ Discrepancy between predicted & measured < 25%

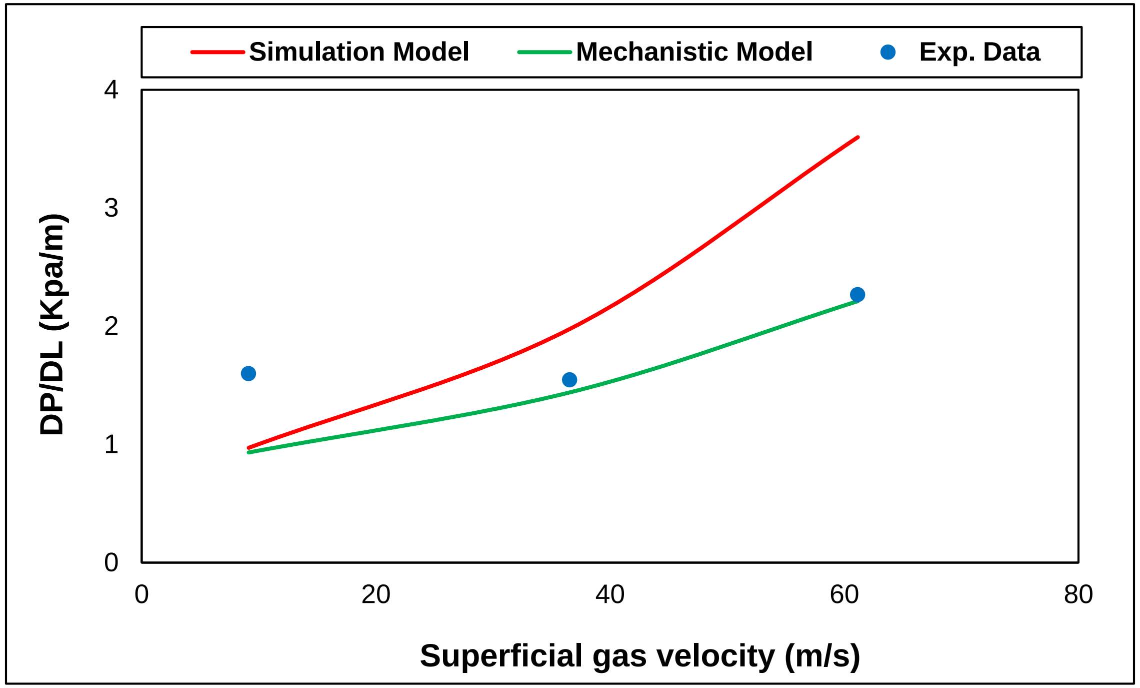
- ✓ Superficial liquid velocity V_{sl} = 0.46 m/s
- ✓ Pipe ID = 12 in
- ✓ Superficial gas velocity = 1.18 – 7.7 m/s.
- ✓ Discrepancy between predicted & measured < 18%

Comparison Between CFD and Mechanistic Model

Single phase flow comparison



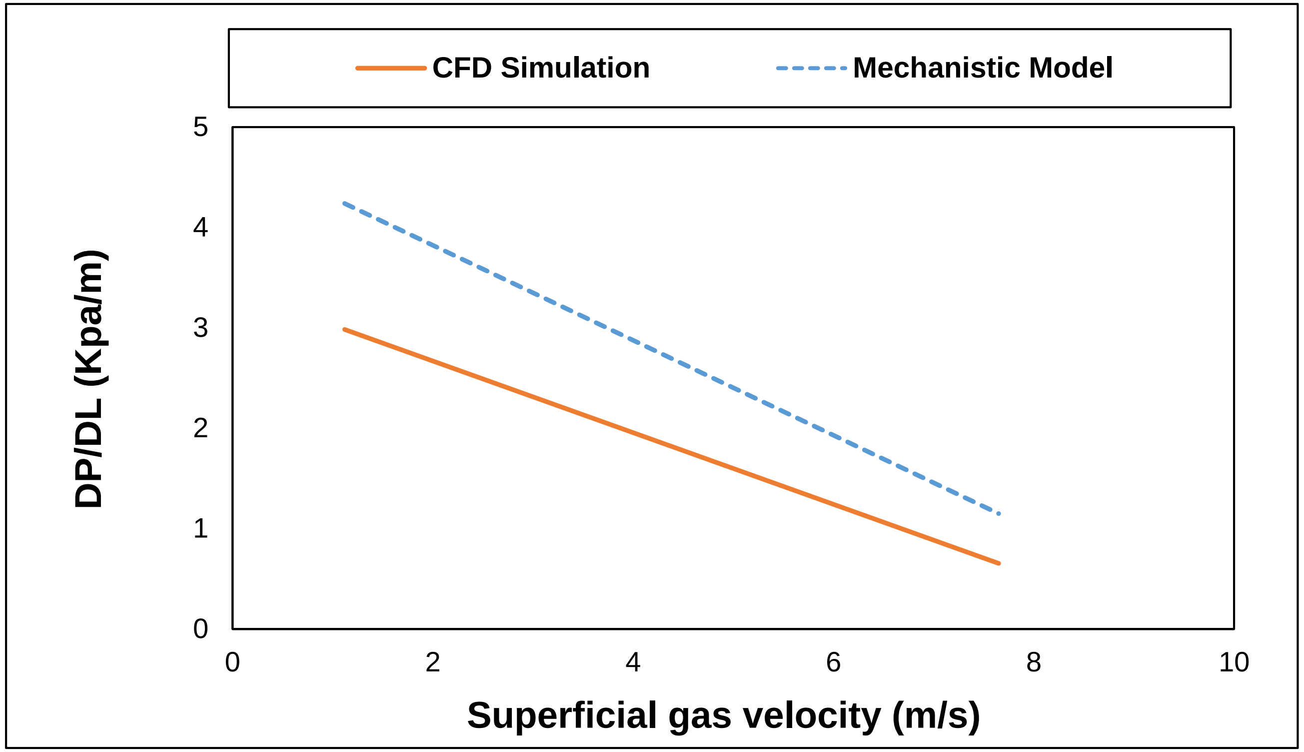
Two phase flow comparison



- 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)



Pipe Diameter	Vsg	Vsl	DP/Dl (Sim)	DP/Dl (Model)	Discrepancy
in	(m/s)	(m/s)	Kpa/m	Kpa/m	%
22	1.12	0.46	2.985	4.24	30%
22	7.65	0.46	0.655	1.15	43%

Conclusions

- 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

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Outlines

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

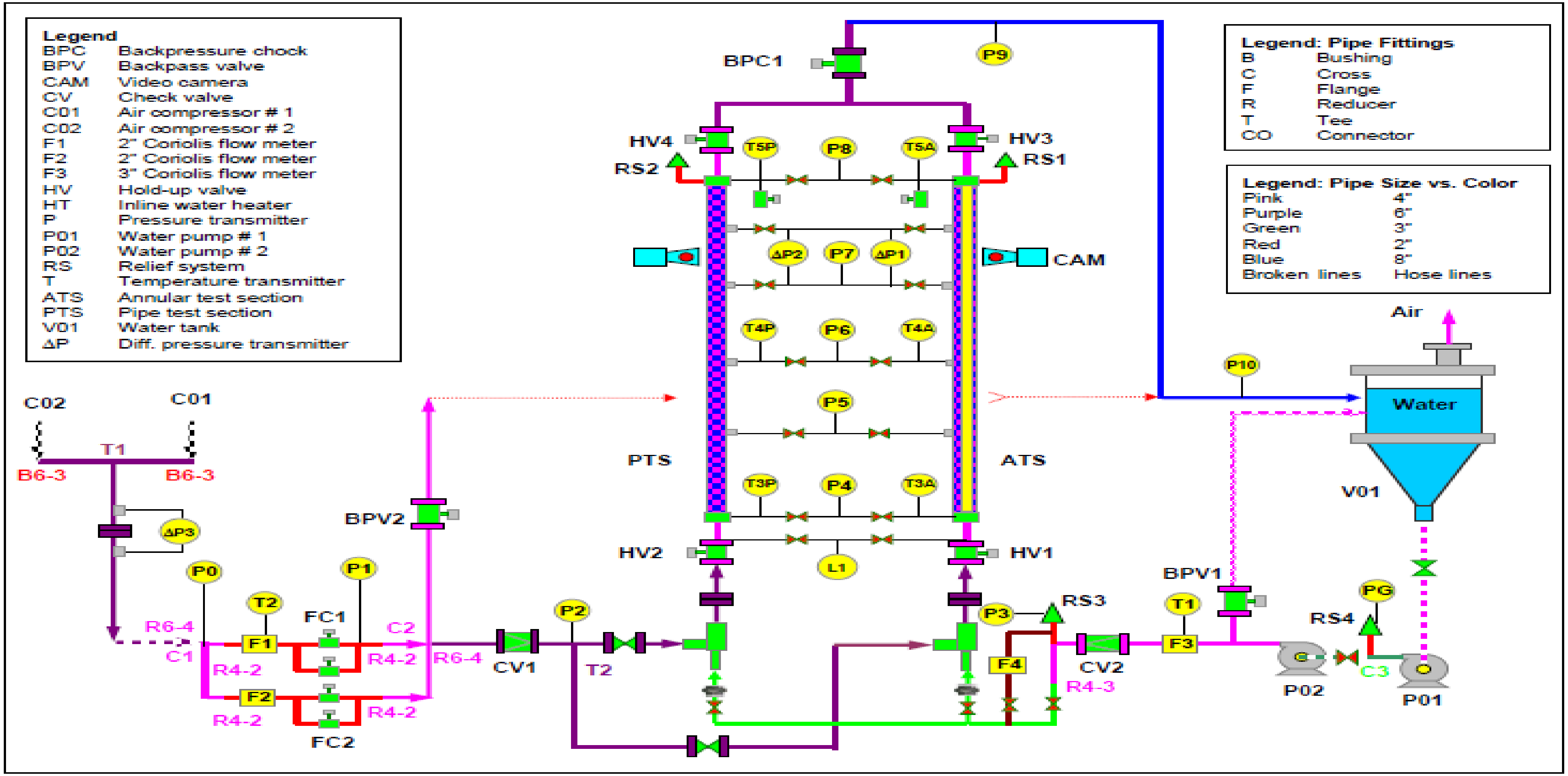
Objectives

- 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



Preliminary Test
(Single Phase Liquid Flow Test)

Pressure loss (ΔP) in any circular duct is related to diameter (D), length (L), fluid density (ρ) and mean fluid velocity (V). Thus:

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

Chen (1979) Friction Factor equ

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

where f_D is Darcy friction factor, which is defined as fourfold Fanning friction factor, ε is the pipe roughness, R_e is a Reynold number

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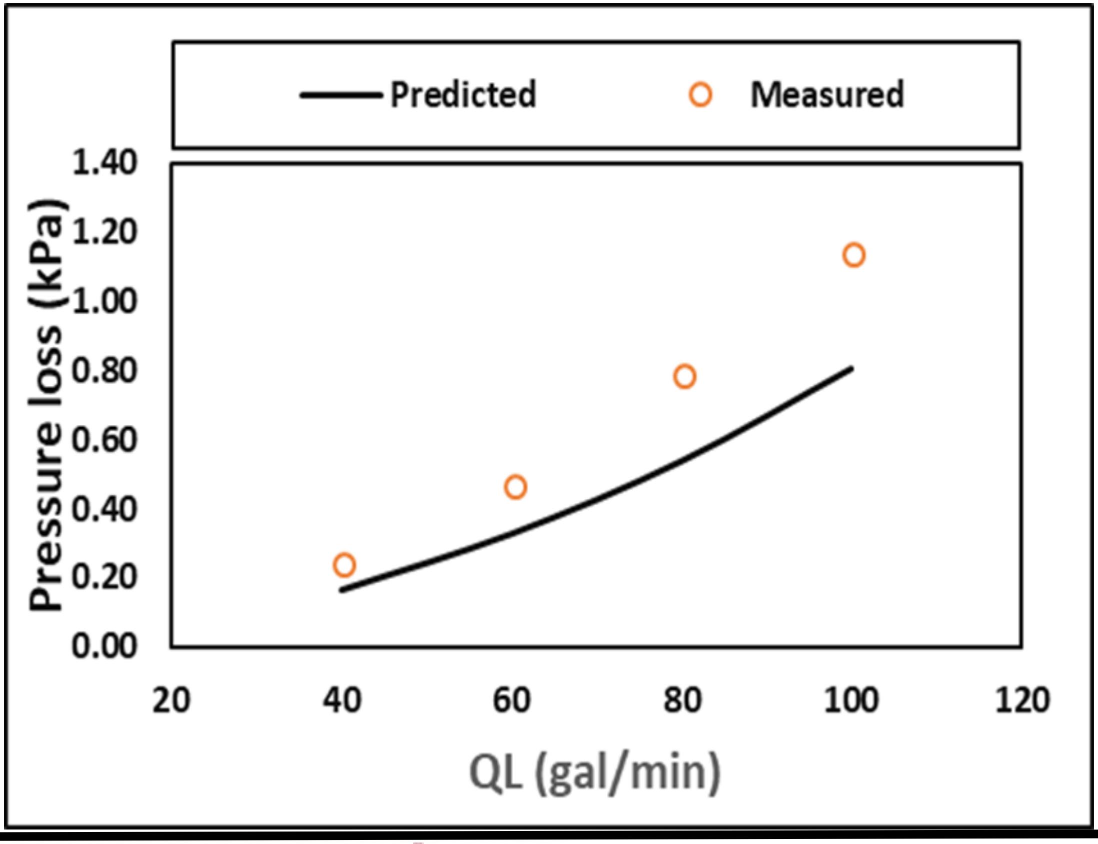
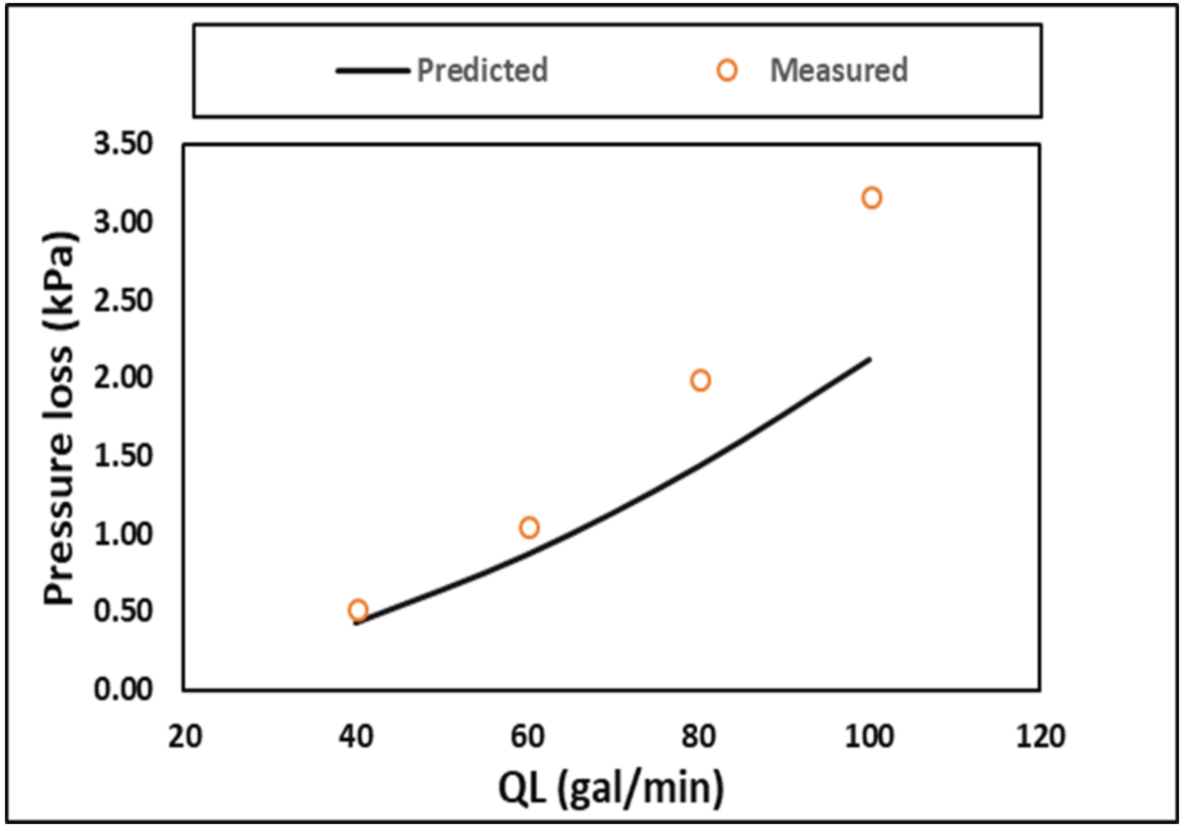
Preliminary Test
(Single Phase Liquid Flow Test)

Pipe



Annulus



Preliminary Test (Liquid Holdup Validation)

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

- DP liquid holdup measurement approach

$$H_L = \frac{\left(P_{wf}/\rho_l g\right)}{(H_T A)} = \frac{P_{wf}}{\rho_l g H_T}$$

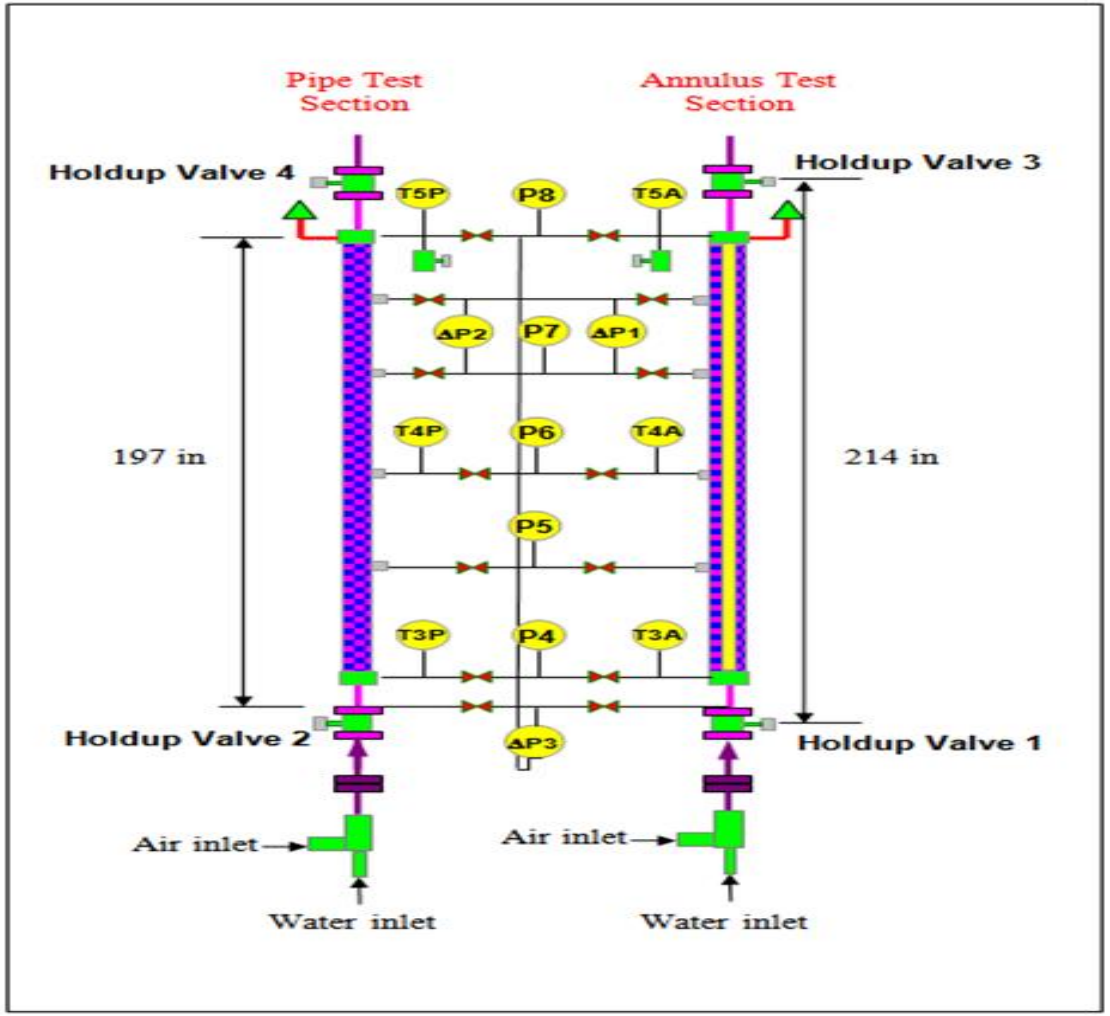
- Pwf is the bottom-hole pressure, A is the cross-section area of the test section, ρl represents liquid density, g depicts the gravity, and HT is the total height of the test section

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.

Q_L (GPM)	Q_g (lb/min)	H_L (DP Cell) %	(Volumetric H_L) %	Error %
35	25	7	8.0	1.0
40	10	14	12.9	1.1

Flow Regime (Churn Flow)

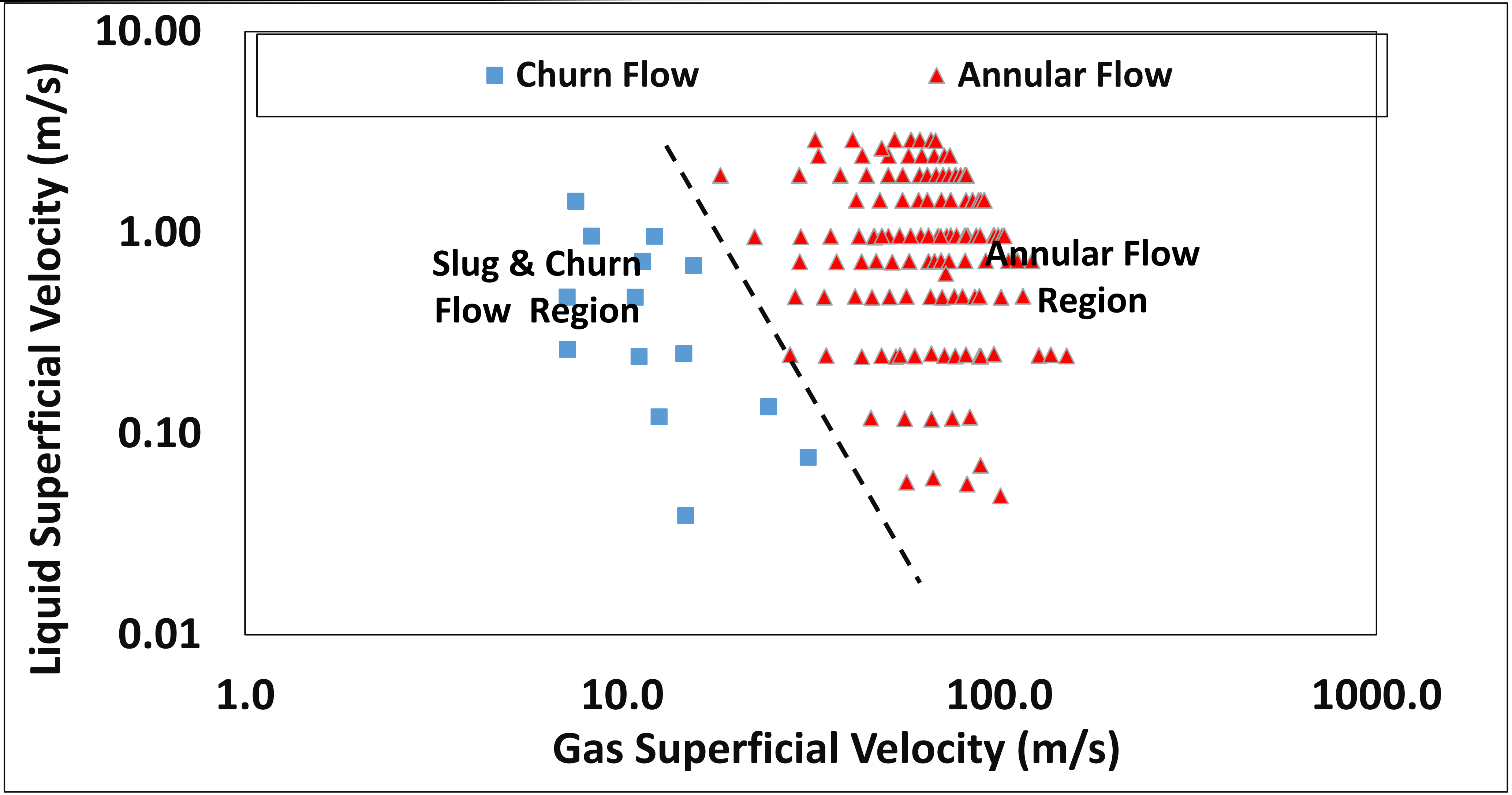
- **The classification of flow regimes is an important part of two-phase flow analysis.**
- **It aids to develop or select an appropriate flow model to predict two-phase behavior in vertical pipe and annulus**
- **Two-phase flow regimes depend on parameters such as liquid and gas velocities, pipe geometries, 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 Pipe



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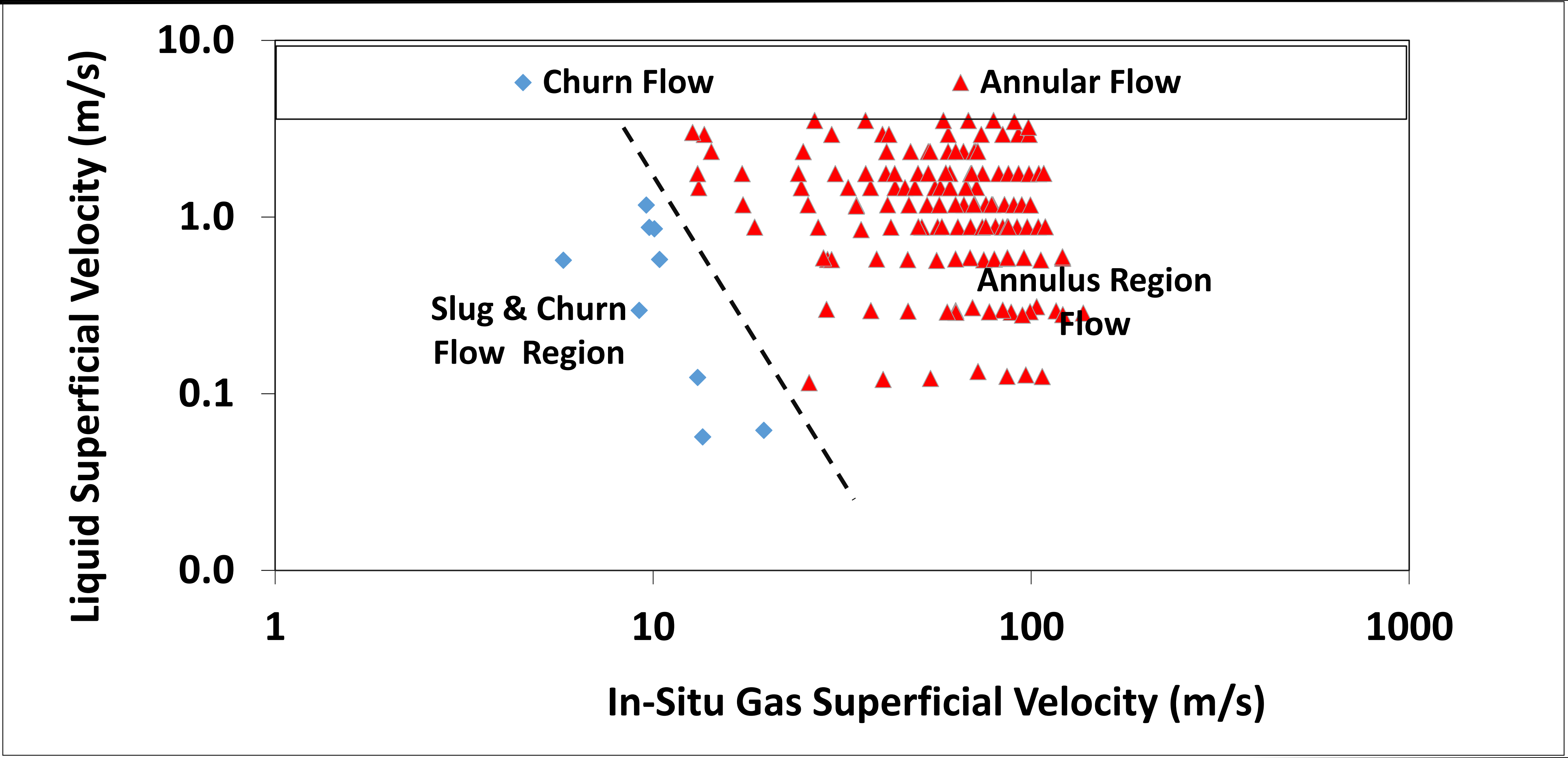
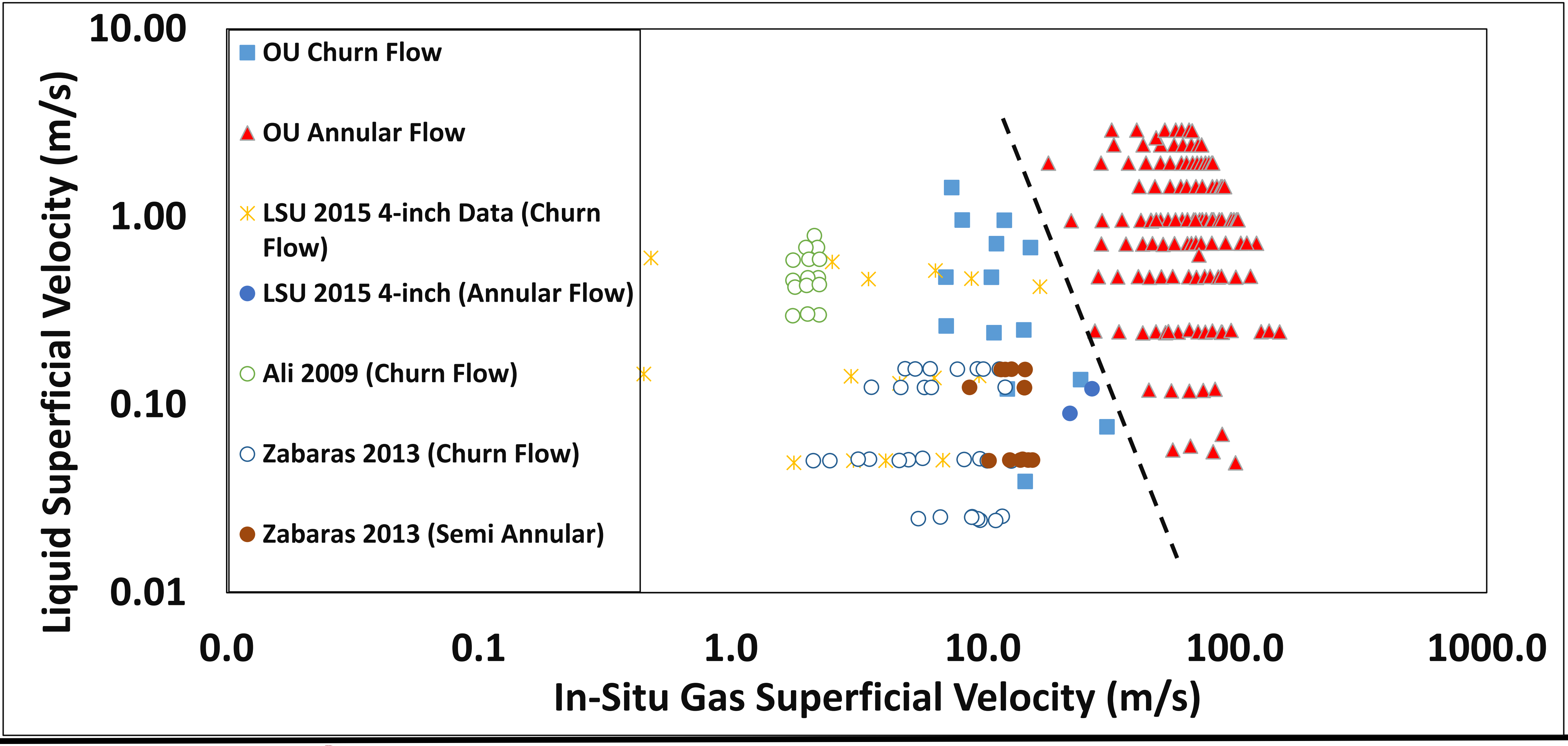
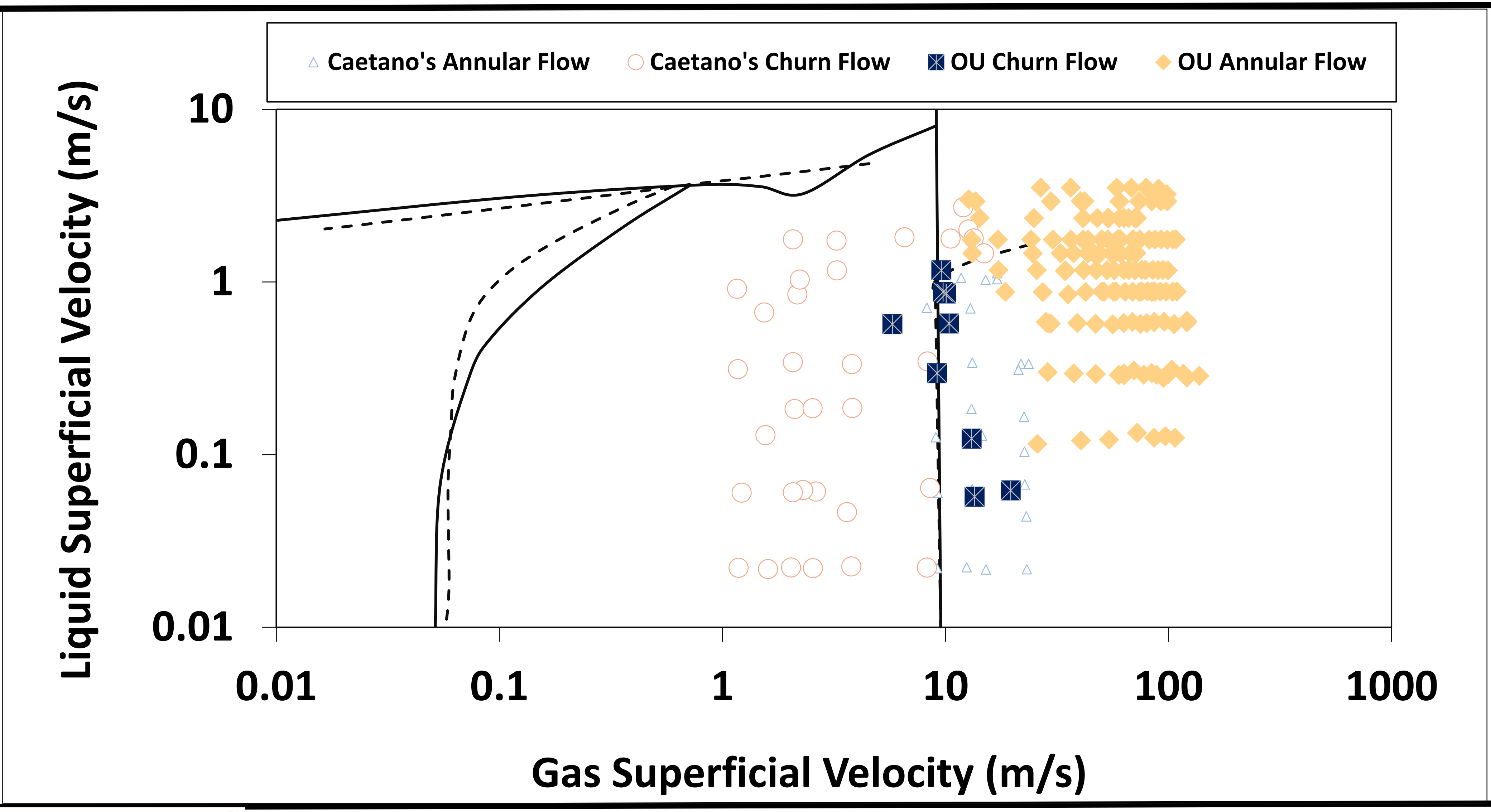
Flow Regime Map for Annulus



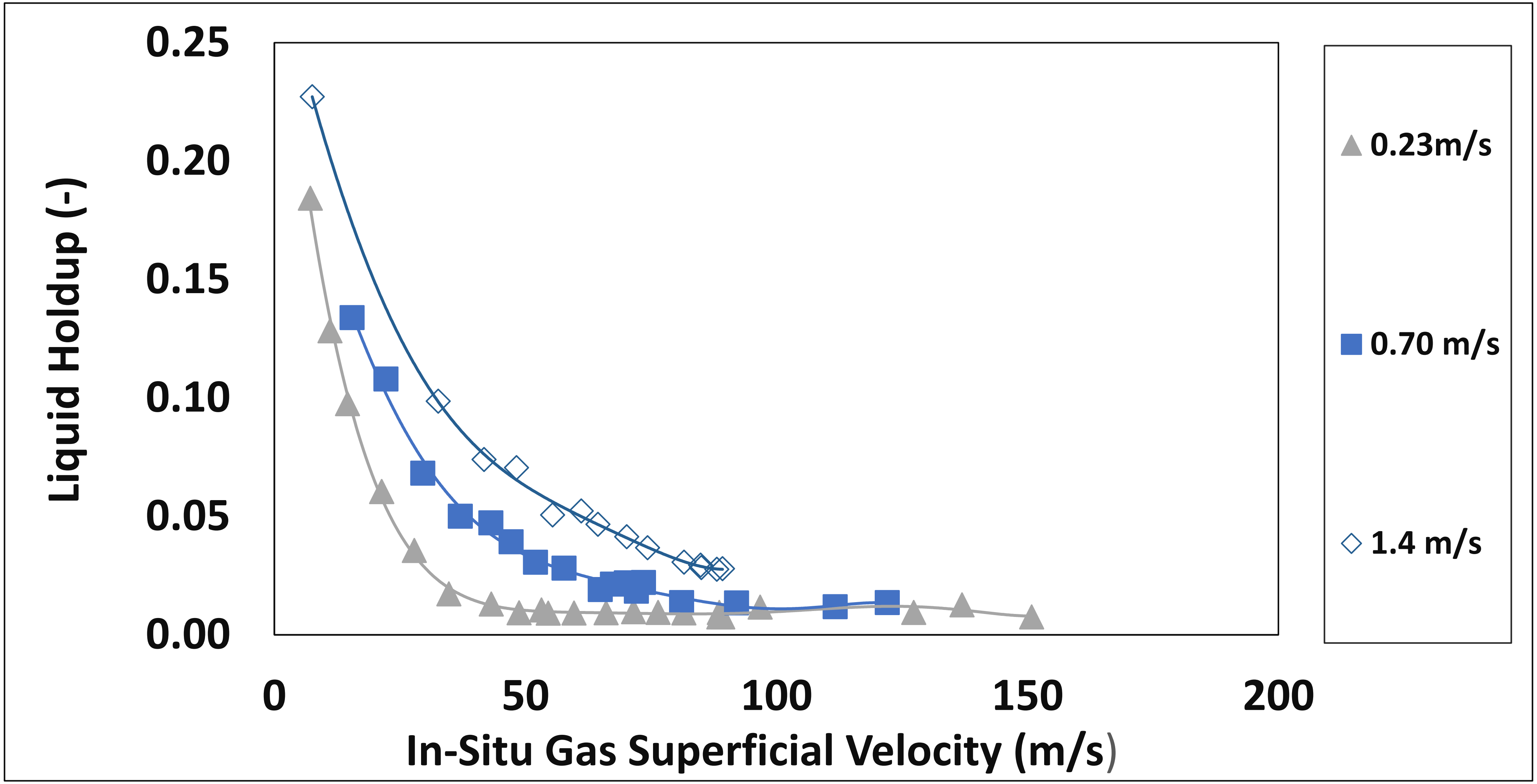
Flow Regime Comparison for Pipe



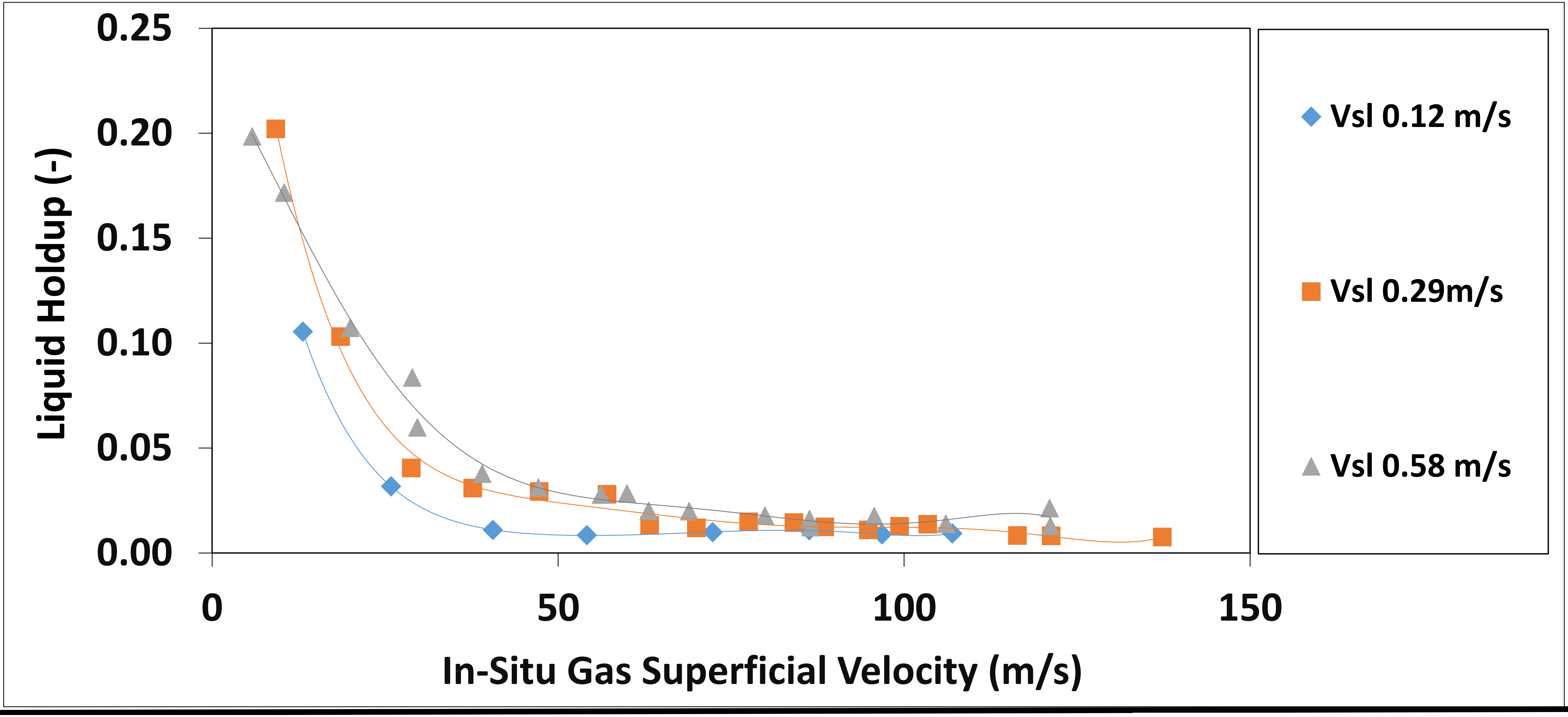
Flow Regime Comparison for Annulus



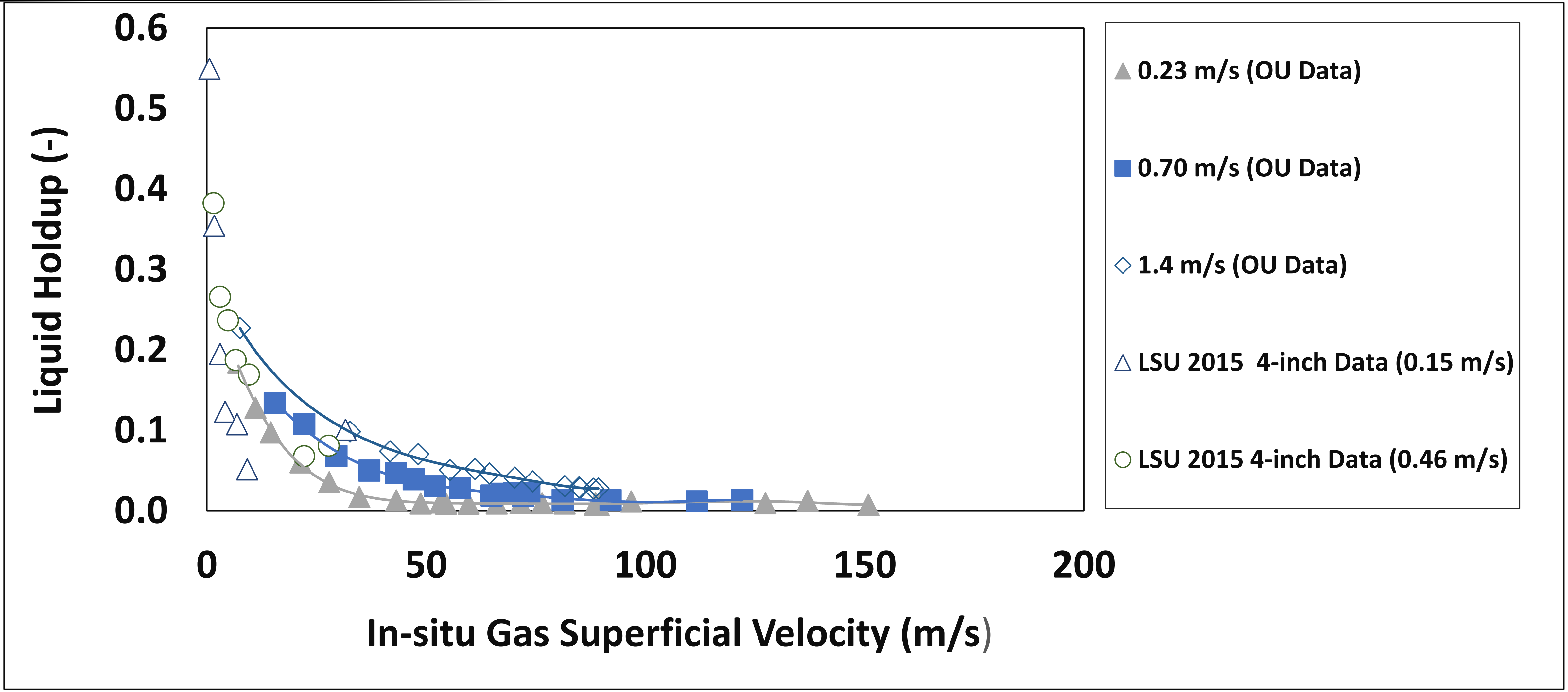
Holdup Measurement in Pipe (OU)



Holdup Measurement in Annulus (OU)



Comparison of Liquid Holdup with LSU data



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**

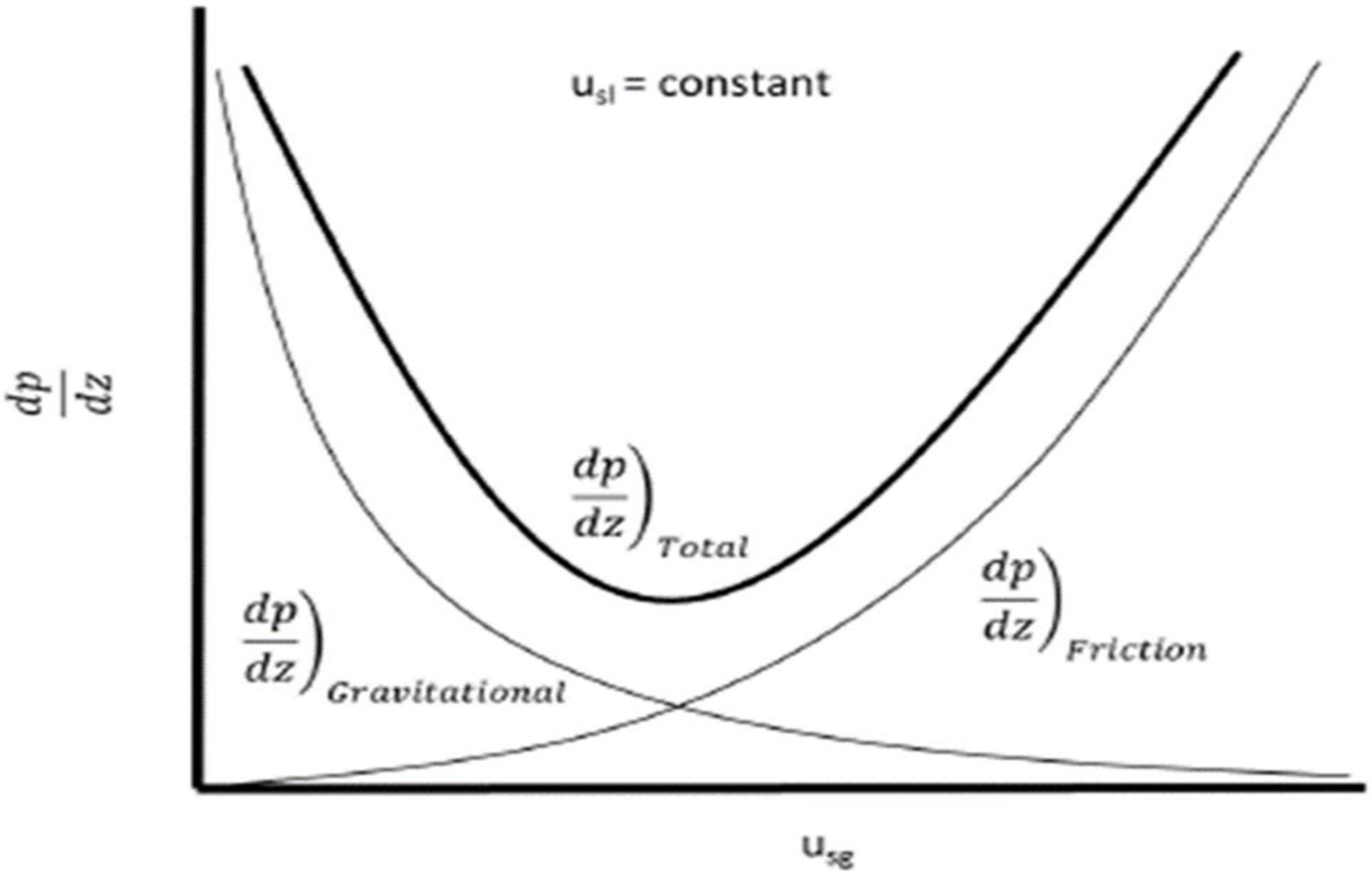
$$\left(\frac{\Delta P}{L}\right)_t = \left(\frac{\Delta P}{L}\right)_h + \left(\frac{\Delta P}{L}\right)_a + \left(\frac{\Delta P}{L}\right)_f$$

Pressure Gradient in Two-Phase Flow

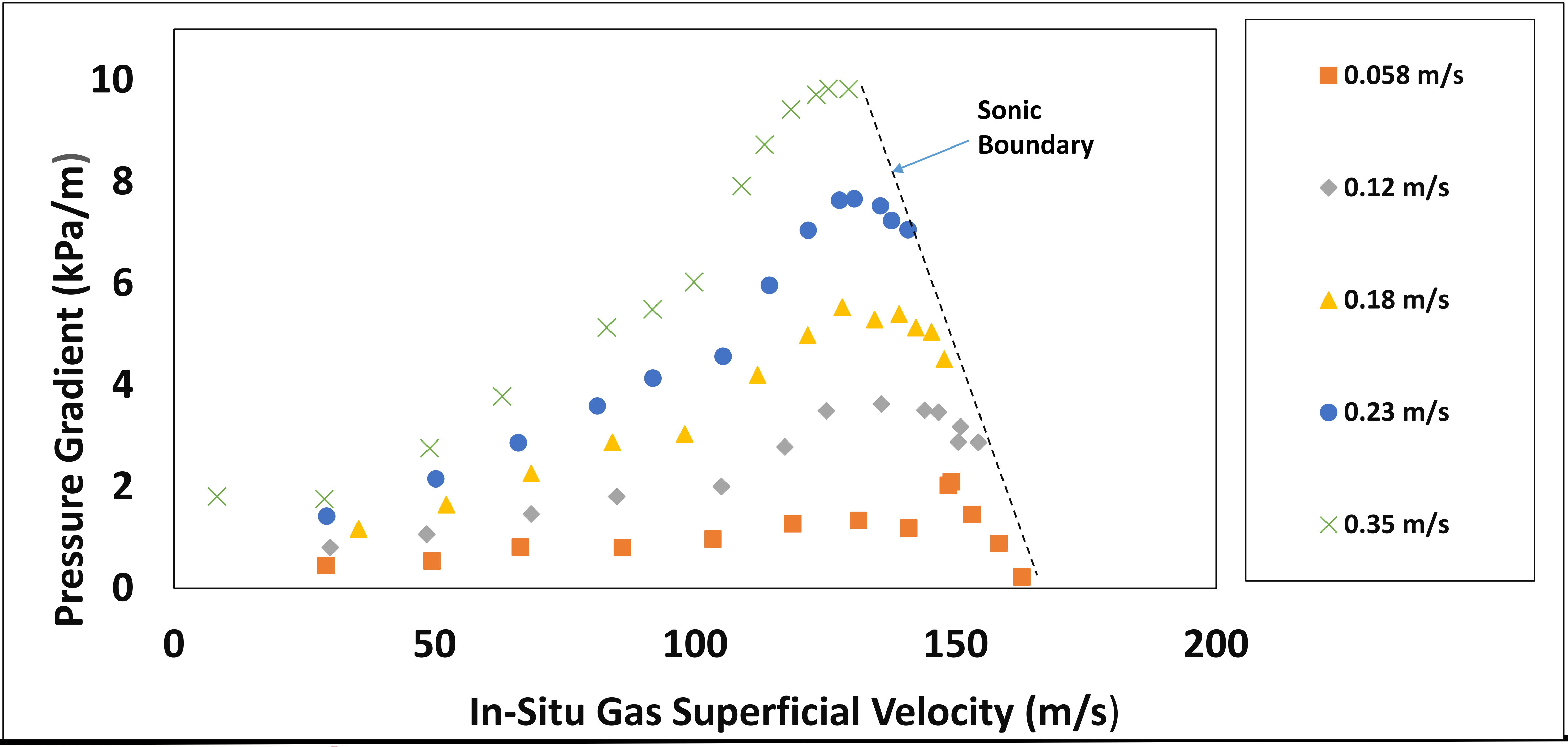
- The existence of hydrostatic component of two-phase pressure drop is due to differences in the density between the gas and liquid phase and the influence of the gravity.

- The acceleration component of pressure drop is usually small and can be neglected

Schematic Pressure Gradient Behavior in Vertical Two-Phase Flow (Shoham, 2005)



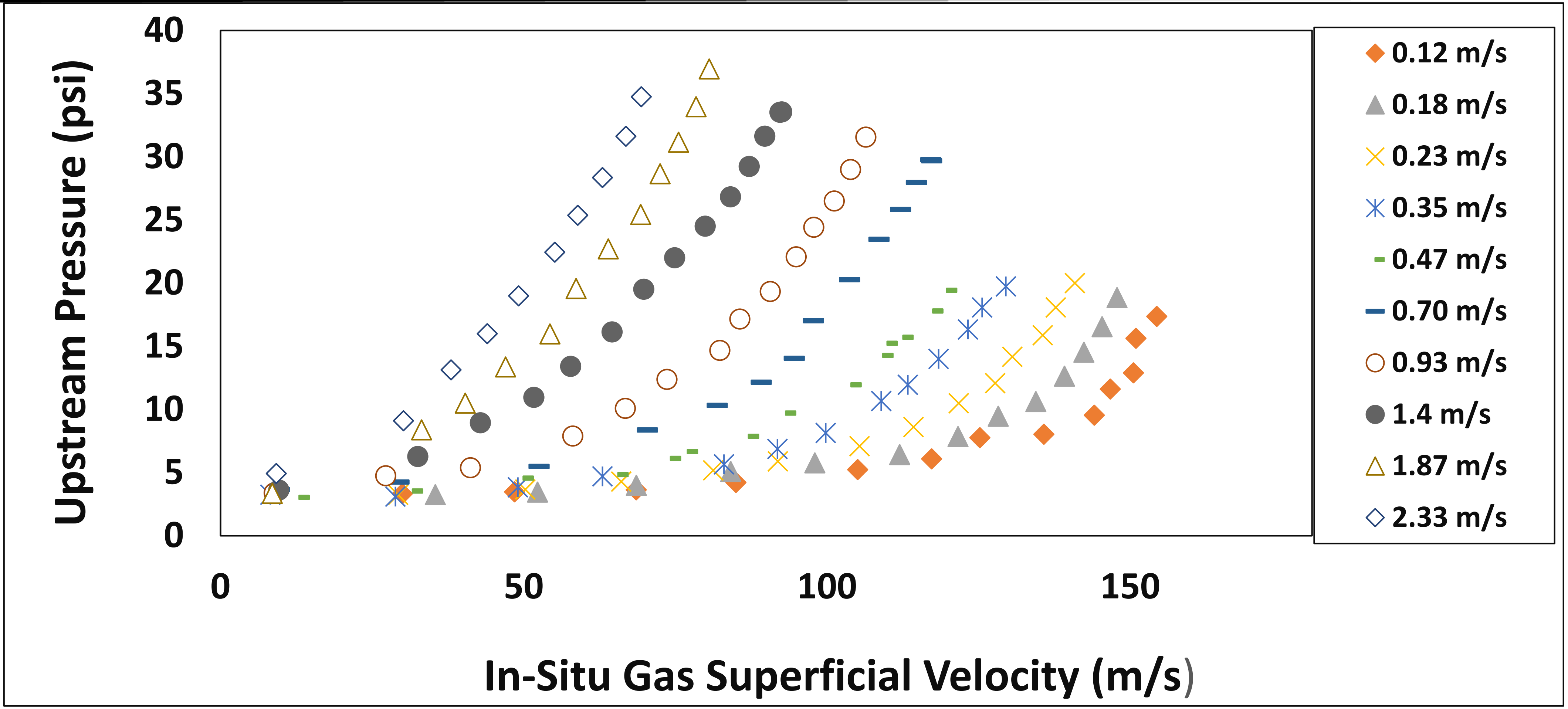
Pressure Gradient at Sonic Boundary (Pipe)



Indication of Sonic Condition

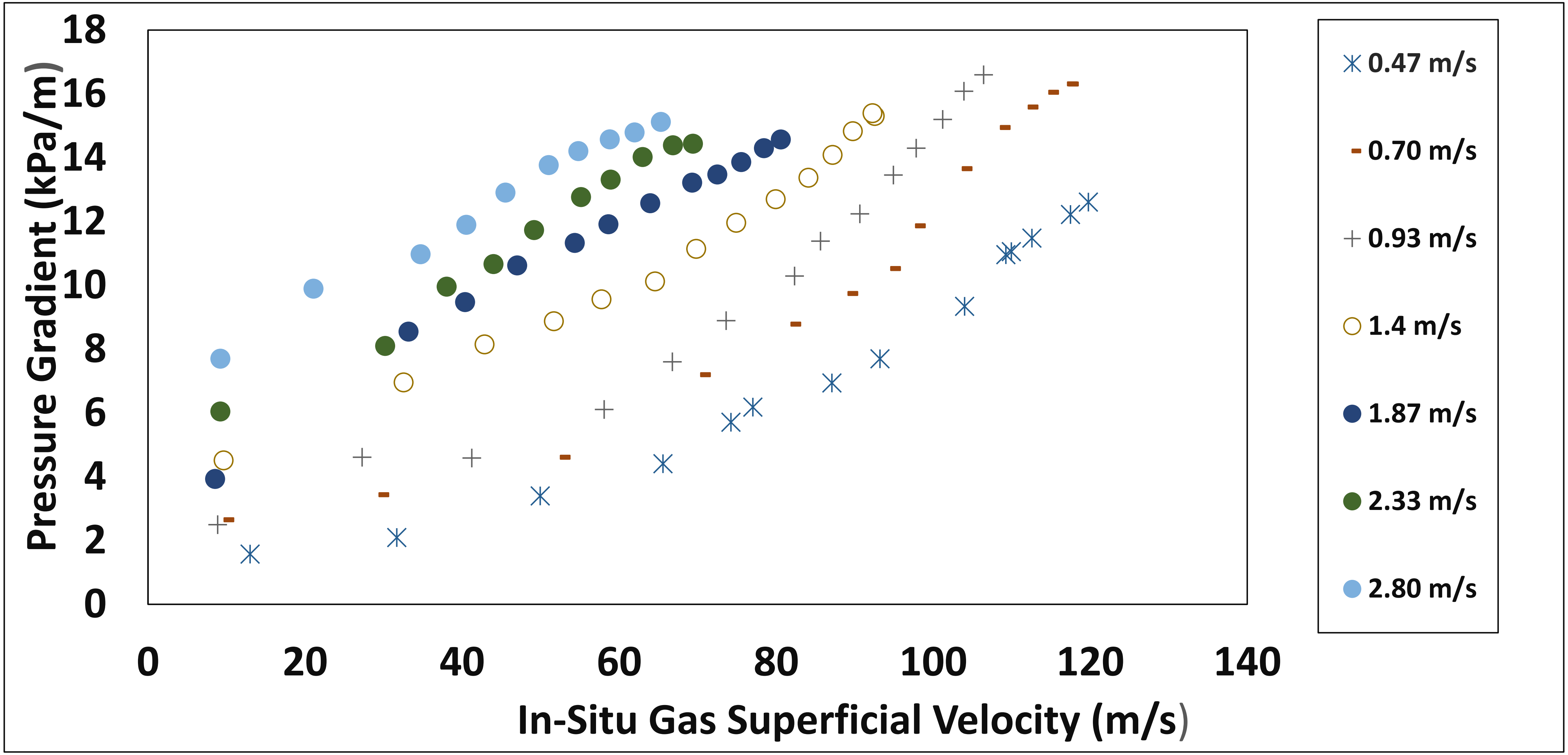
- Upstream Vs Gas Superficial Velocity
- Shock Wave
- Shock Wave Sound
- Pressure Reversal

Upstream Pressure VS Gas Superficial Velocity (Pipe)



Sample of Supersonic- Video (Vsl =0.058 m/s, Vsg = 162.57 m/s, Pipe ID:0.083M)

Pressure Gradient Without Sonic Boundary (Pipe)



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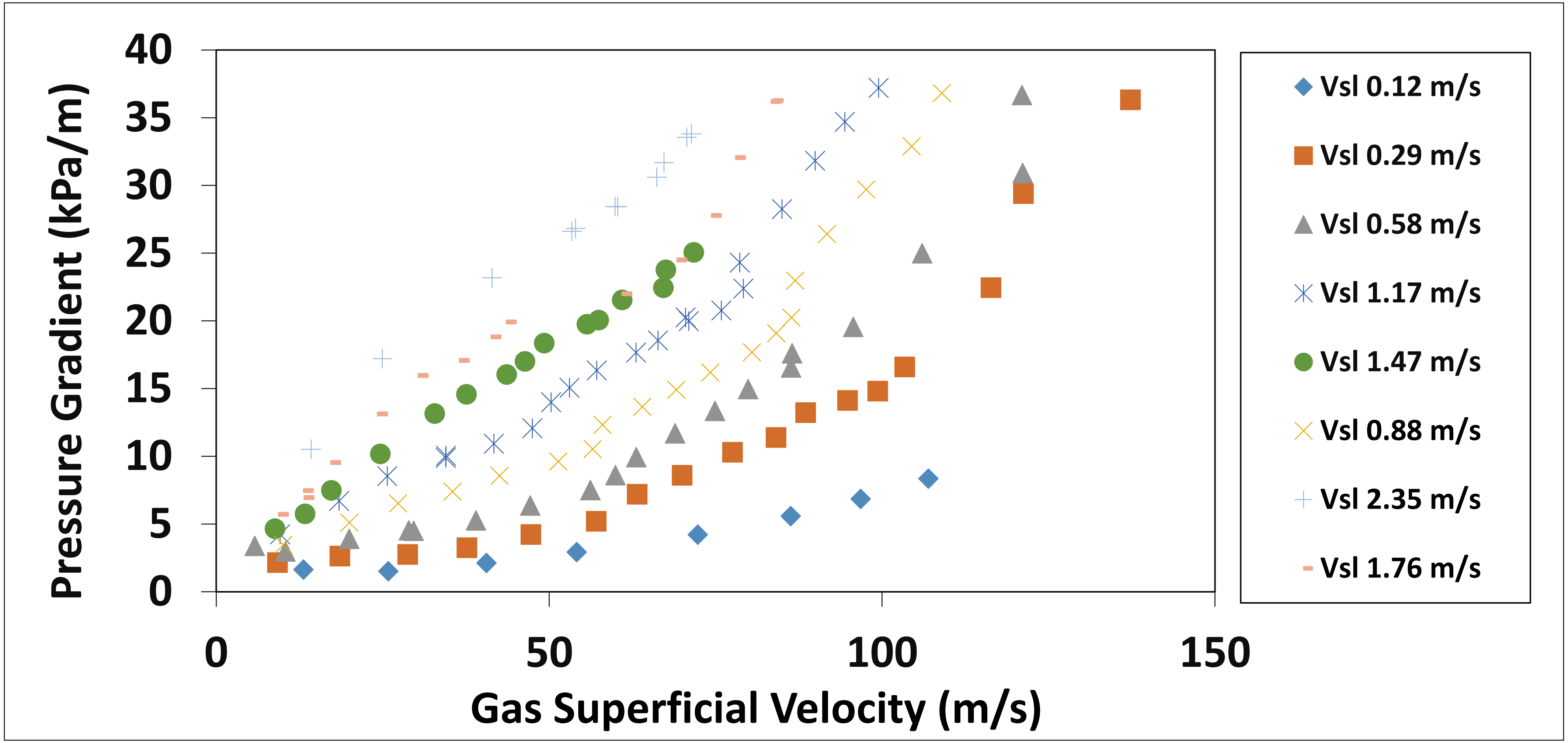
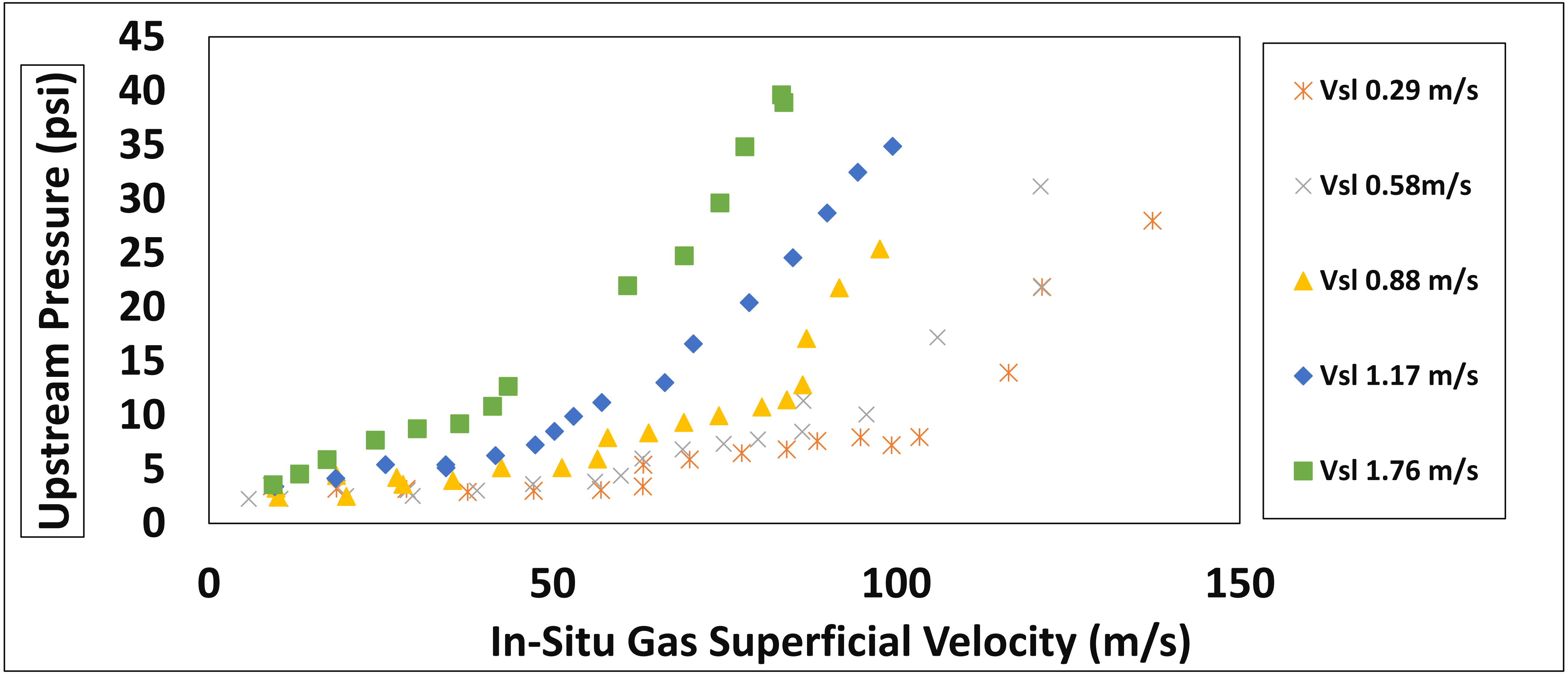
Pressure Gradient (Annulus)



Upstream Pressure VS Gas Superficial Velocity (Annulus)



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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

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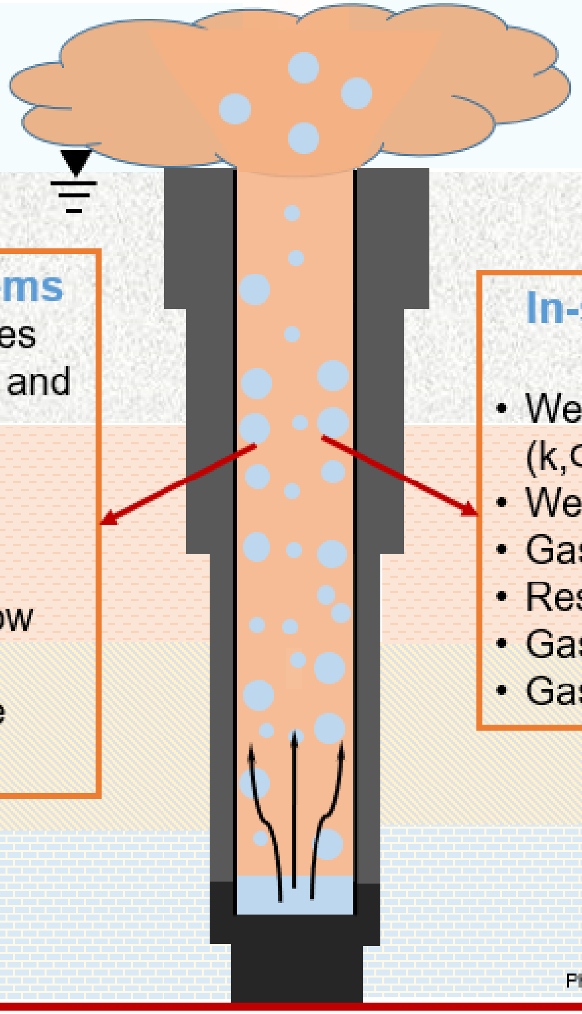
Outline

- **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,Φ, J)
- Well depth
- Gas in place
- Reservoir thickness
- Gas solubility in oil
- Gas liquid ratio

*k: Permeability; Φ: Porosity
J: Productivity Index

Photograph Courtesy: Kiran and Salehi, 2017

Way Forward

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

CFD Modeling

Identifying Problem

1. Goals
2. Domain

Pre-processing

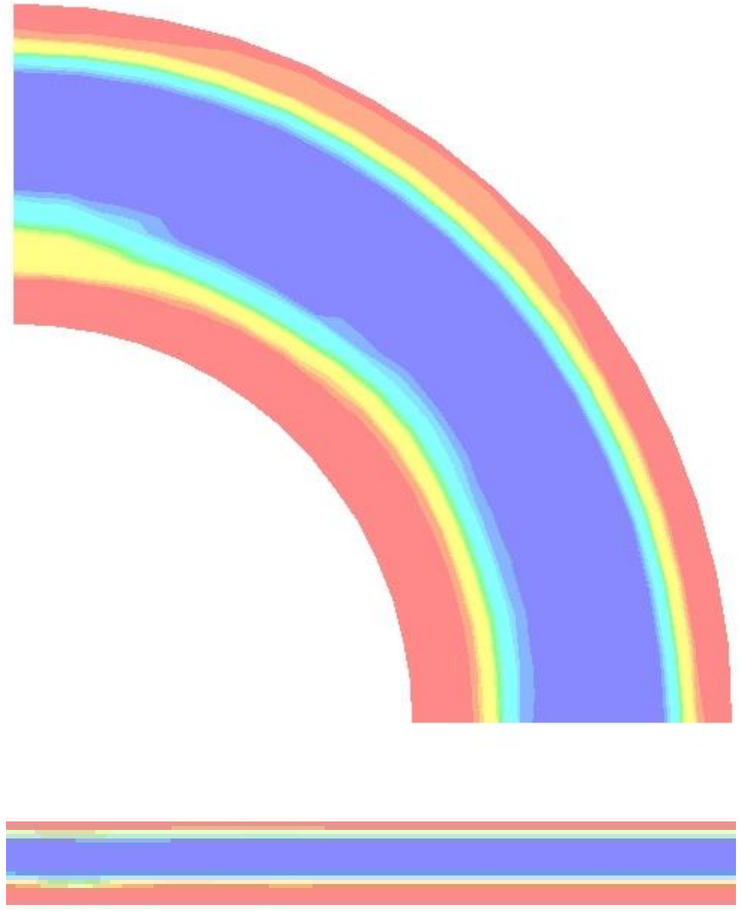
3. Geometry
4. Mesh
5. Physics
6. Solver setting

Solve

7. Computation

Post-processing

8. Results



Experimental data simulation

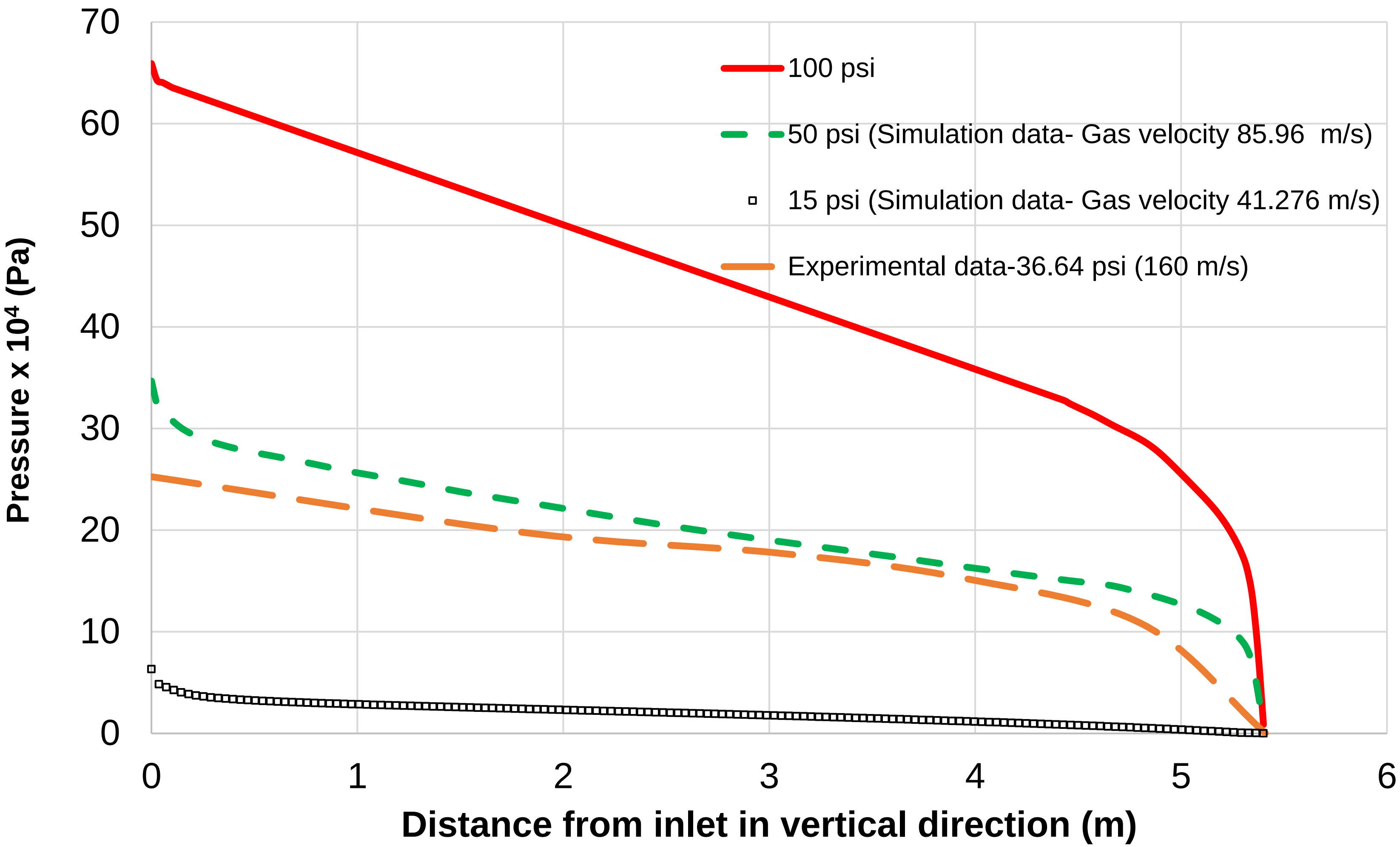
- Simulation results for air-water flow using VOF approach

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

- Simulation for air-water flow using Eulerian approach

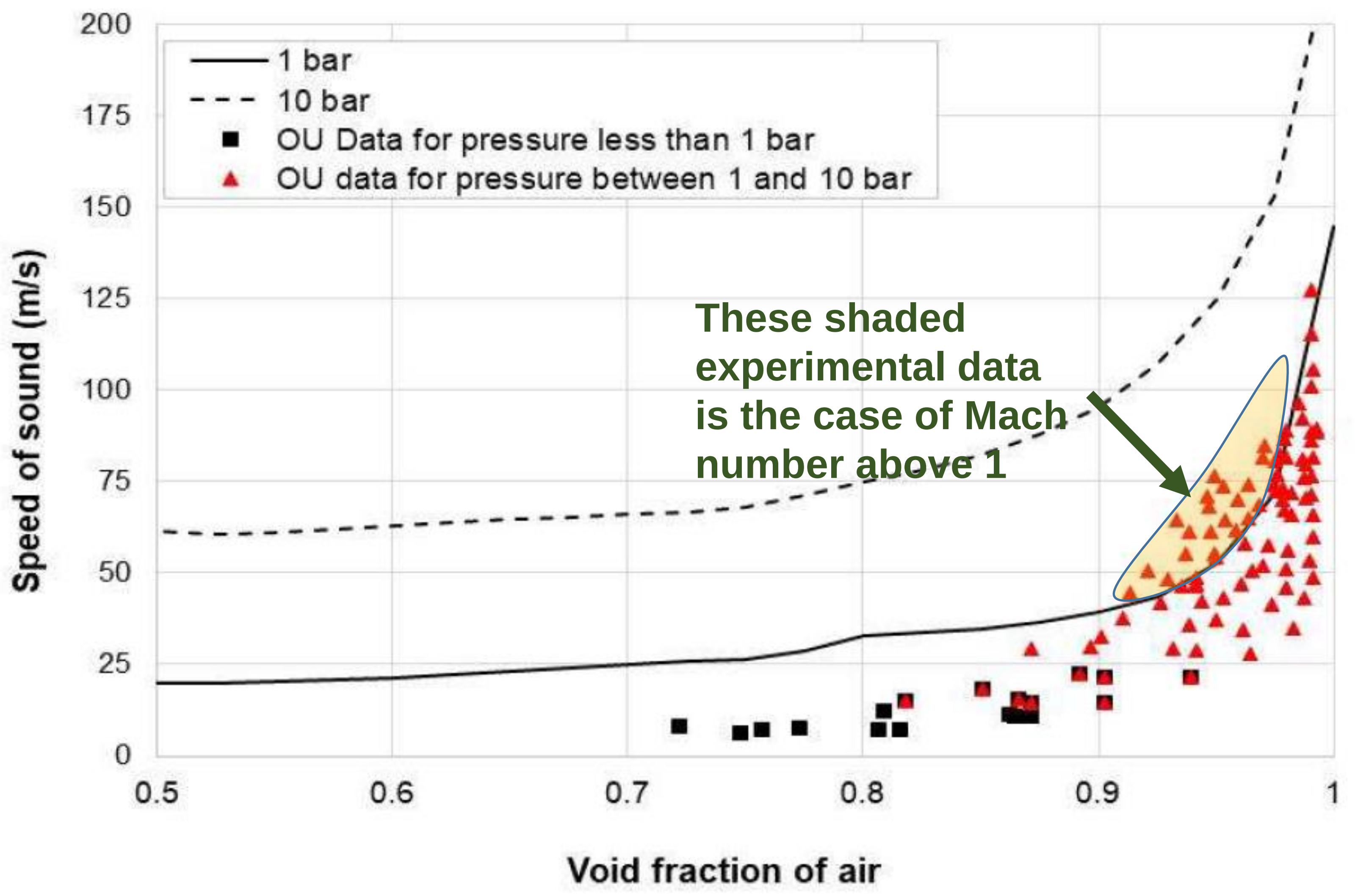
V_{sg} (m/s)	V_{sl} (m/s)	Pattern	Simulated Pressure Gradient (Pa/m)	Experimental Pressure Gradient (Pa/m)	Error	Slip ratio
0.44	0.10	SL	5056	5086	-0.6%	4.327
13.02	0.30	AN	2486	3176	-22.2%	43

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).

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.

Sonic Condition Determination Model

If P<100 bar

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

Otherwise

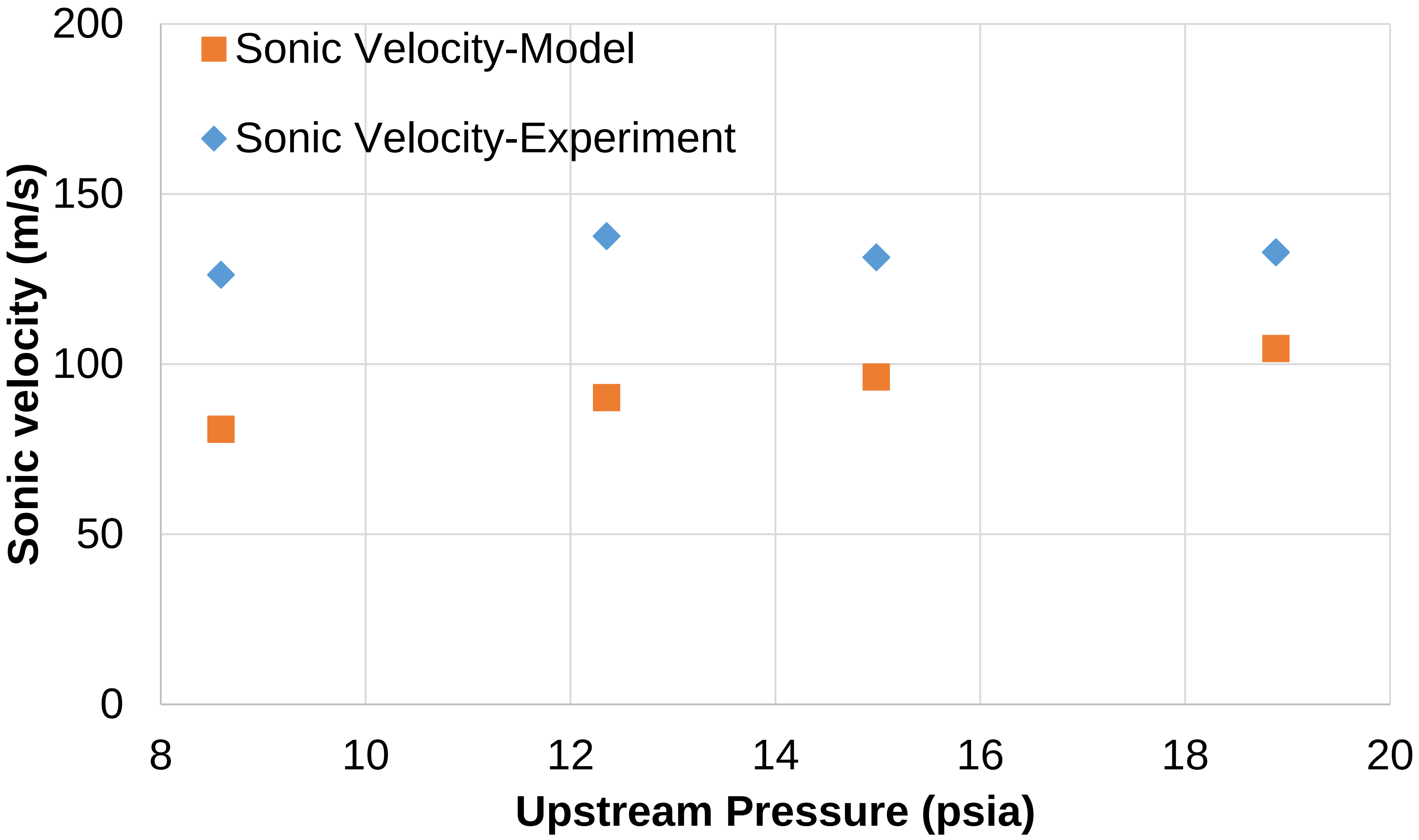
$$V_{sound} = (1804P^{-0.01989})x^2 - (0.0002878P^2 + 0.8032P + 1884)x + 220.4P^{0.2486} + 20$$

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 Vsg is the superficial gas velocity and Vsl 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

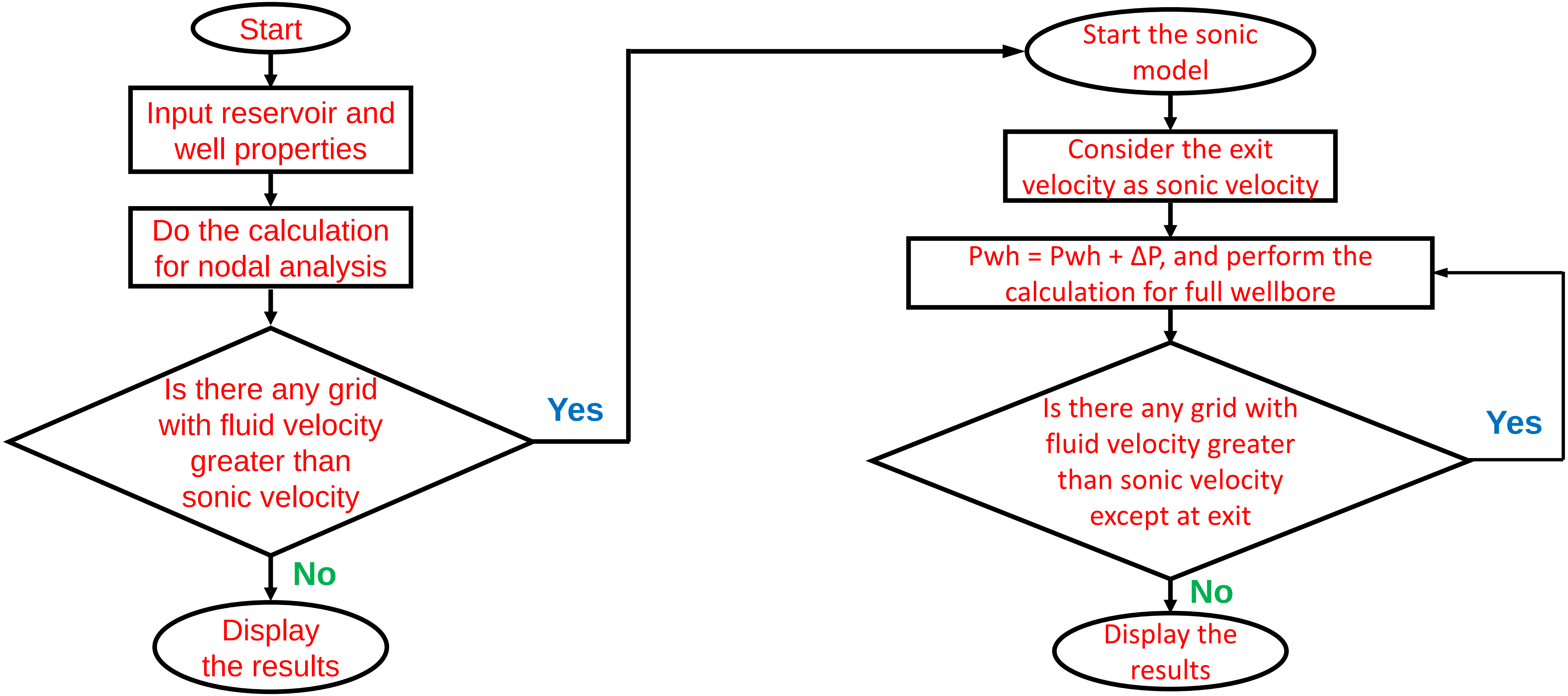
Subsonic conditions

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

Sonic conditions

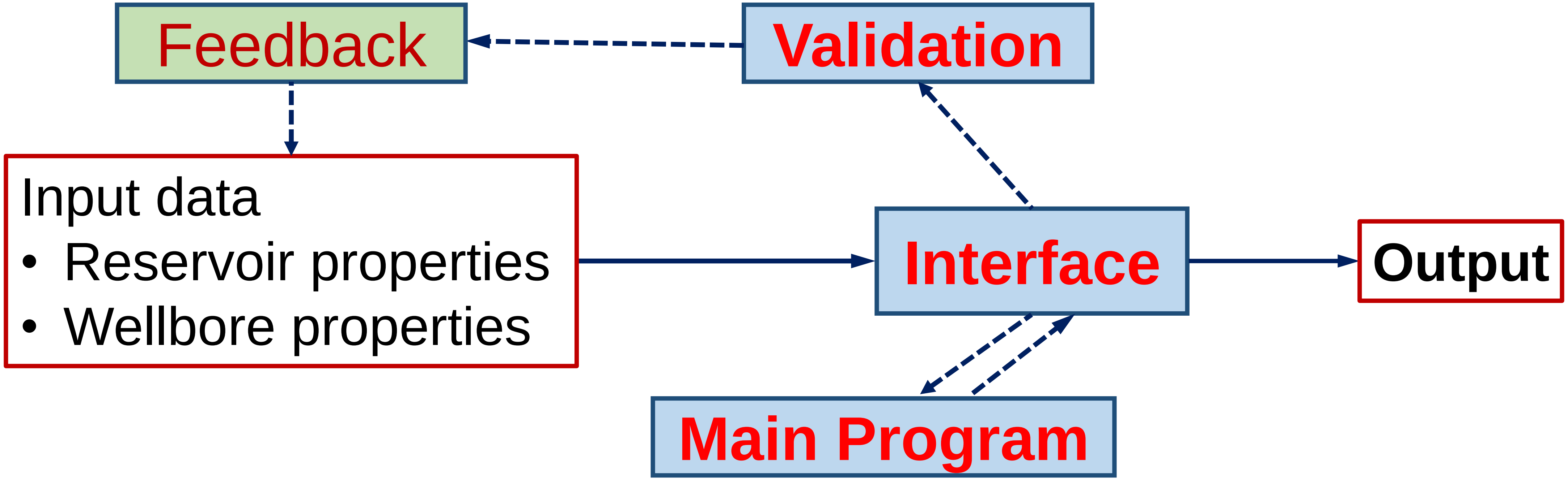
- Mach number 1 at the exit
- Wellhead pressure controlled by sonic condition
- Fluid velocity governed by sonic velocity at the exit

How the sonic model works?



WCD Tool

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

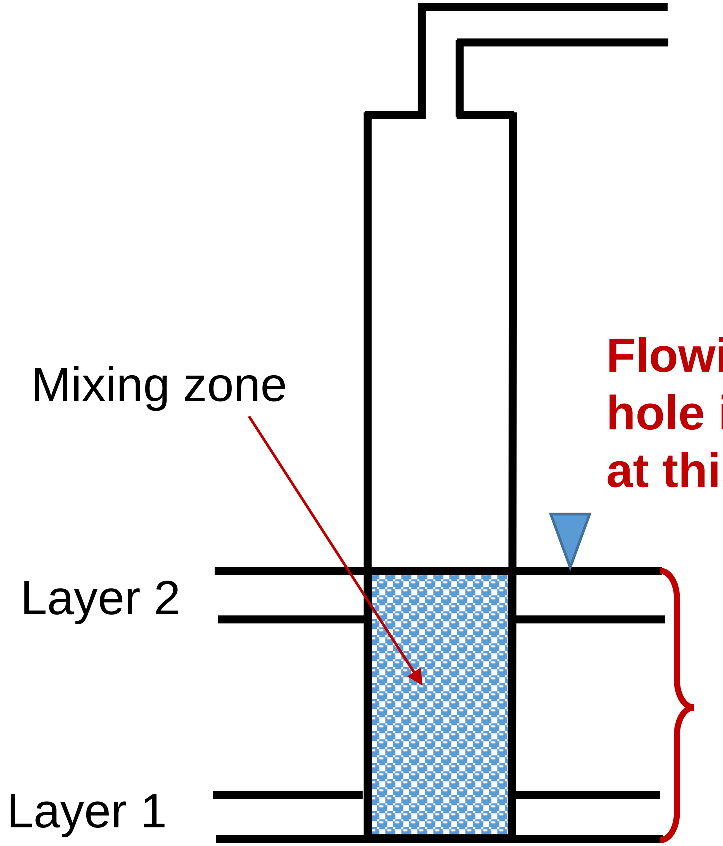


Capability

- 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?

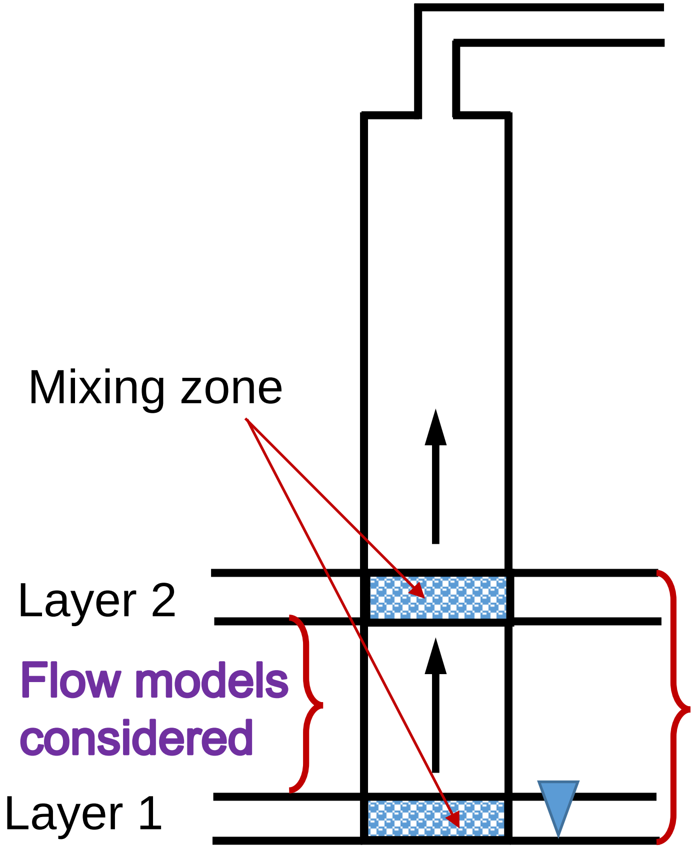
Traditional available software



Flowing bottom hole is considered at this point

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

OU WCD Computational Tool

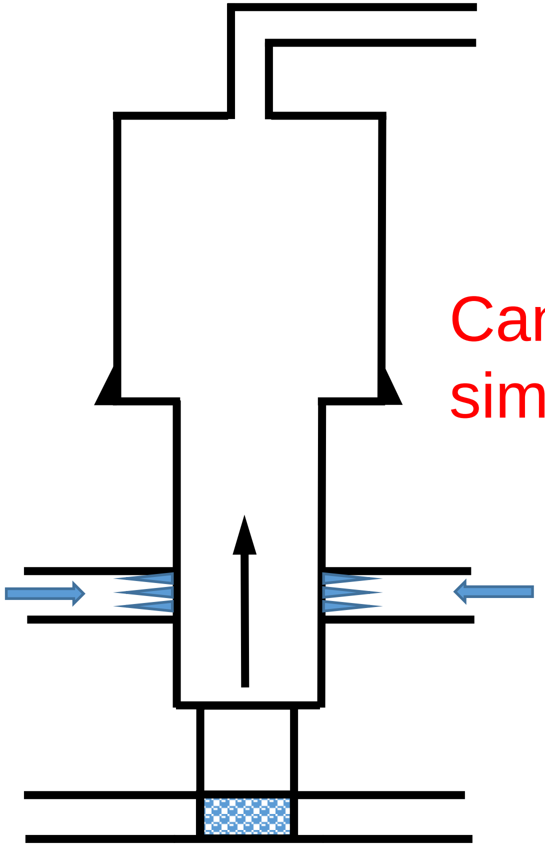


Reservoir model and hydraulics model, both works simultaneously

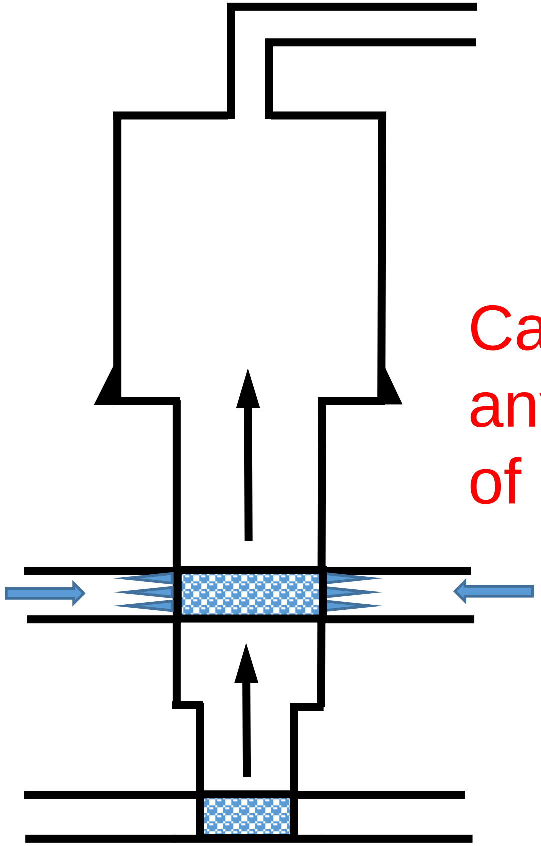
Flowing bottom hole is considered at the bottom-most point of the wellbore

How this tool is different?

Traditional available software

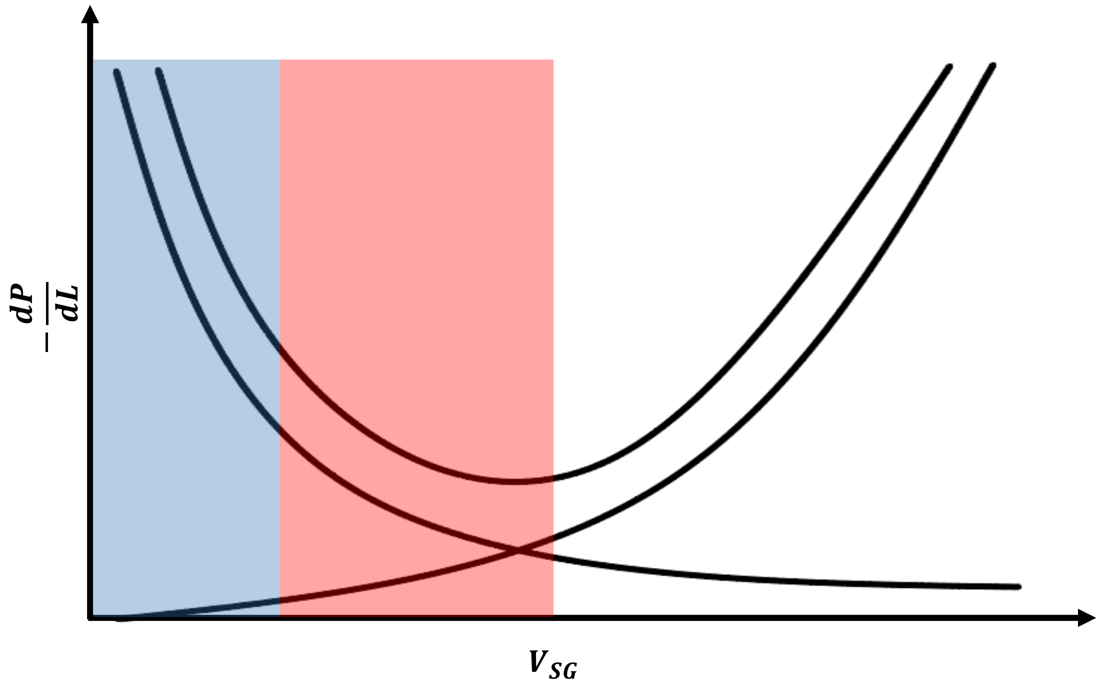


OU WCD Computational Tool



How this tool is different?

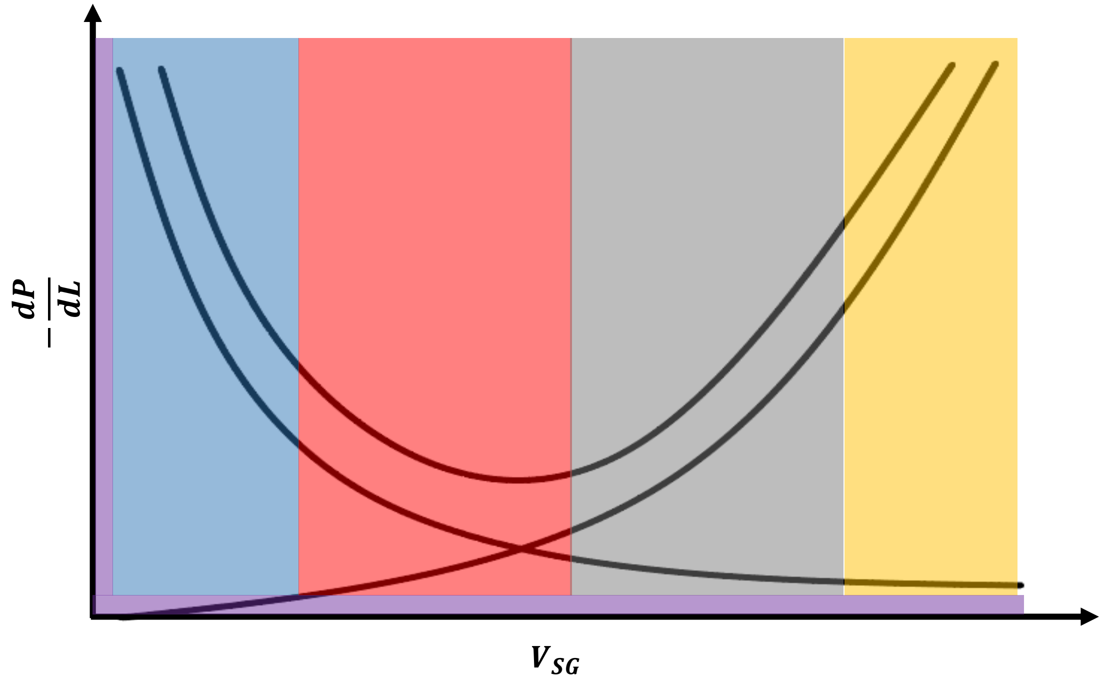
Traditional available software



Low velocity region

Transient region

OU WCD Computational Tool



Single phase region

Low velocity region

Transient region

High velocity region

Sonic region

How this tool is different?

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

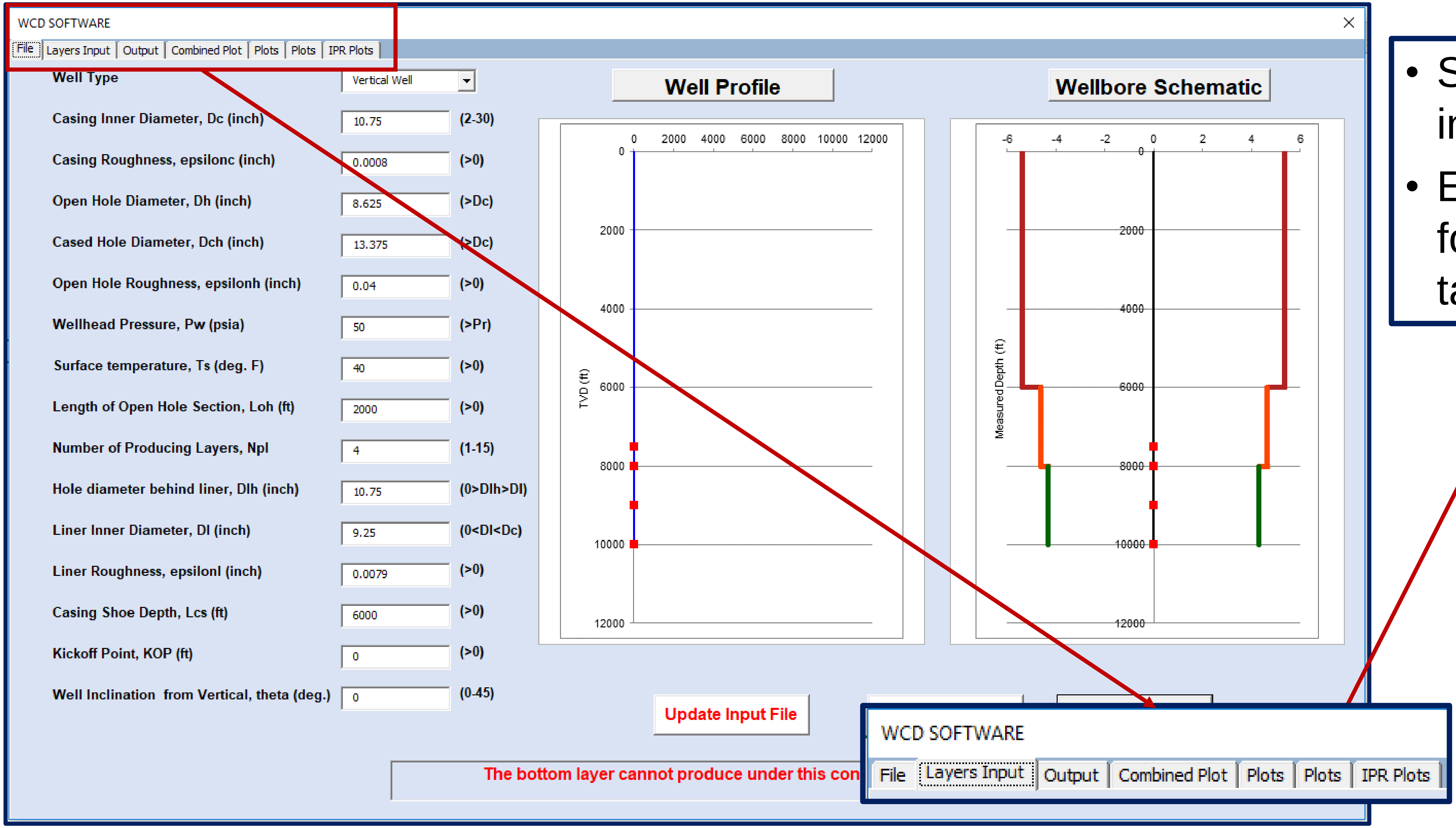
How this tool is different?

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

Assumptions

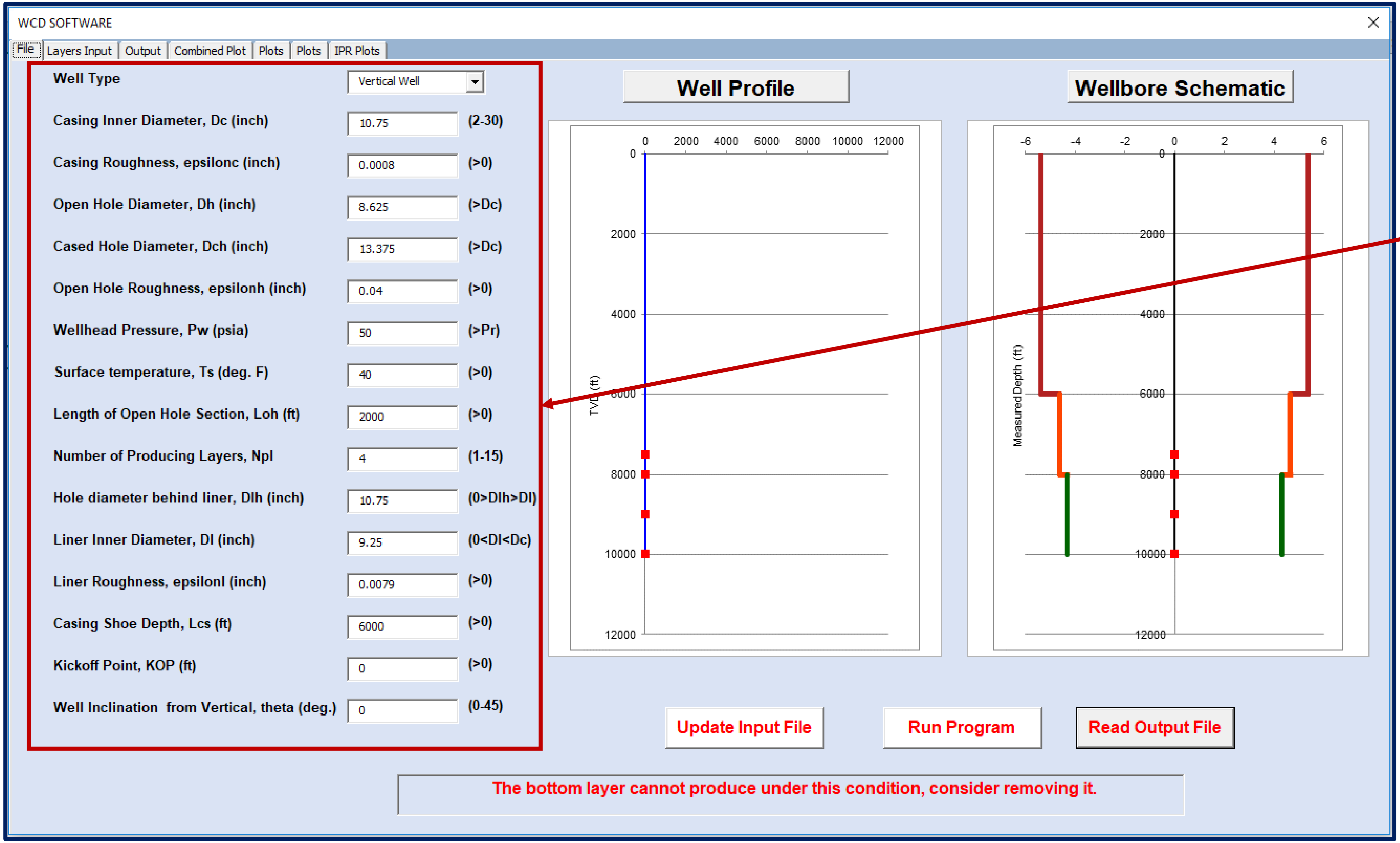
- Radial and steady state reservoirs.
- All input layers are producing with minimum of 0 flow rate.
- Geothermal temperature gradient is considered for the temperature profile.
- The bottom-most layer is always considered to be producing (if negative flow encountered, update the input with upper layer as bottom-most layer).
- Different reservoirs are not communicating to each other

WCD Tool



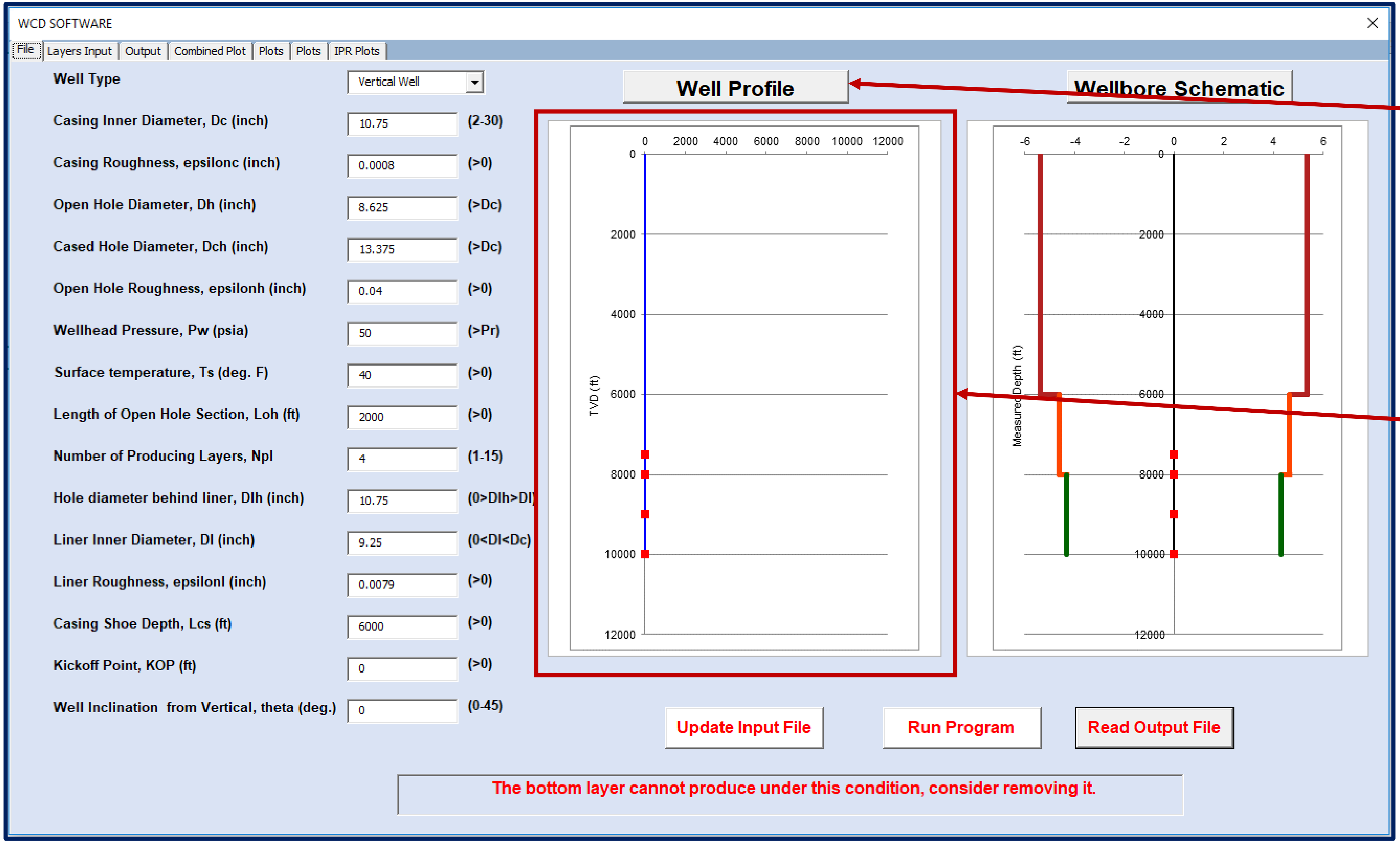
- Seven tabs in ribbon.
- Each tab is for distinct task.

WCD Tool



Input page for wellbore properties.

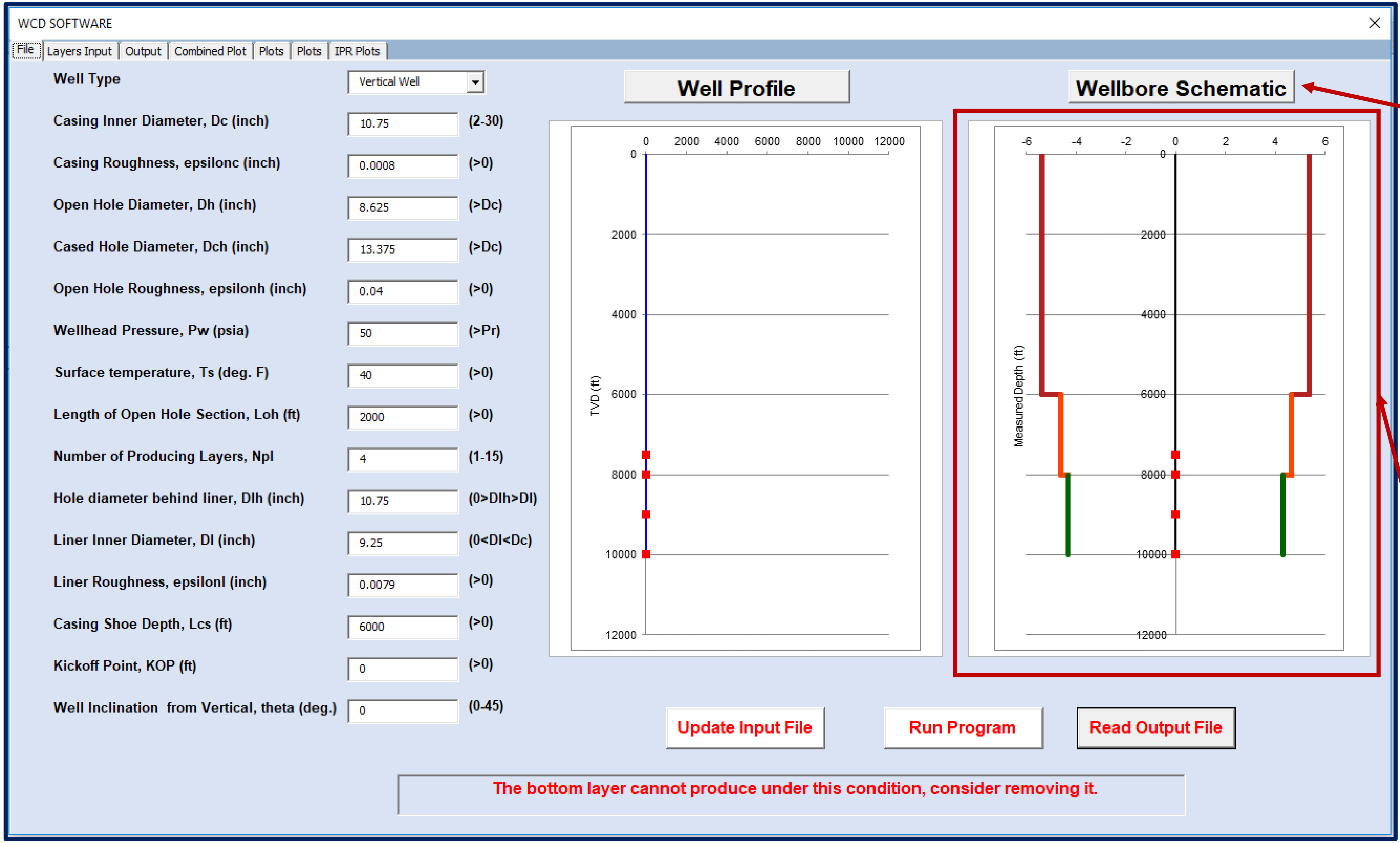
WCD Tool



Button to display the well profile

Users can Visualize the number of layers, wellbore type and path.

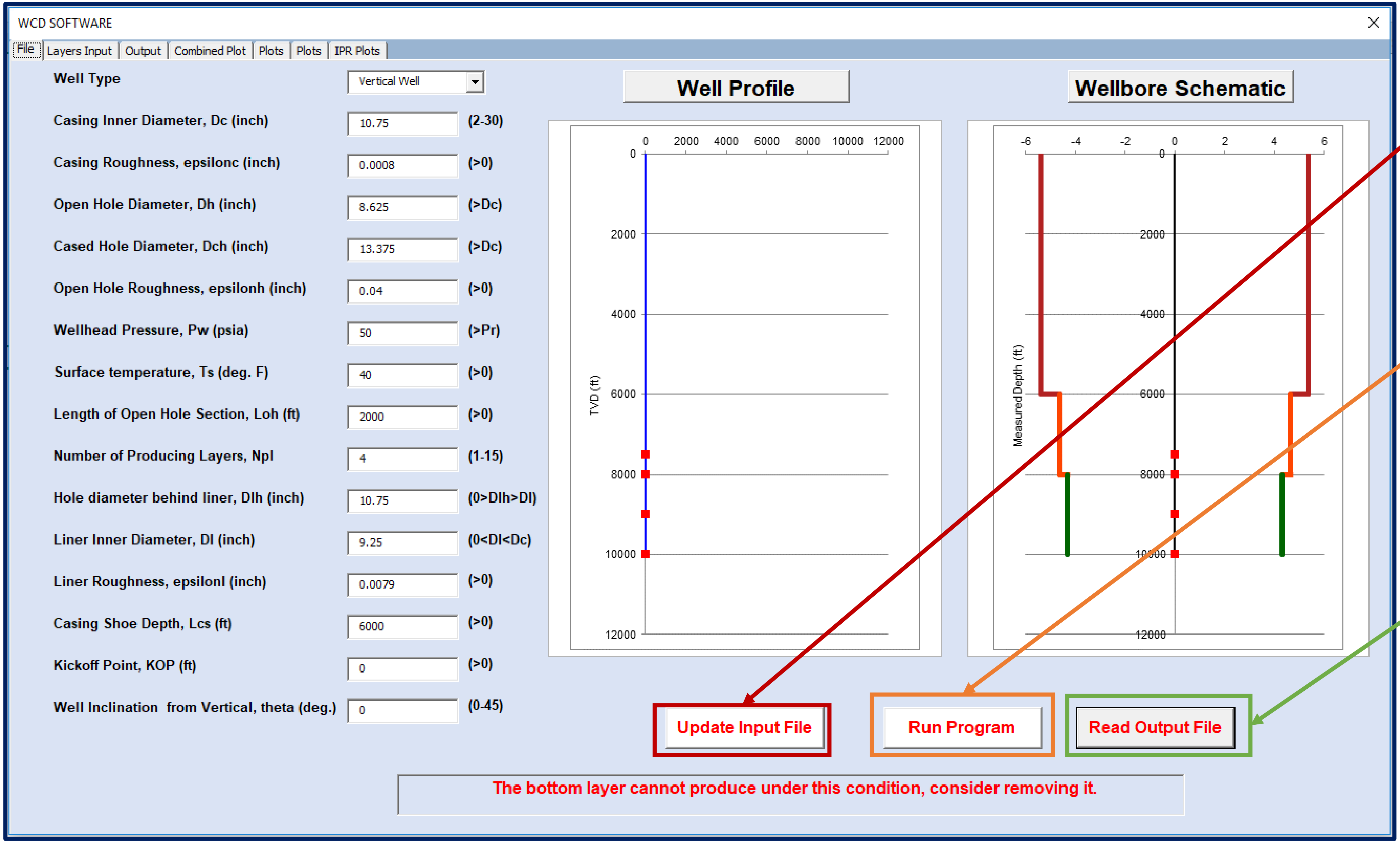
WCD Tool



Button to display the wellbore schematic

Users can Visualize the number of layers, casing inner diameter, open hole diameter, liner diameter.

WCD Tool



Updates the input file to run the main program.

Runs the main program

Reads the output file generated from the main program

WCD Tool

If the reservoir pressure is low, the software will point out this anomaly and will display

WCD Tool

WCD SOFTWARE

File | Layers Input | Output | Combined Plot | Plots | Plots | IPR Plots

	Reservoir Type	Formation Type	Payzone Height (ft)	Pay Zone Bottom Depth	Reservoir Temperature (F)	API Gravity of Oil (o)	Gas Specific Gravity (-)	Drainage Raduis (ft)	Permeability (mD)	Reservoir Pressure (psia)	Bubble Point Pressure (psia)	Gas Saturation	Water Saturation	Irreducible Water Saturation	Critical Gas Saturation	Critical Oil Saturation	Skin	Condensate Yield (stb/MMscf)	Salt Content %
Layer 1	Oil	ConsolidatedSand	100	10000	160	45	0.6	10000	250	11000	7000	0.5	0.2	0.15	0.001	0.1	0.15	10	3
Layer 2	Gas	UnconsolidatedSand	100	9000	150	45	0.6	10000	250	6000	8000	0.5	0.2	0.15	0.001	0.1	0.15	10	3
Layer 3	Water	UnconsolidatedSand	100	8000	140	45	0.6	10000	250	6000	8000	0.3	0.5	0.15	0.001	0.1	0.15	10	3
Layer 4																			
Layer 5																			
Layer 6																			
Layer 7																			
Layer 8																			
Layer 9																			
Layer 10																			
Layer 11																			
Layer 12																			
Layer 13																			
Layer 14																			
Layer 15																			

Validation

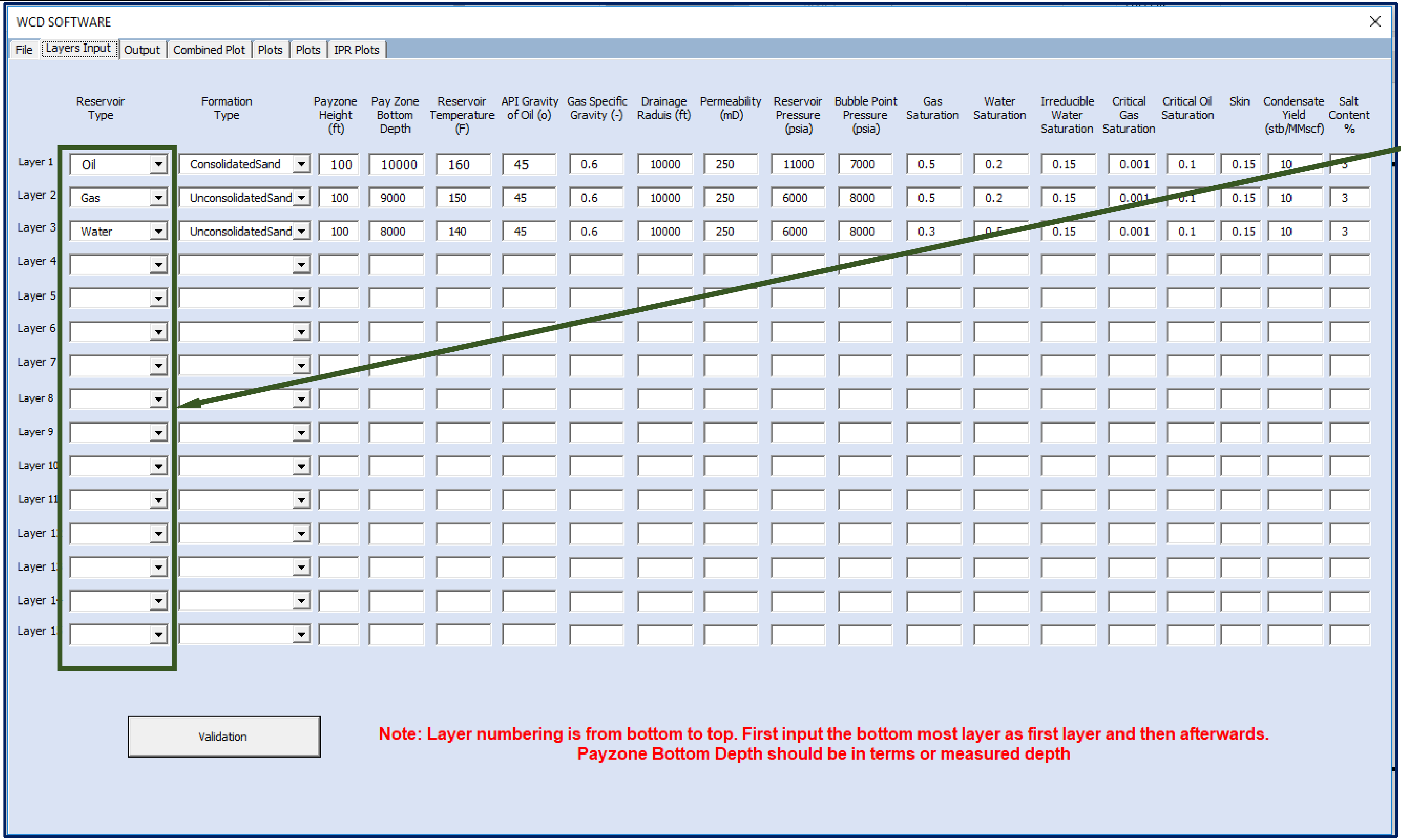
Note: Layer numbering is from bottom to top. First input the bottom most layer as first layer and then afterwards.
Payzone Bottom Depth should be in terms or measured depth

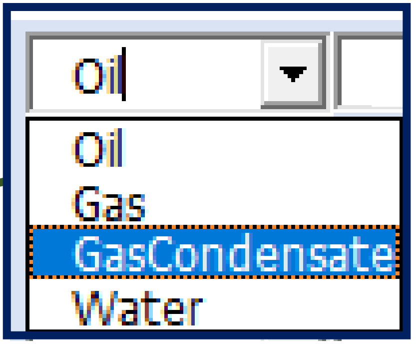
Reservoir properties for flow

15 layers overall

Note for the way the layer properties should be entered

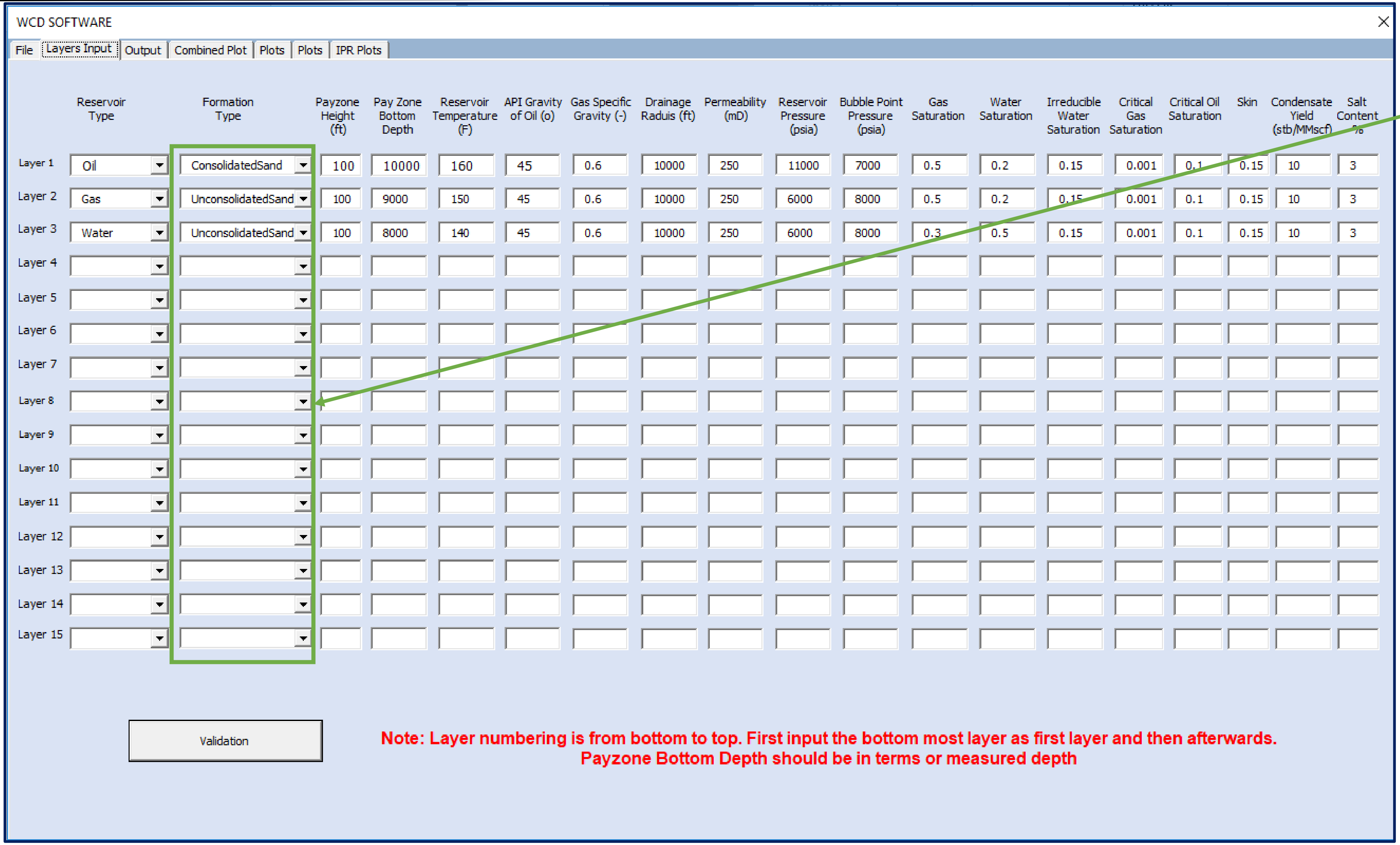
WCD Tool

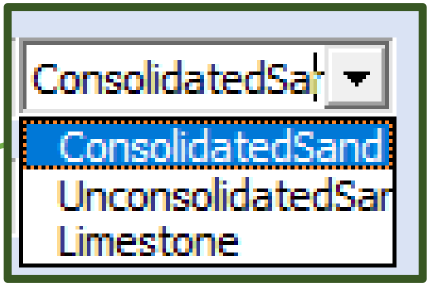




User can select any of four reservoir fluid

WCD Tool





User can choose any of three formation types:

- ✓ Unconsolidated sand
- ✓ Consolidated sand
- ✓ Limestone

WCD Tool

WCD SOFTWARE

File | Layers Input | Output | Combined Plot | Plots | Plots | IPR Plots

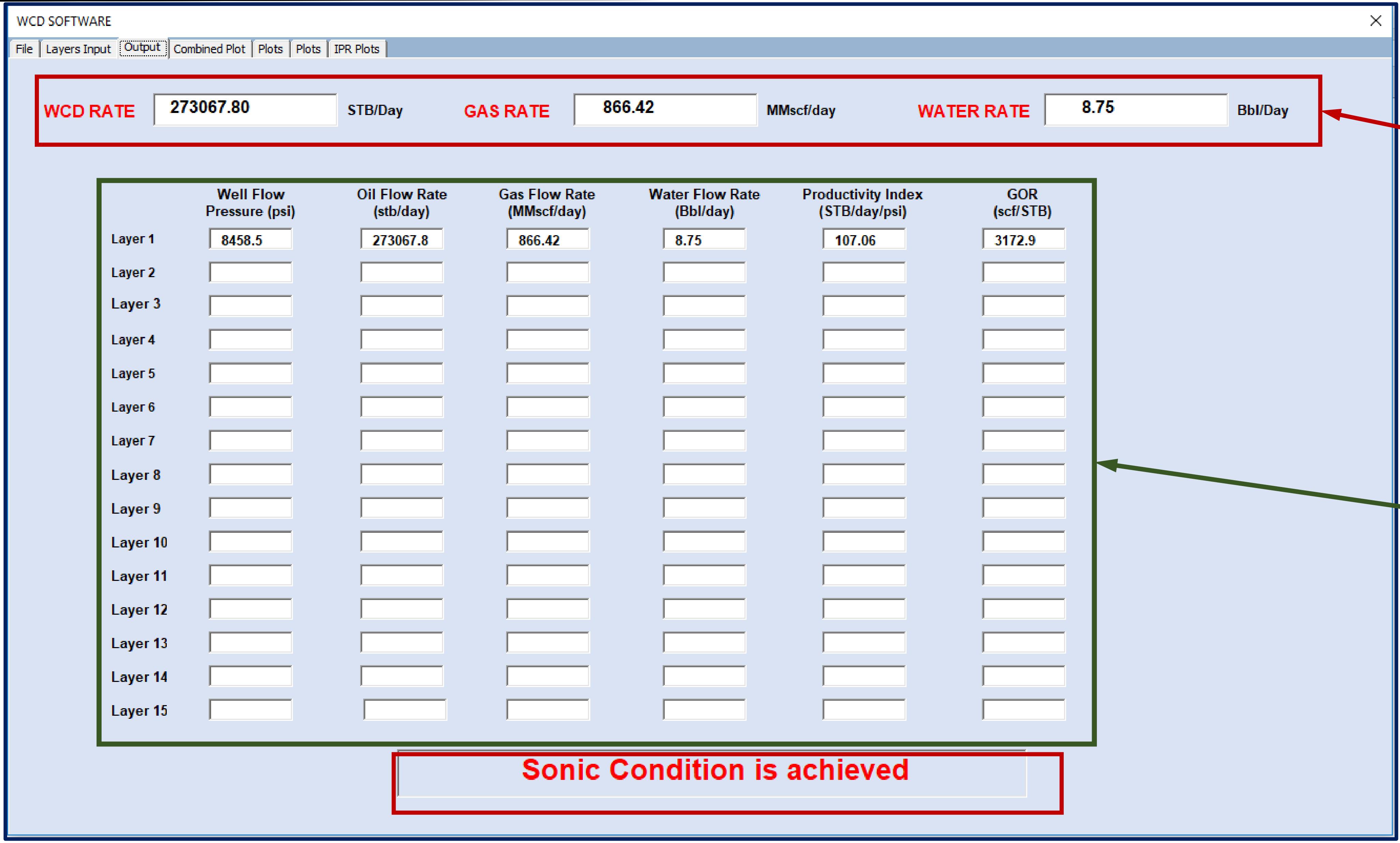
	Reservoir Type	Formation Type	Payzone Height (ft)	Pay Zone Bottom Depth	Reservoir Temperature (F)	API Gravity of Oil (o)	Gas Specific Gravity (-)	Drainage Raduis (ft)	Permeability (mD)	Reservoir Pressure (psia)	Bubble Point Pressure (psia)	Gas Saturation	Water Saturation	Irreducible Water Saturation	Critical Gas Saturation	Critical Oil Saturation	Skin	Condensate Yield (stb/MMscf)	Salt Content %
Layer 1	Oil	ConsolidatedSand	100	10000	160	45	0.6	10000	250	11000	7000	0.5	0.2	0.15	0.001	0.1	0.15	10	3
Layer 2	Gas	UnconsolidatedSand	100	9000	150	45	0.6	10000	250	6000	8000	0.5	0.2	0.15	0.001	0.1	0.15	10	3
Layer 3	Water	UnconsolidatedSand	100	8000	140	45	0.6	10000	250	6000	8000	0.3	0.5	0.15	0.001	0.1	0.15	10	3
Layer 4																			
Layer 5																			
Layer 6																			
Layer 7																			
Layer 8																			
Layer 9																			
Layer 10																			
Layer 11																			
Layer 12																			
Layer 13																			
Layer 14																			
Layer 15																			

Validation

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

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

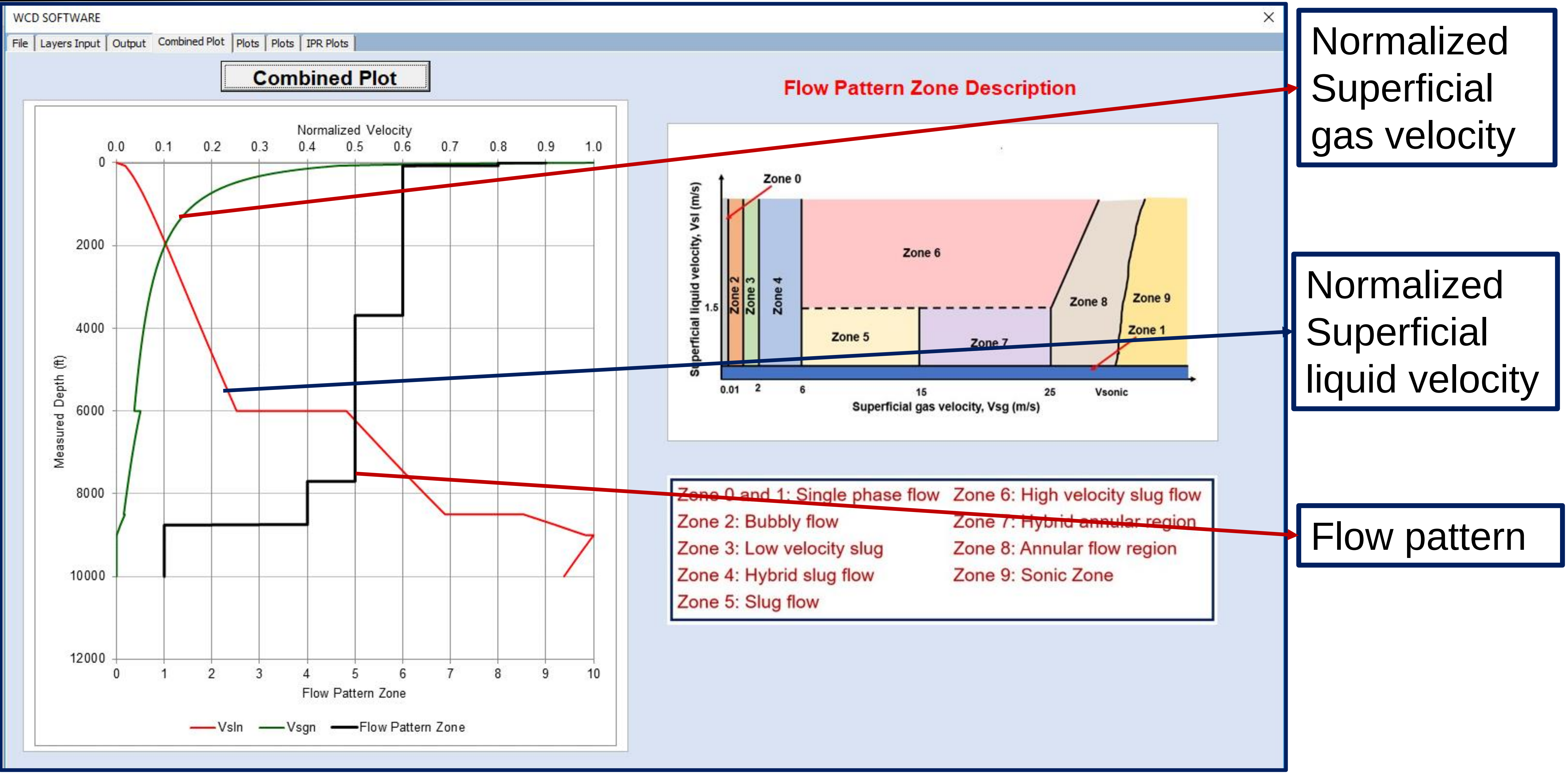
WCD Tool



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

WCD Tool


WCD SOFTWARE
File
Layers Input
Output
Combined Plot
Plots
Plots
IPR Plots
Combined Plot
Normalized Velocity
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
0
2000
4000
6000
8000
10000
12000
Measured Depth (ft)
0 1 2 3 4 5 6 7 8 9 10
Flow Pattern Zone
Vsln
Vsgn
Flow Pattern Zone
Flow Pattern Zone Description
Zone 0
Zone 2
Zone 3
Zone 4
Zone 6
Zone 5
Zone 7
Zone 8
Zone 9
Zone 1
1.5
Superficial liquid velocity, Vsl (m/s)
0.01
2
6
15
25
Vsonic
Superficial gas velocity, Vsg (m/s)
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
Normalized Superficial gas velocity
Normalized Superficial liquid velocity
Flow pattern

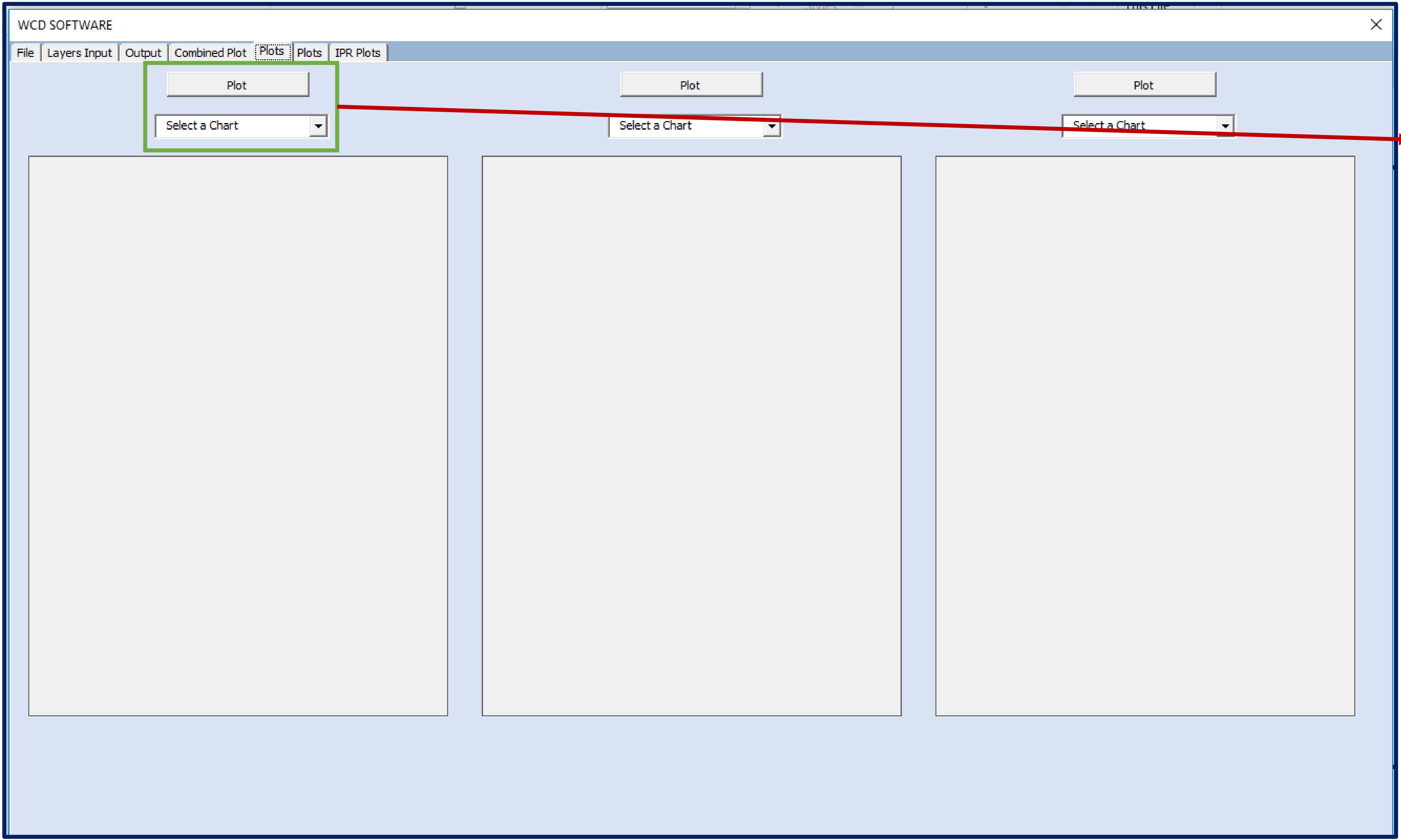
WCD Tool

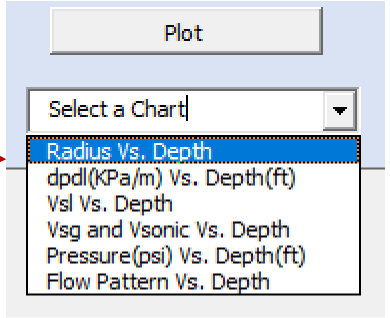
Flow pattern zones

Zones description

Flow patterns along the measured depth

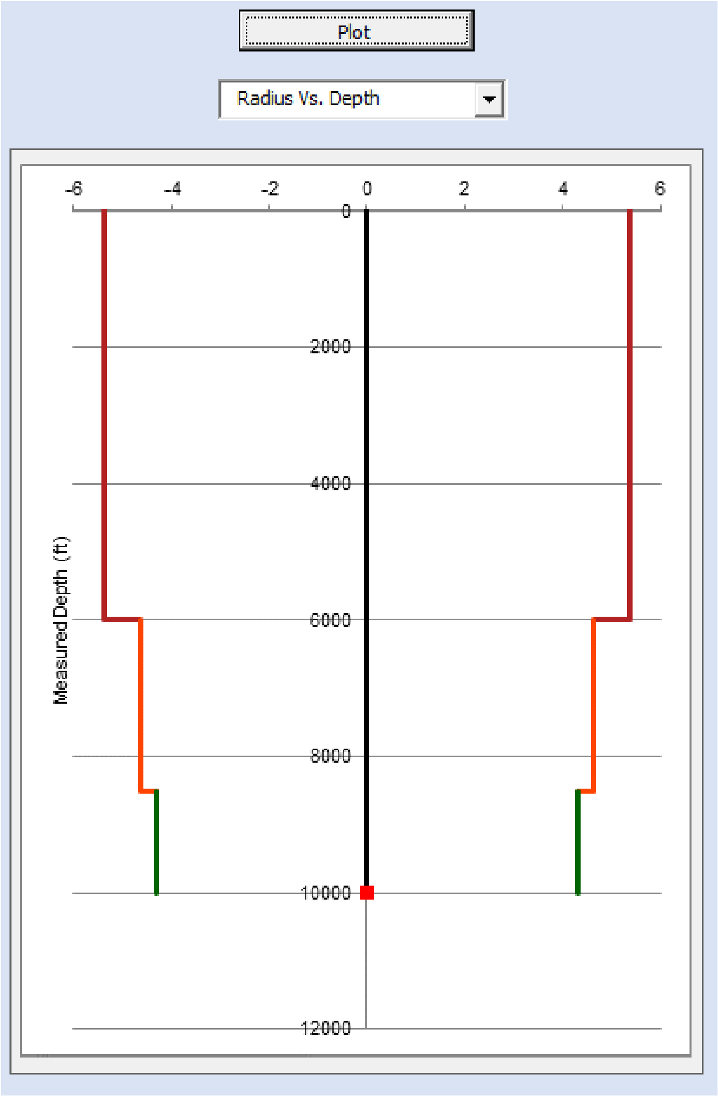
WCD Tool



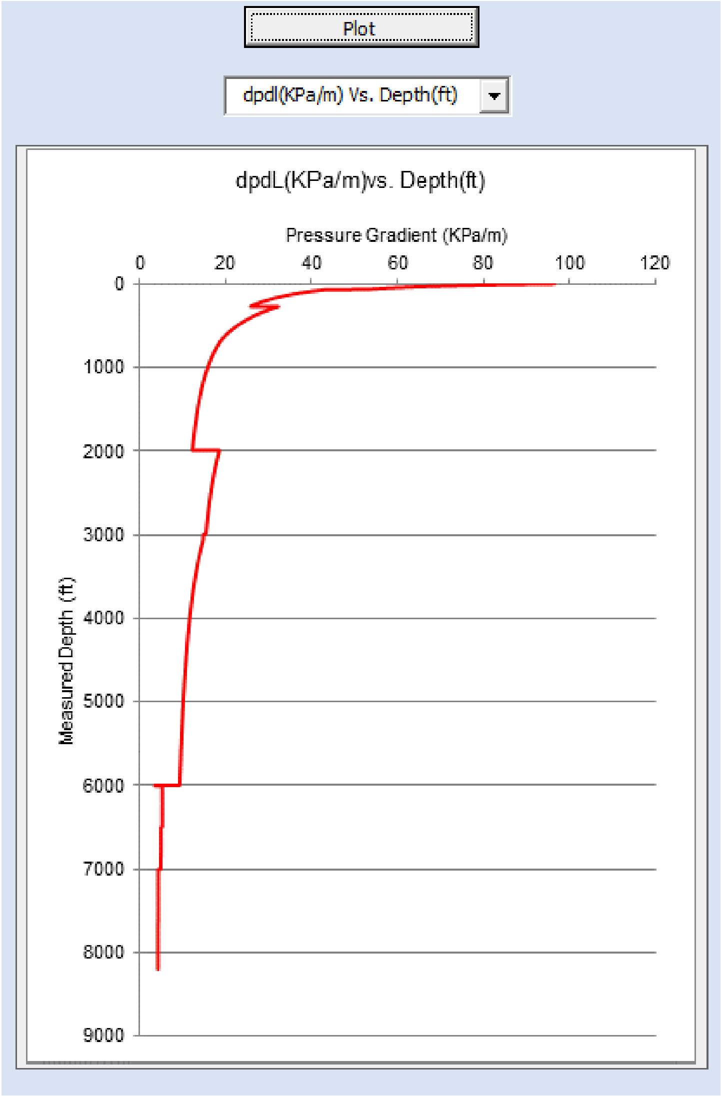


User can choose and see any of these six plots in the window below

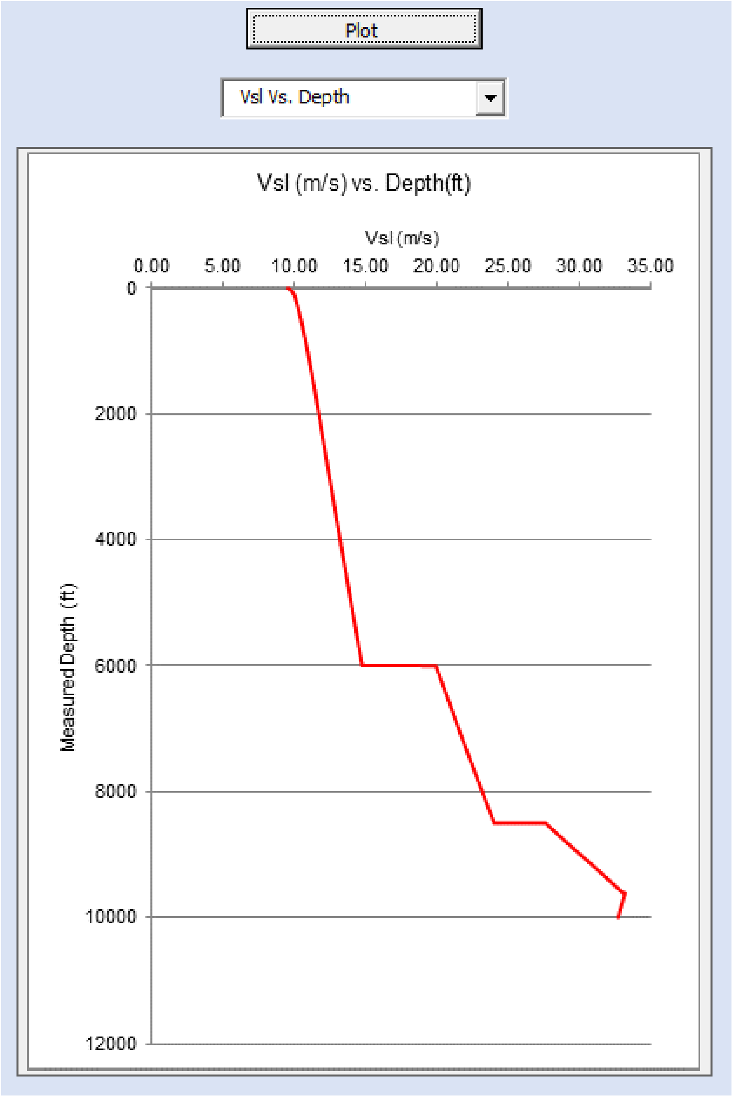
WCD Tool



Radius Vs Depth

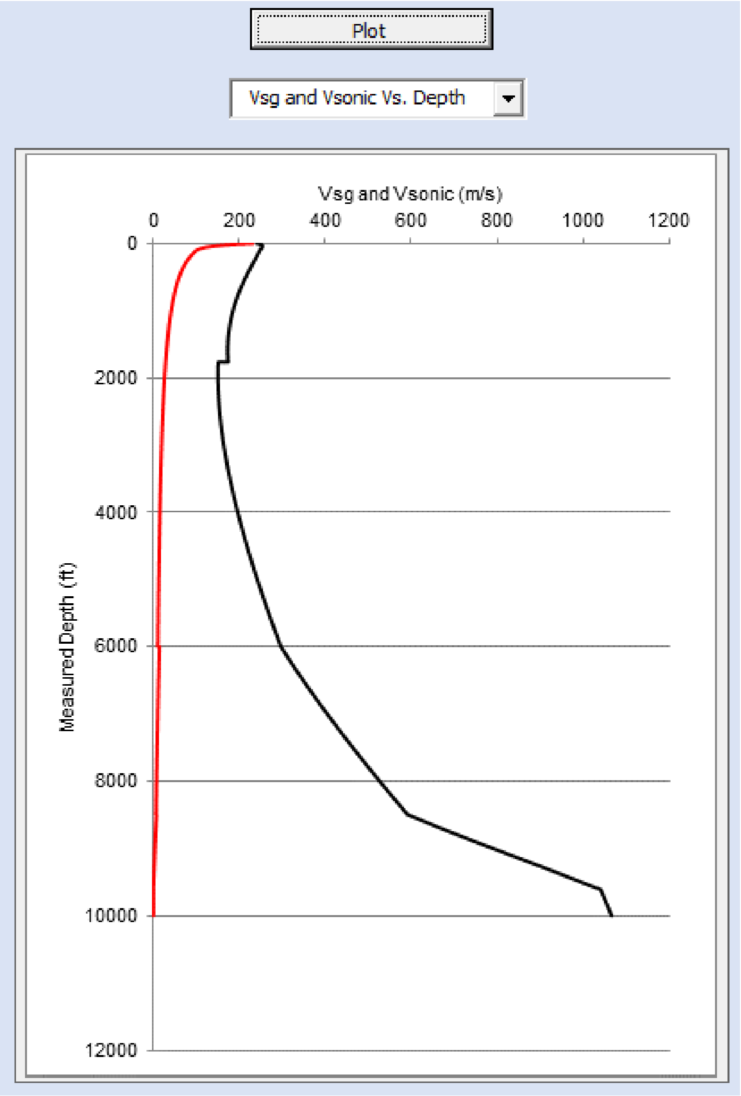


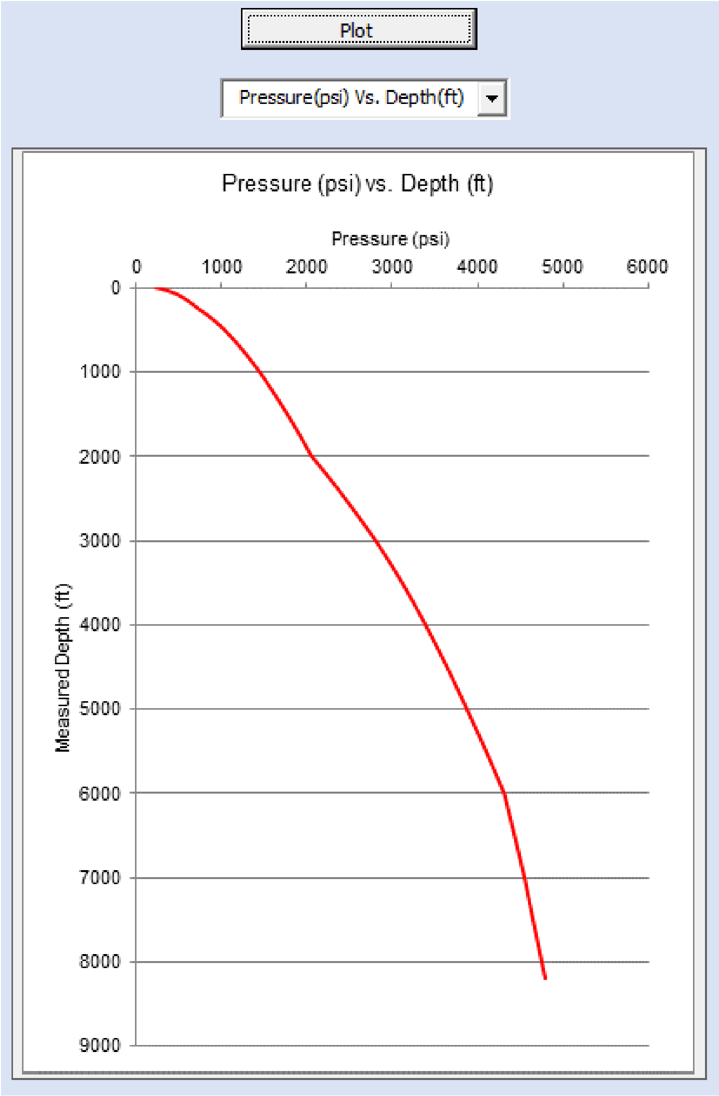
Pressure Gradient Vs Depth

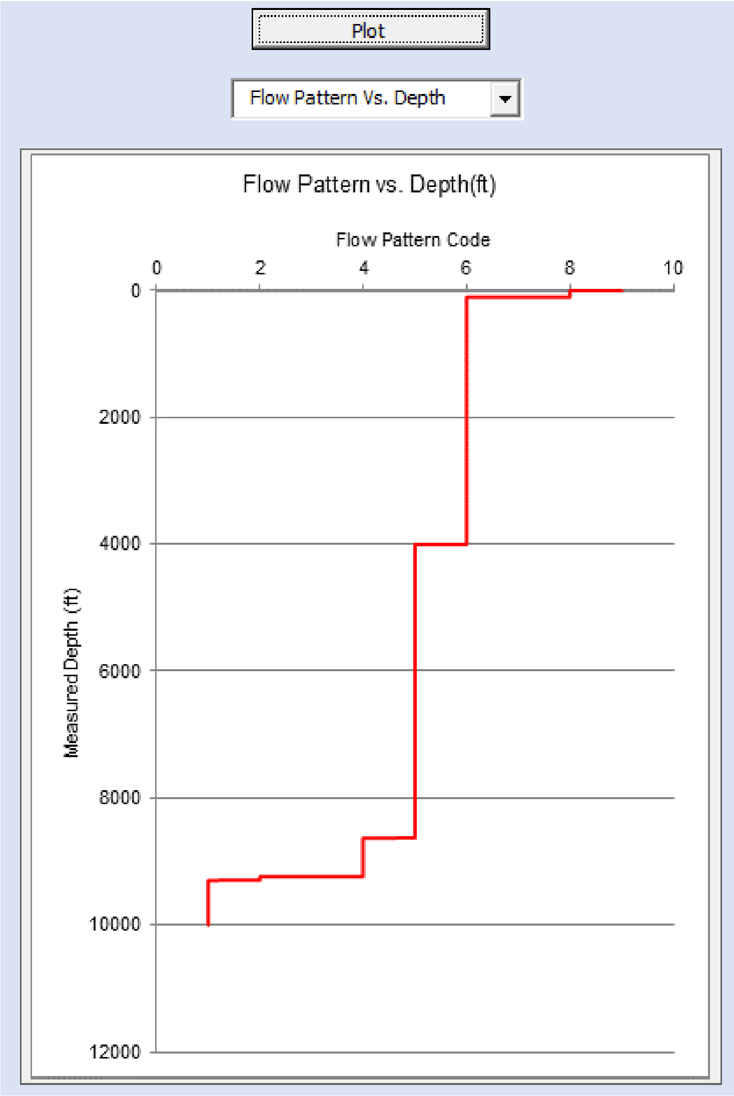


Superficial liquid velocity Vs Depth

WCD Tool





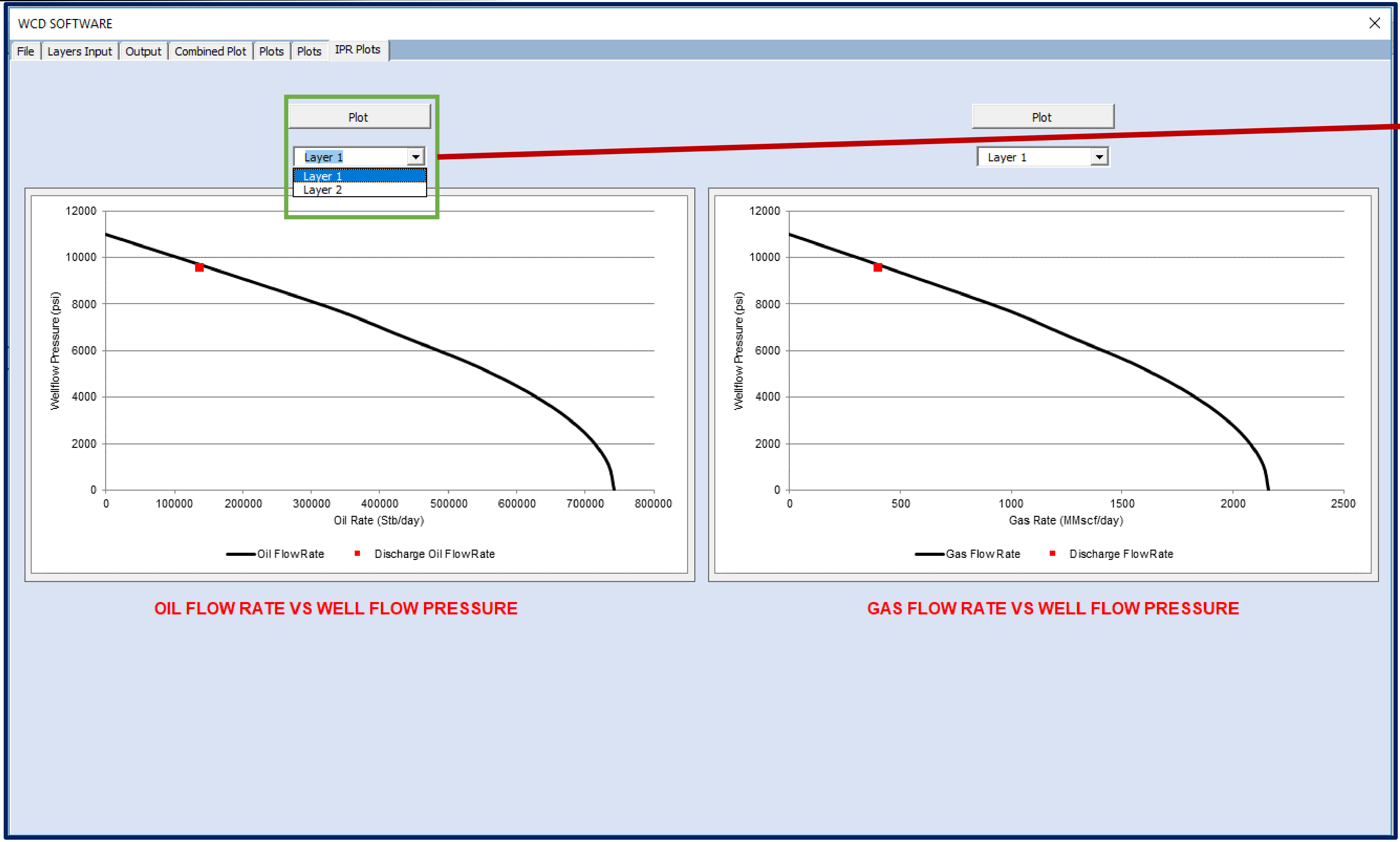


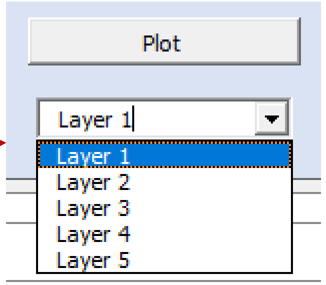
Superficial gas and sonic velocity vs. Depth

Pressure vs. Depth

Flow Pattern vs. Depth

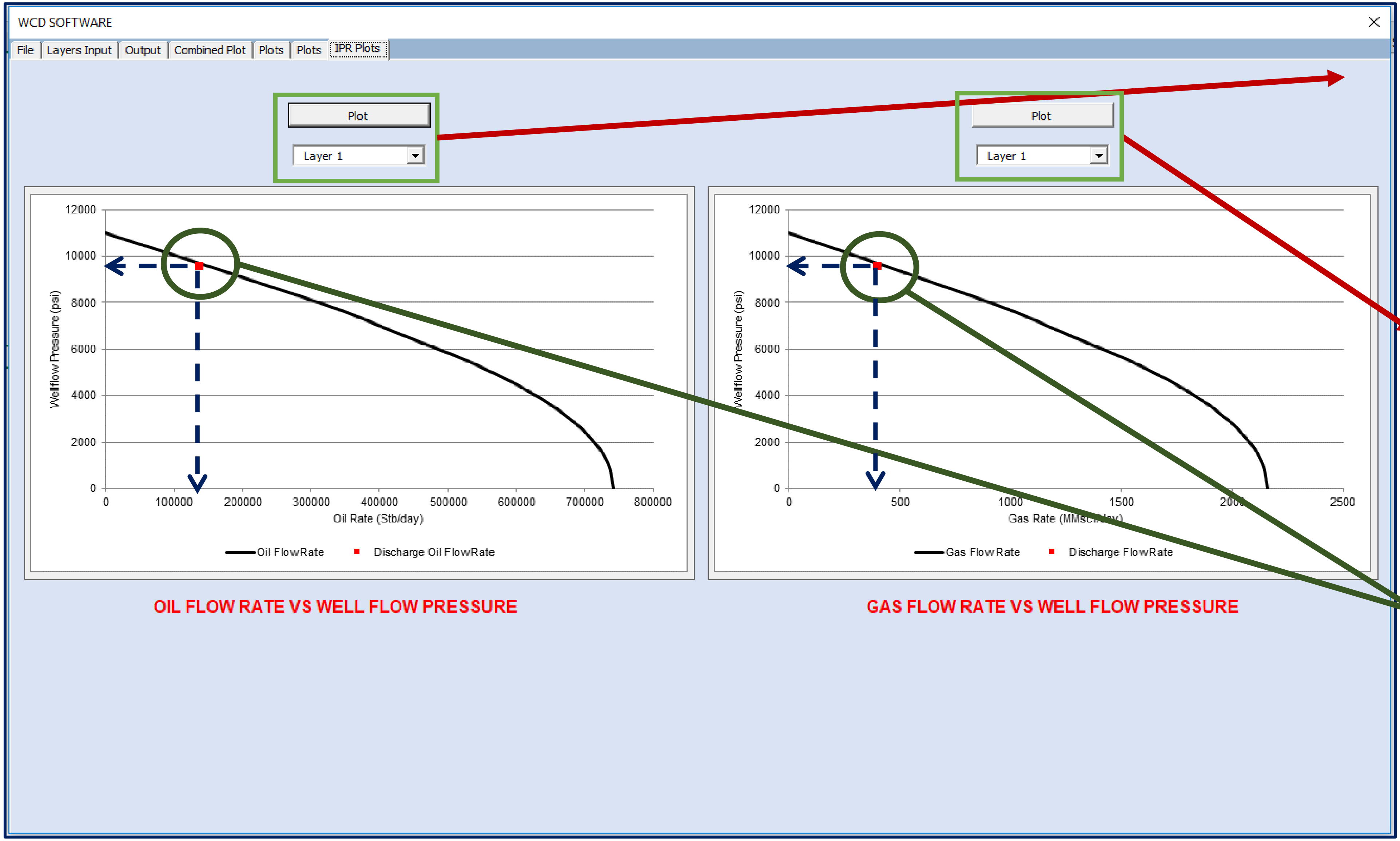
WCD Tool





- IPR Plots
- Shows Oil and Gas flow rate with respect to well flow pressure
- User can visualize the flow rate from different layers

WCD Tool



Oil flow rate Vs. Well flow pressure

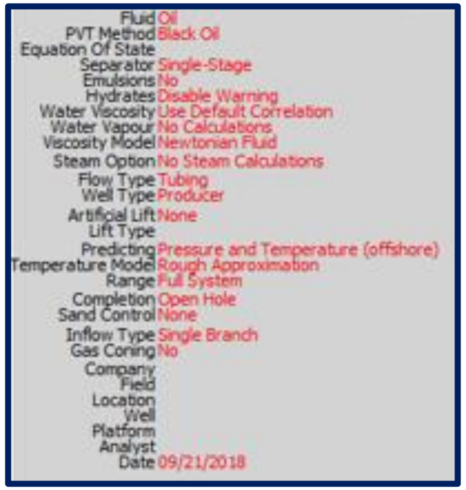
Gas flow rate Vs. Well flow pressure

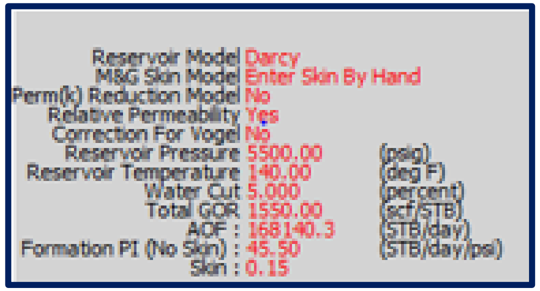
Discharge flow rate with well flow pressure

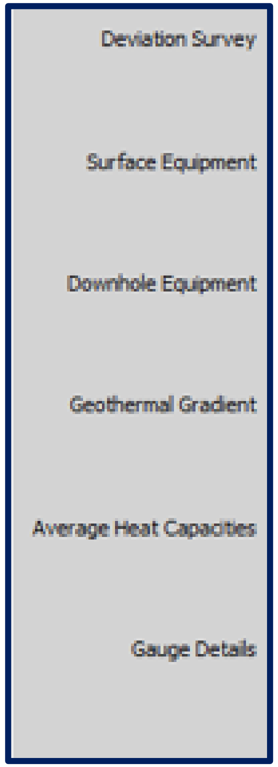
Comparative study with Prosper

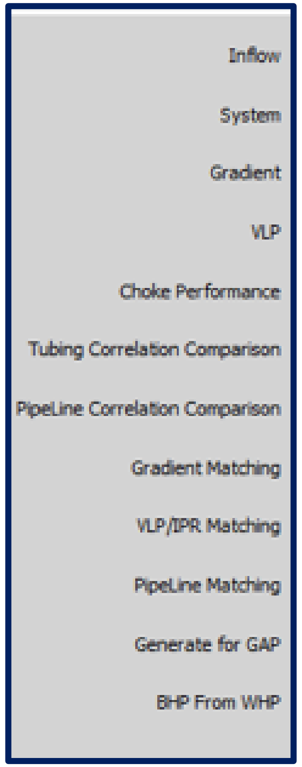
Work flow

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









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)

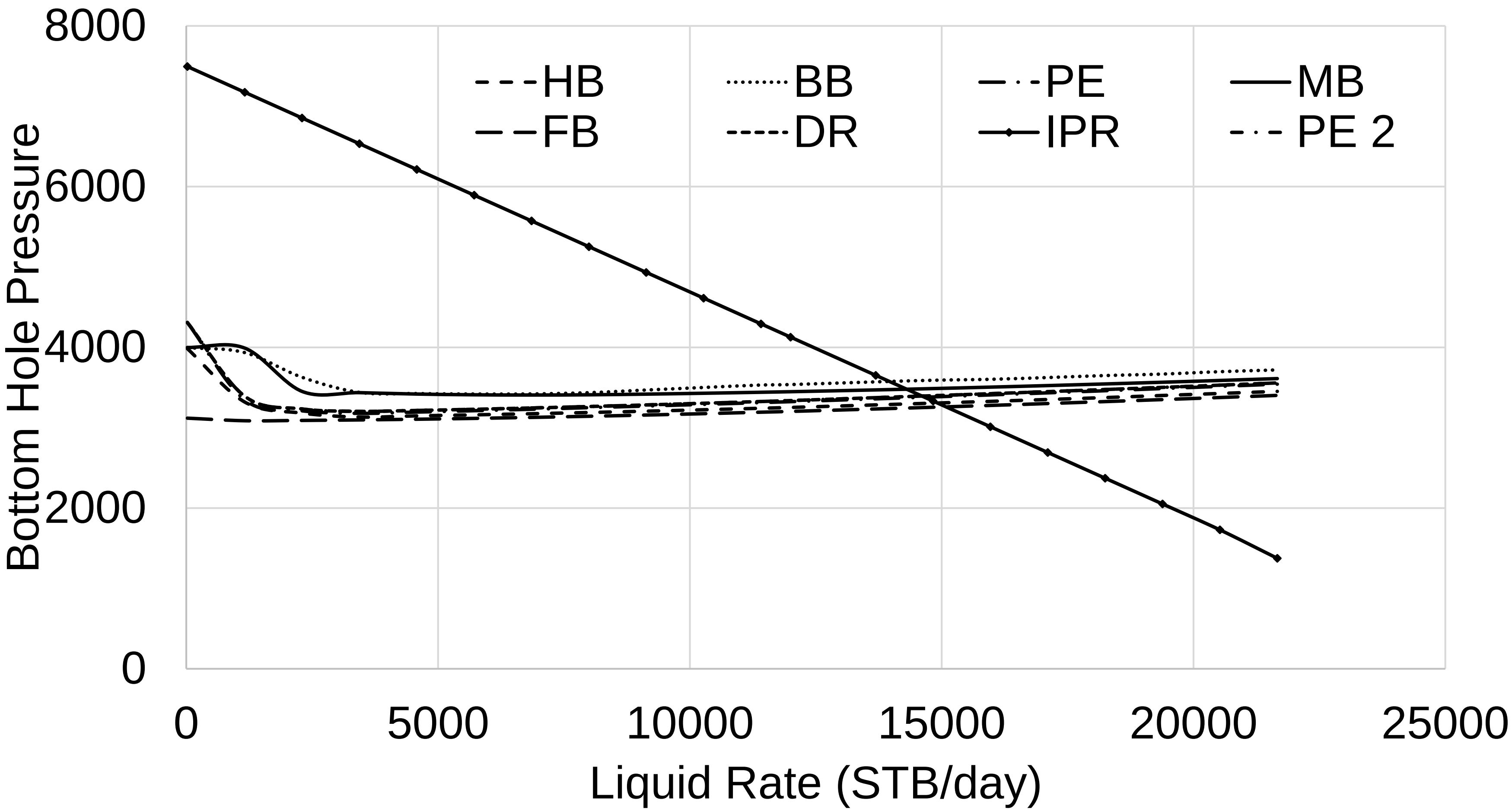
Comparative study

Case study

Parameters	Value	Unit
Oil Gravity	28	ºAPI
Gas specific gravity	0.6	
Bubble point pressure	1404	psi
Reservoir pressure	7500	psi
Gas oil ratio	235	scf/STB

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

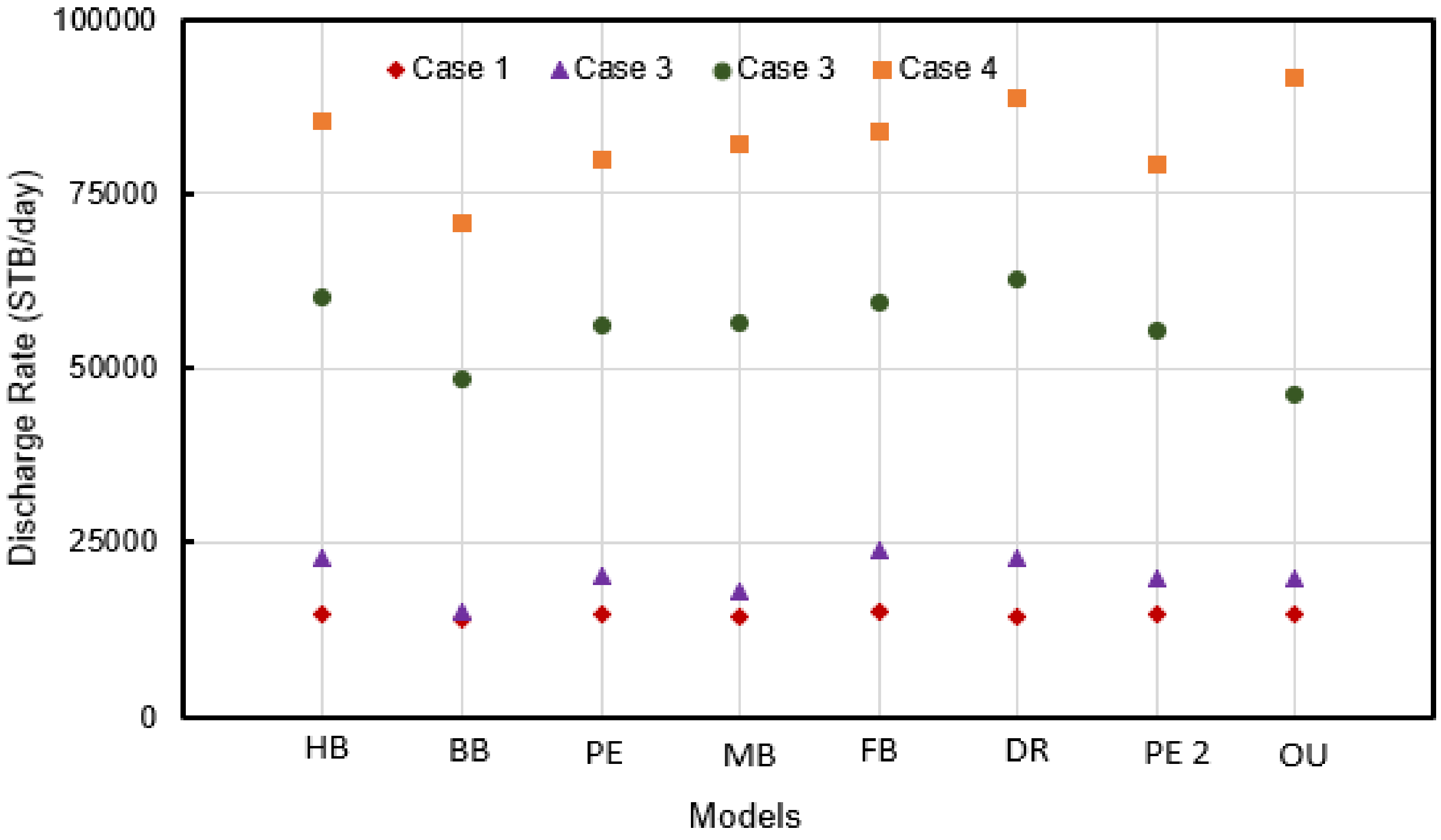
Comparative study

Case study: under subsonic conditions

Case	Oil Gravity	Gas specific gravity	Bubble Point Pressure	Reservoir Pressure	GOR
	^{o}API		(psi)	(psi)	scf/STB
1	28	0.6	1403.6	7500	235
2	35	0.8	2000	3000	650
3	45	0.8	2165	3000	865
4	55	0.82	2560	3000	1376

Comparative study

Case study: under subsonic conditions



Case	WCD Rate	WCD Rate	Diff.
	OU Model	Prosper	%
	STB/day	STB/day	
1	14796.5	14567	1.6
2	19886	20368.4	-2.4
3	46094	56980.4	-19.1
4	91598	81442	12.5

Comparative study

Case study: under sonic conditions

Case	Oil Gravity	Gas specific gravity	Bubble Point Pressure	Reservoir Pressure	GOR	WCD Rate	WCD Rate	Diff.
						OU Model	Prosper	%
	^{o}API		(psi)	(psi)	scf/STB	STB/day	STB/day	
1	50	0.8	3250	7500	1600	99597.26	86376	15.3
2	55	0.8	5000	3000	2586	134563.8	114368	17.6

Comparative study

Case study: GoM

Reservoir Properties	Value	Unit
Reservoir temperature	210	^{o}F
Reservoir permeability	246	mD
Drainage area	5894	Acres
Dietz shape factor	31.6	
Reservoir thickness	106	ft
Reservoir pressure	11305	psi

Well Properties	Value	Unit
Well type	Vertical	
Measured Depth	16726	ft
Casing inner diameter	13.375	in
Liner inner diameter	10.75	in
Open hole diameter	8.375	in
Casing shoe depth	8850	ft
Length of open hole section	5076	ft

Case	Oil Gravity	Bubble Point Pressure
	^{o}API	(psi)
1	35	5500
2	45	6900

Comparative study

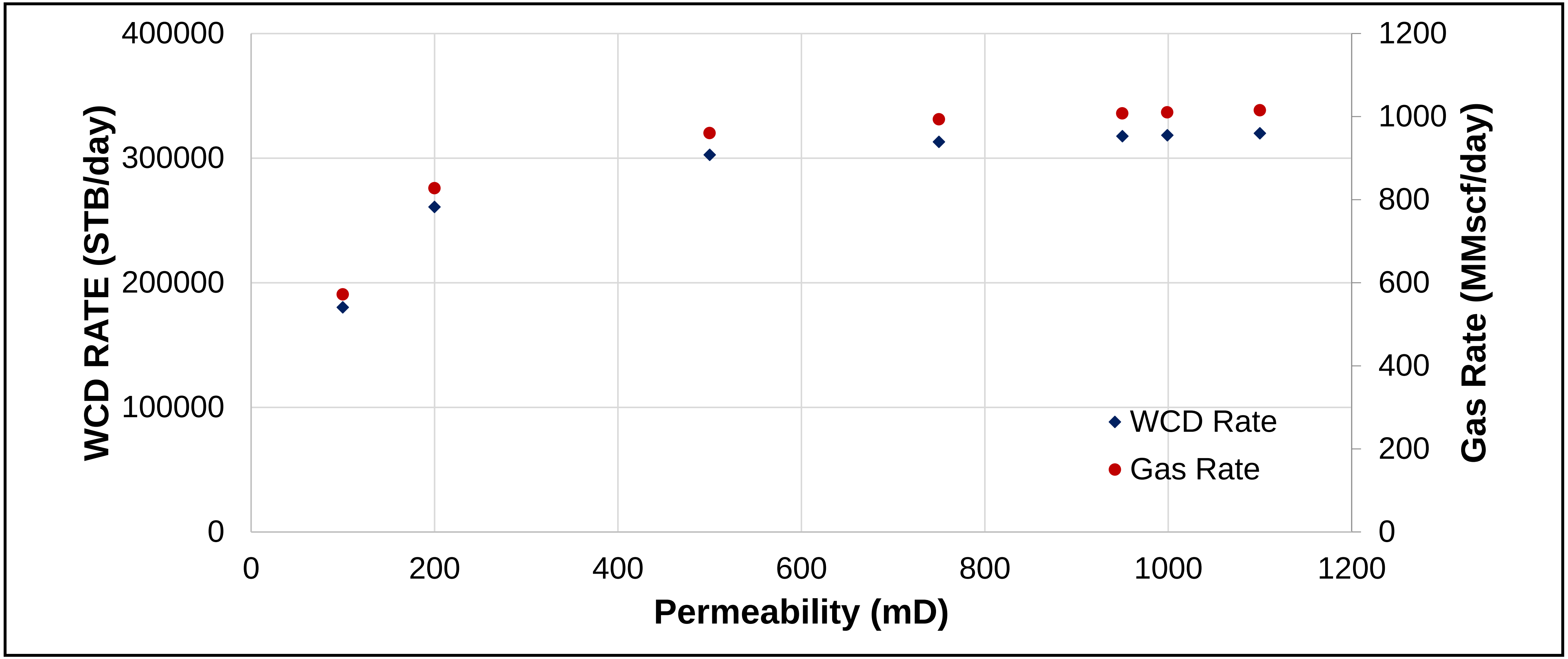
Case study: GoM

Case	WCD Rate	WCD Rate	Diff.
	OU Model	Prosper	%
	STB/day	STB/day	
1	302783	284519	6.4
2	275248	264912	3.9

Conservative

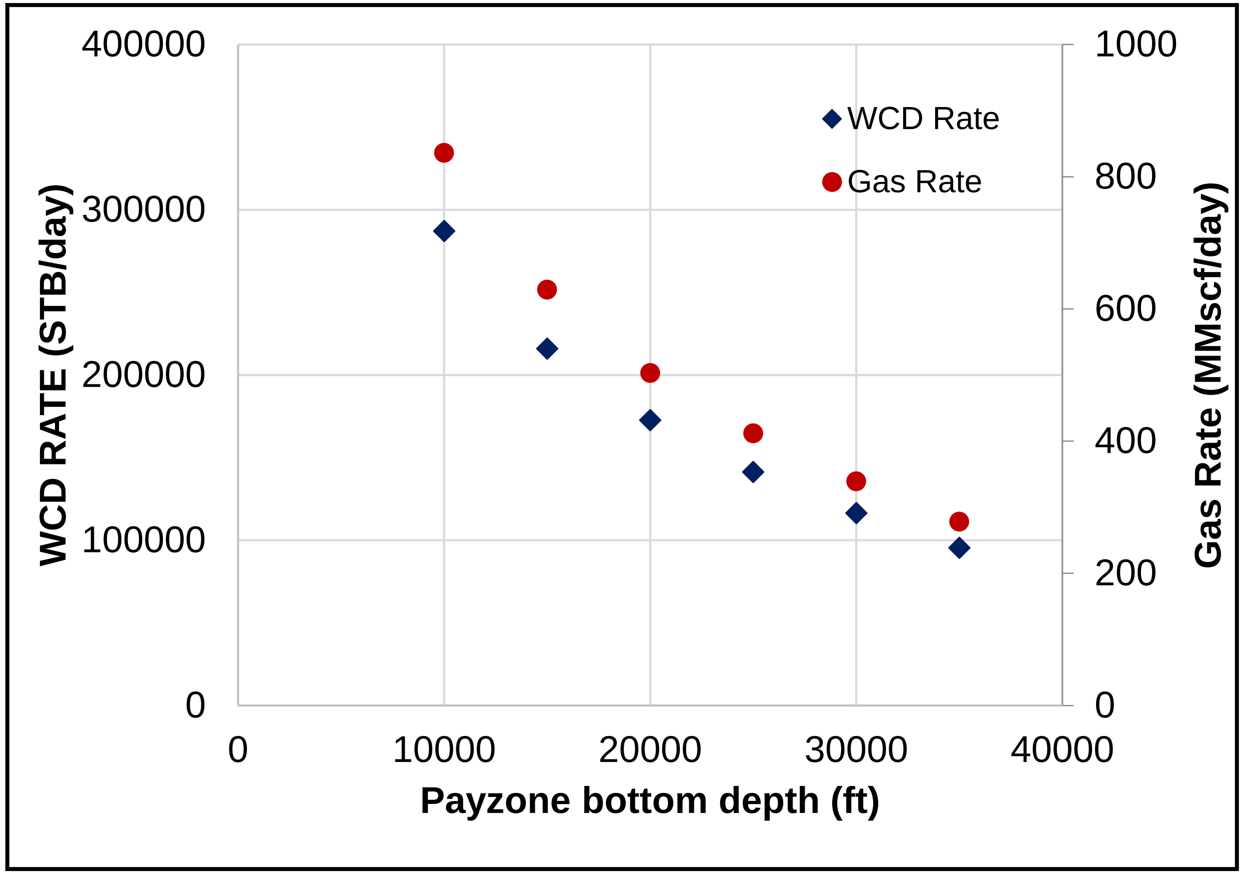
Sensitivity Analysis

Change in Permeability

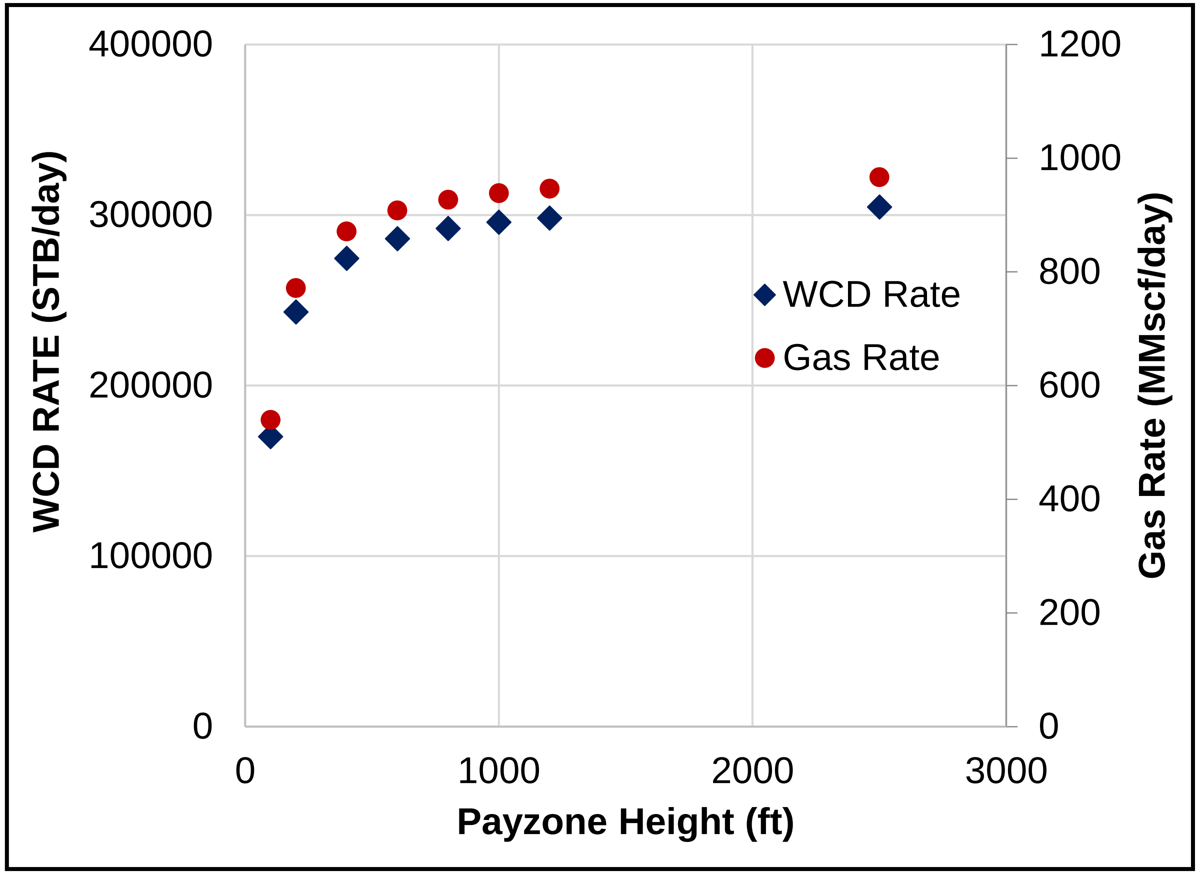


Sensitivity Analysis

Change in Payzone Bottom Depth

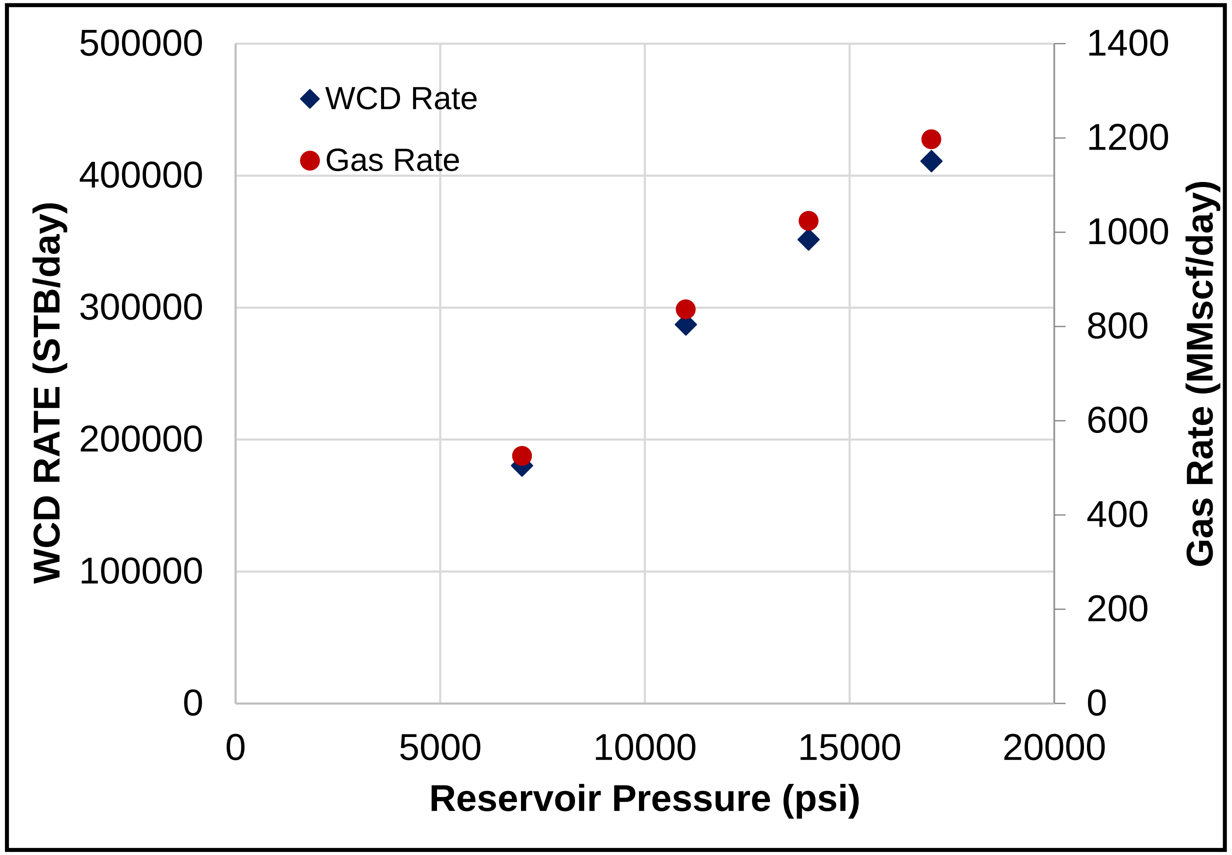


Change in Payzone Height

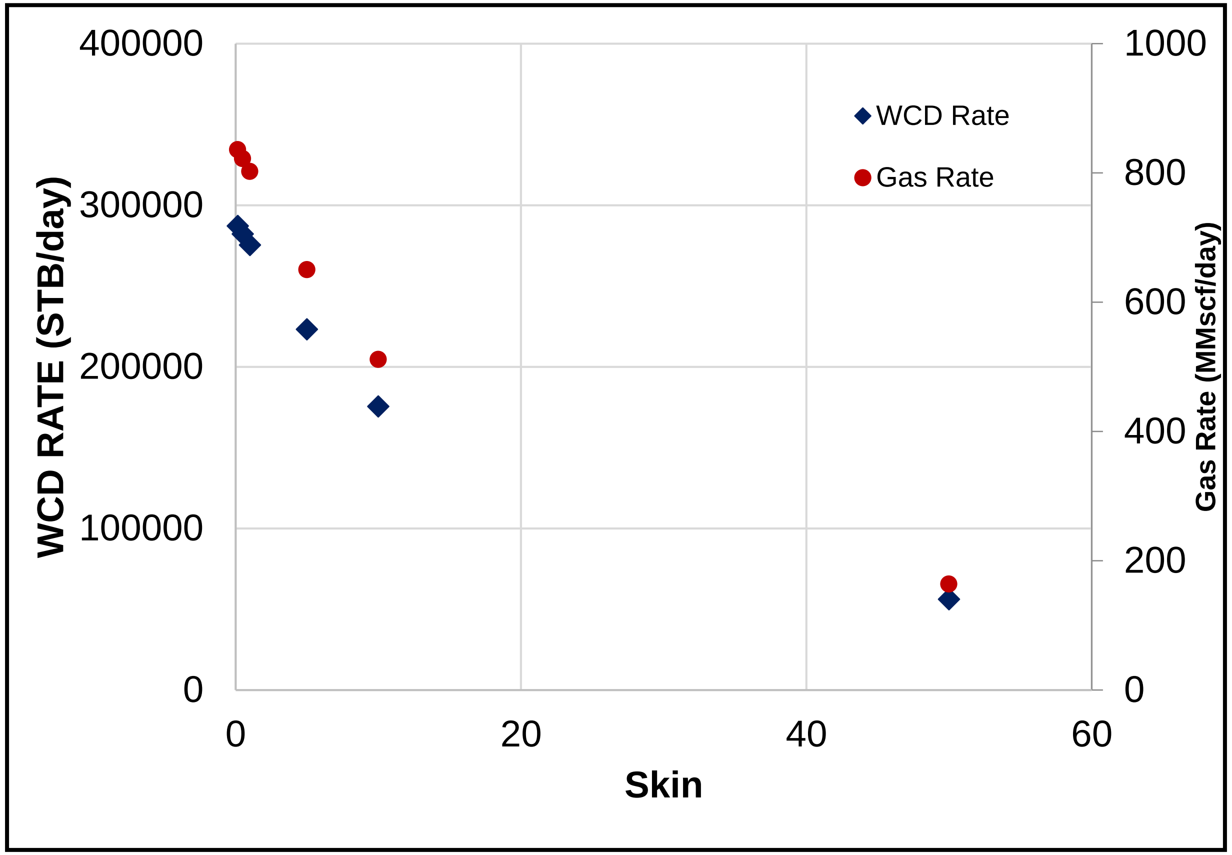


Sensitivity Analysis

Change in Reservoir Pressure



Change in Skin



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

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- Jeff McCaskill

Thank you !!!