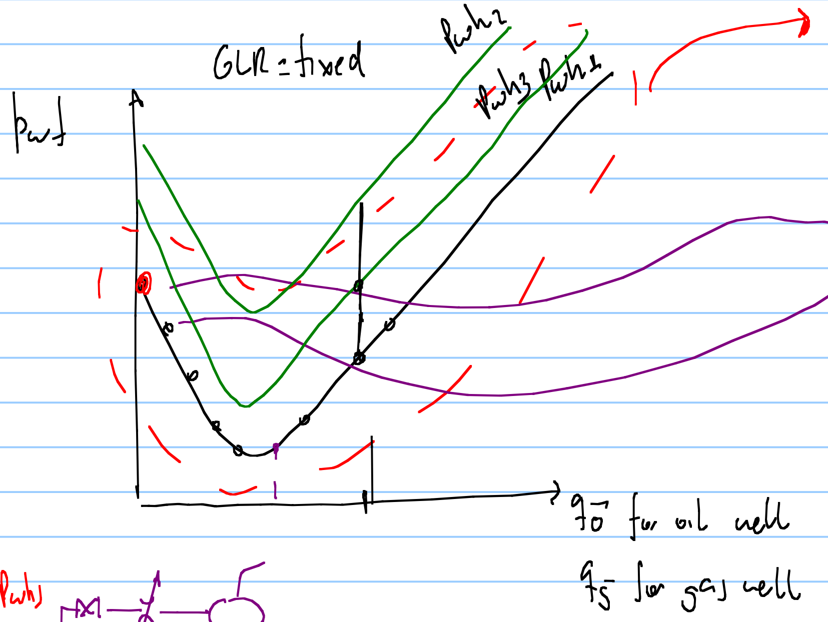
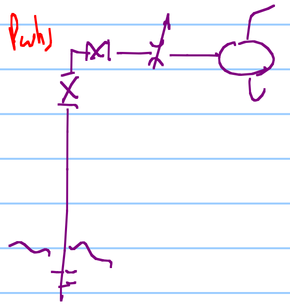
Day 8

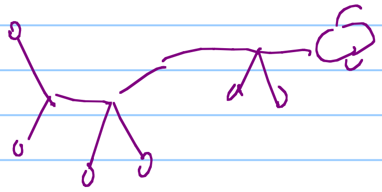
Multiphase flow:
- Tubing tables
- pressure traverse curves ~
- multiphase flow theory (flow patterns, maps, definitions)
- methods to study multiphase flow
- Conversion from s.c to local condition using BO properties.



Pwh = Pwh1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	Pwf	Twh
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-





Pwh = Pwh1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	Pwf	Twh
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

Pwh = Pwh2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	Pwf	Twh
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

Pwh = Pwh3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	Pwf	Twh
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

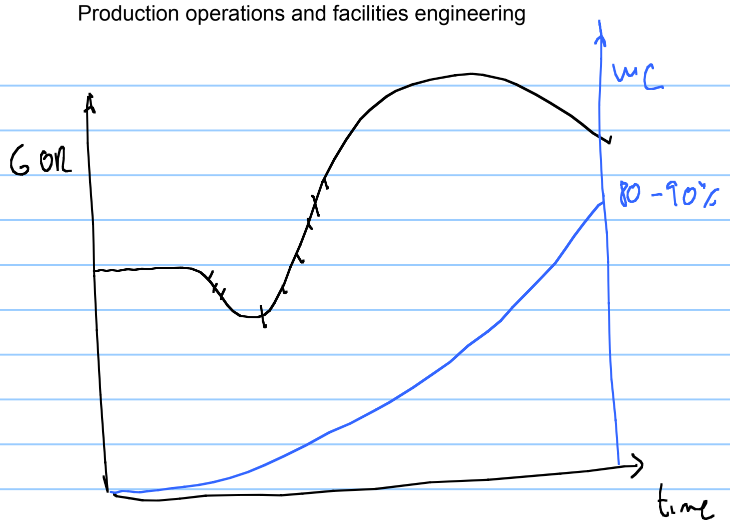
Pwh range for {200 bara ~> 30 bara}

↓ | | | | | ↓

if i want Pwh = 185

Pwh = 200

Pwh = 30



GLR and WC change during the life of the well

$P_{wh} = P_{wh1}$ GOR_1 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh2}$ GOR_1 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh3}$ GOR_1 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh1}$ GOR_2 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh2}$ GOR_2 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh3}$ GOR_2 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh1}$ GOR_3 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh2}$ GOR_3 WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$P_{wh} = P_{wh3}$ $GO3$ WC_1

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				

$wh = P_{wh1}$ GOR_1 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh_2}$ GOR_1 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh_3}$ GOR_1 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh1}$ GOR_2 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh_2}$ GOR_2 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh_3}$ GOR_2 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh1}$ GOR_3 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh_2}$ GOR_3 WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$P_{wh} = P_{wh_3}$ $GO3$ WC_2

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	p_{wf}	J_{wh}
0				
-	-	-	-	-
	-	-	-	-
	-	-		-

$wh = P_{wh1}$ GOR_1 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh2}$ GOR_1 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh3}$ GOR_1 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh1}$ GOR_2 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh2}$ GOR_2 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh3}$ GOR_2 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh1}$ GOR_3 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh2}$ GOR_3 WC_3

10

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh3}$ GO_3 WC_3

$q_{\bar{o}}$	$q_{\bar{g}}$	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$N_{tables} = N_{P_{wh}} \times N_{GORs} \times N_{WC} = 3 \times 3 \times 3 = 27$.

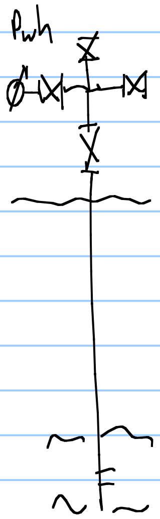
$N_{simulations}$ per tables $= 10$ (rates $q_{\bar{o}}$)

$= 270$! calculations of Δp in tubing

- Reservoir simulator uses tables
- GAP uses tables for wells
  ↳ commercial production simulator by PETEX

If you use tables use appropriate number of points to ensure a good interpolation!

- Pressure traverse curves: graphical method to solve pressure drop calculation in vertical oil wells



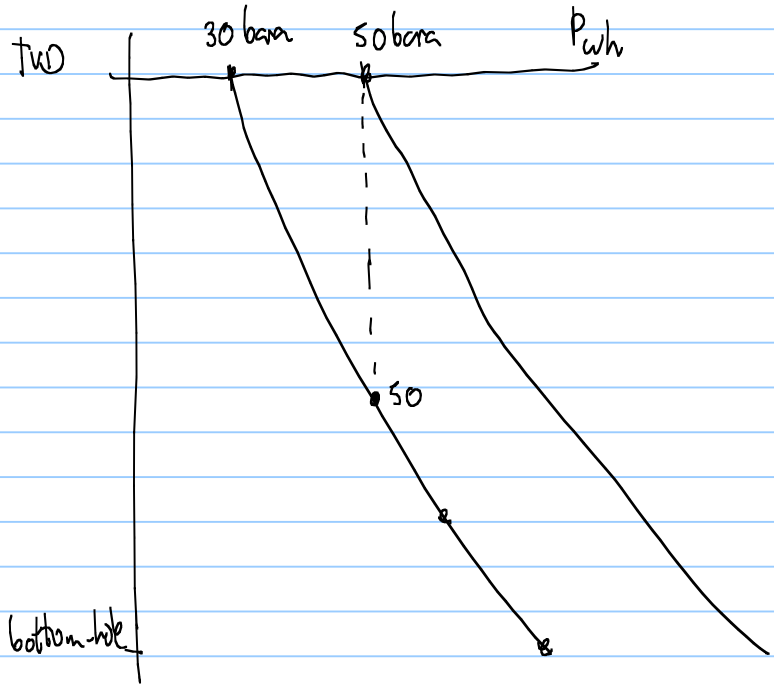
$q_{\bar{o}}$ = constant

θ = constant

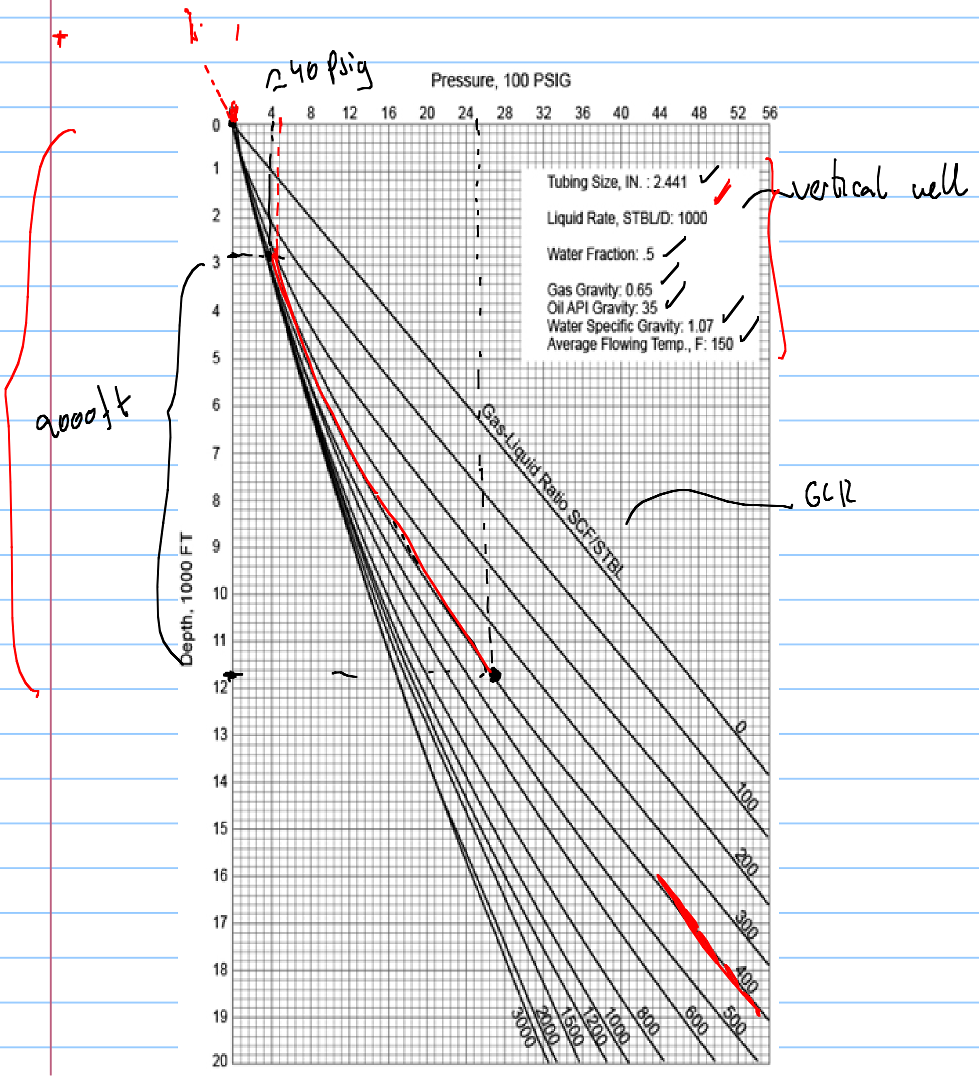
GLR = constant

γ_o = constant

γ_g = constant



$$\frac{dp}{dz} = f(p) \sim$$



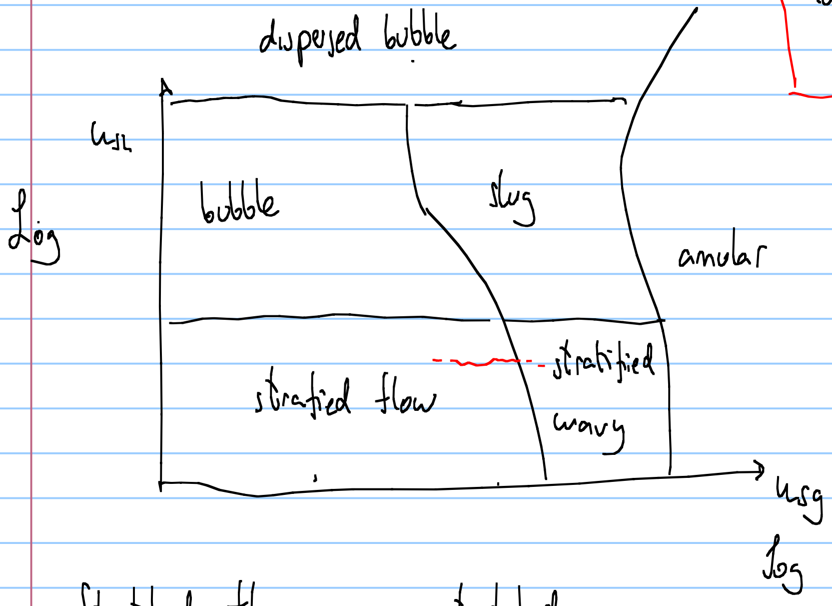
- Use the pressure traverses from the textbook to determine the Wellhead pressure for the following oil production well:
  - Bottomhole flowing pressure – 2500 psi
  - Well depth 9000 ft
  - Tubing 2.441" ID (2 7/8")
  - Total Flow rate 1000 bpd
  - Water Cut 50%
  - GLRp = 400 scf/bbl

$$GLR = \frac{q_{\bar{g}}}{q_{\bar{o}} + q_{\bar{w}}}$$

superficial velocity: $u_{sL} = \frac{q_L}{A}$ → local volume rate @ p,T m/s
↳ cross section area of pipe

$u_{sg} = \frac{q_g}{A}$ m/s

flow pattern map:

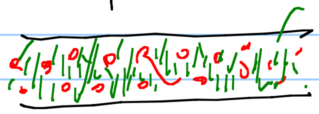


horizontal line

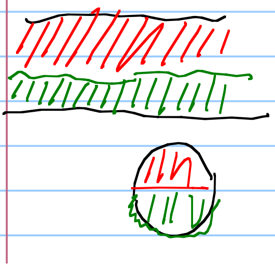
everything else is constant
- ρ_L
- ρ_g
- θ ~> pipe inclination angle
- ε
- σ_{Lg}
- μ_g
- μ_L

bubble

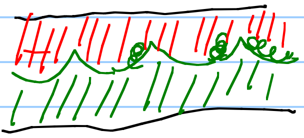
dispersed bubble



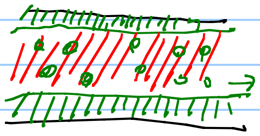
Stratified flow



stratified wavy

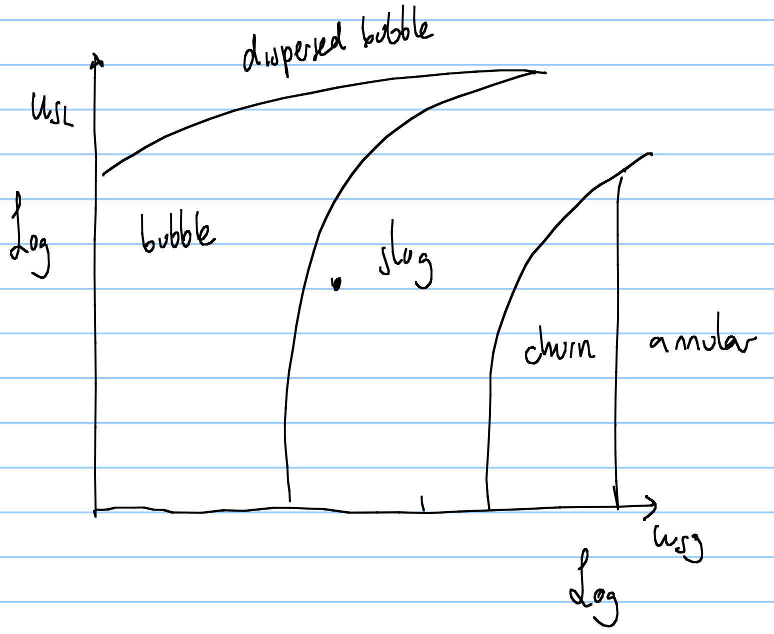


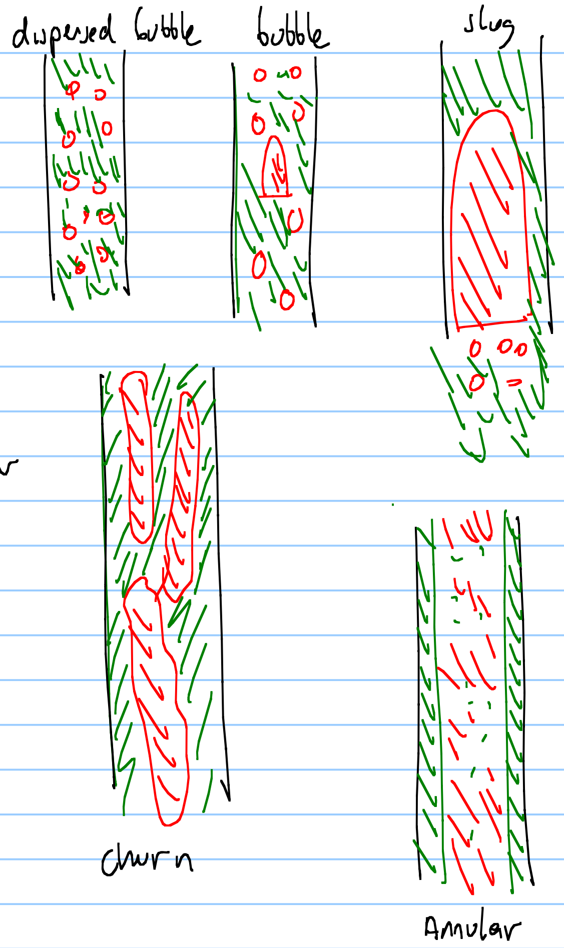
annular



slug

for vertical pipe

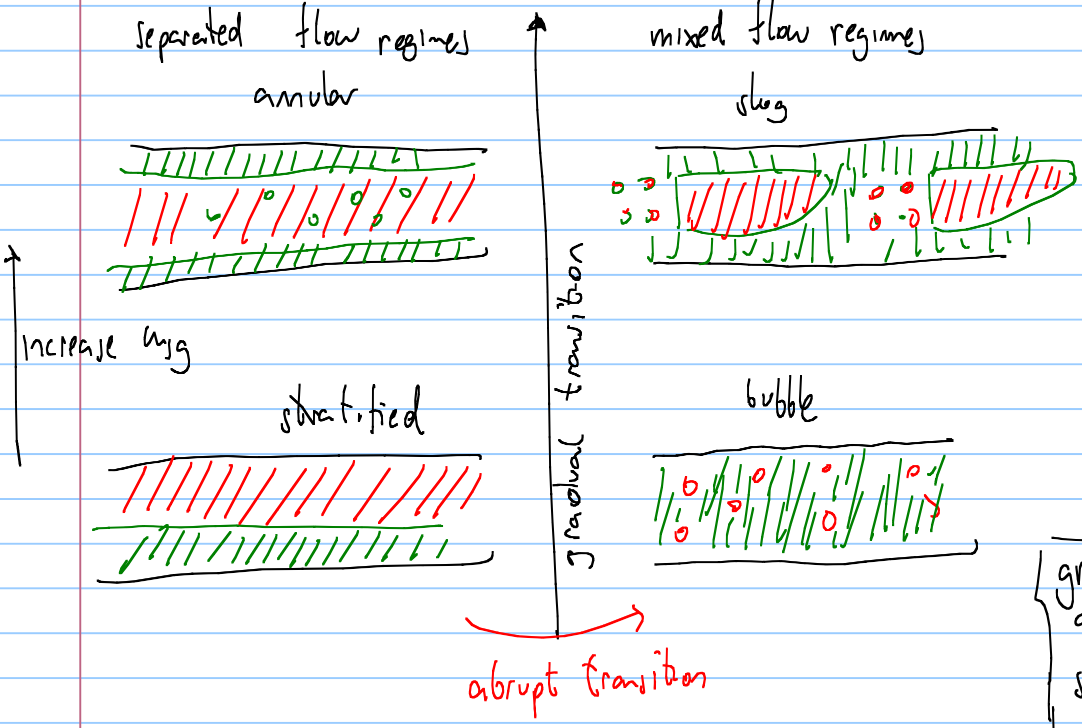




Re_L $\quad We \quad$ weber number $= \frac{\rho \cdot v^2 \cdot D}{\sigma} \rightsquigarrow$ inertia

Re_g

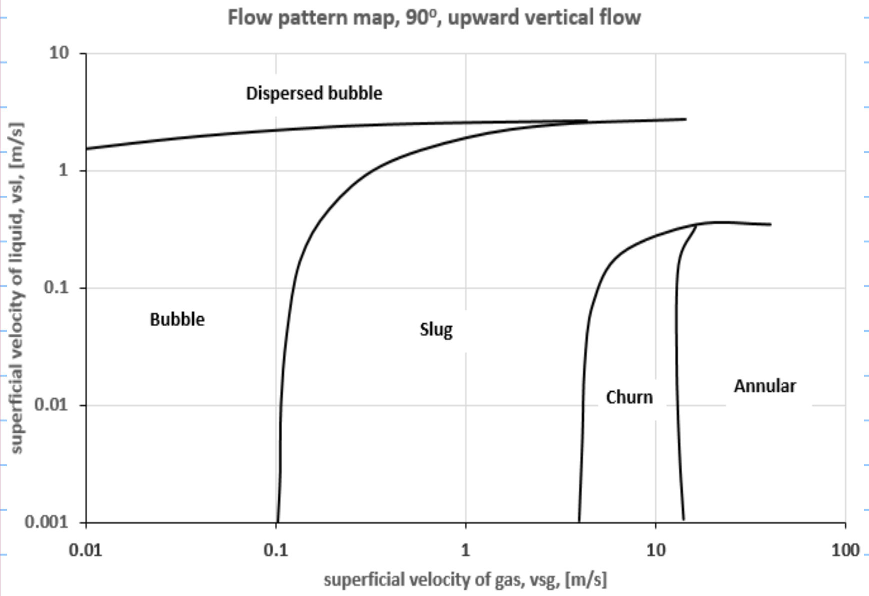
$$\text{Froude} = \frac{v^2}{gD} \checkmark$$



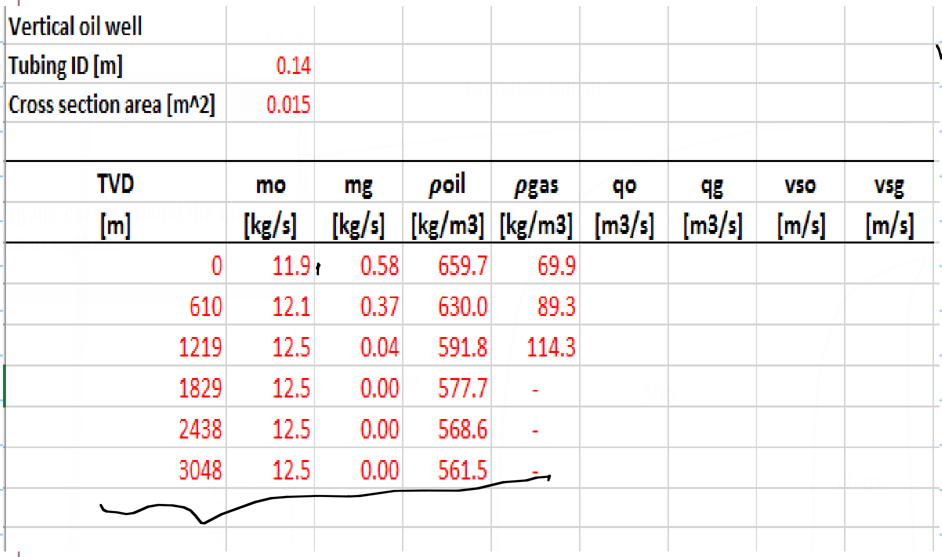
the transition and occurrence of flow patterns is dictated by an force equilibrium on the phase

segregating forces	mixing forces
gravitational acceleration	inertia v^2
surface forces	viscosity
viscosity	

class exercise to define flow pattern along tubing

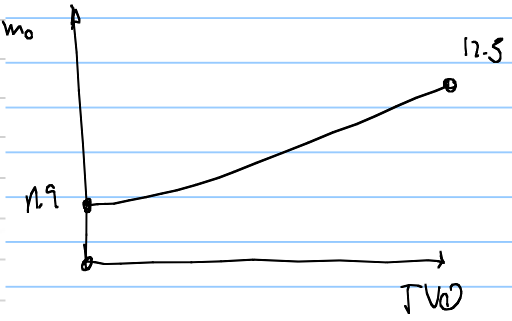


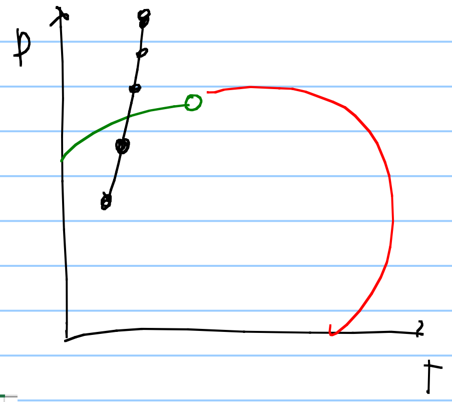
Assumption: the map doesn't change along the tubing
it is not affected by changes in fluid properties



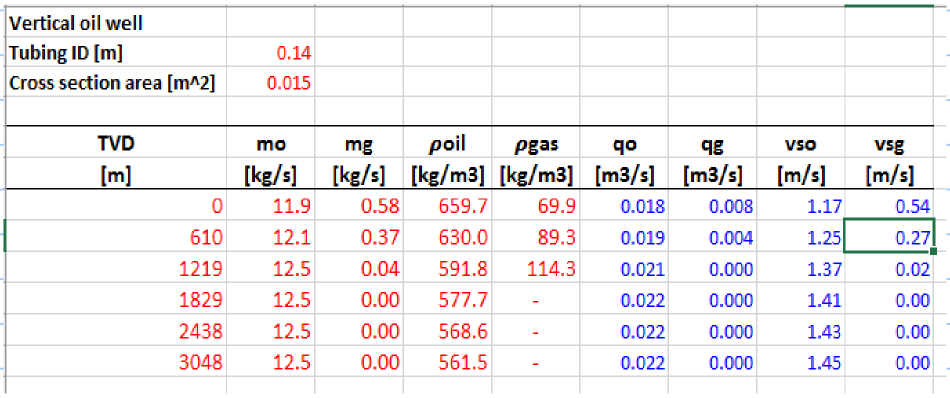
Vertical oil well
Tubing ID [m] 0.14
Cross section area [m^2] 0.015

TVD [m]	mo [kg/s]	mg [kg/s]	ρoil [kg/m3]	ρgas [kg/m3]	qo [m3/s]	qg [m3/s]	vso [m/s]	vsg [m/s]
0	11.9	0.58	659.7	69.9				
610	12.1	0.37	630.0	89.3				
1219	12.5	0.04	591.8	114.3				
1829	12.5	0.00	577.7	-				
2438	12.5	0.00	568.6	-				
3048	12.5	0.00	561.5	-				





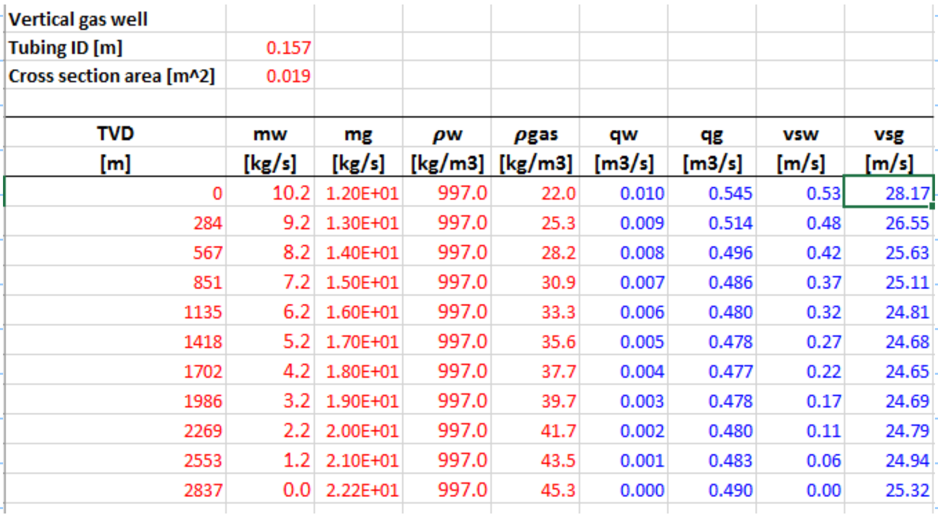
oil well



Vertical oil well
Tubing ID [m] 0.14
Cross section area [m^2] 0.015

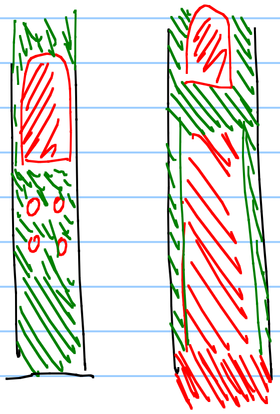
TVD [m]	mo [kg/s]	mg [kg/s]	ρoil [kg/m3]	ρgas [kg/m3]	qo [m3/s]	qg [m3/s]	vso [m/s]	vsg [m/s]
0	11.9	0.58	659.7	69.9	0.018	0.008	1.17	0.54
610	12.1	0.37	630.0	89.3	0.019	0.004	1.25	0.27
1219	12.5	0.04	591.8	114.3	0.021	0.000	1.37	0.02
1829	12.5	0.00	577.7	-	0.022	0.000	1.41	0.00
2438	12.5	0.00	568.6	-	0.022	0.000	1.43	0.00
3048	12.5	0.00	561.5	-	0.022	0.000	1.45	0.00

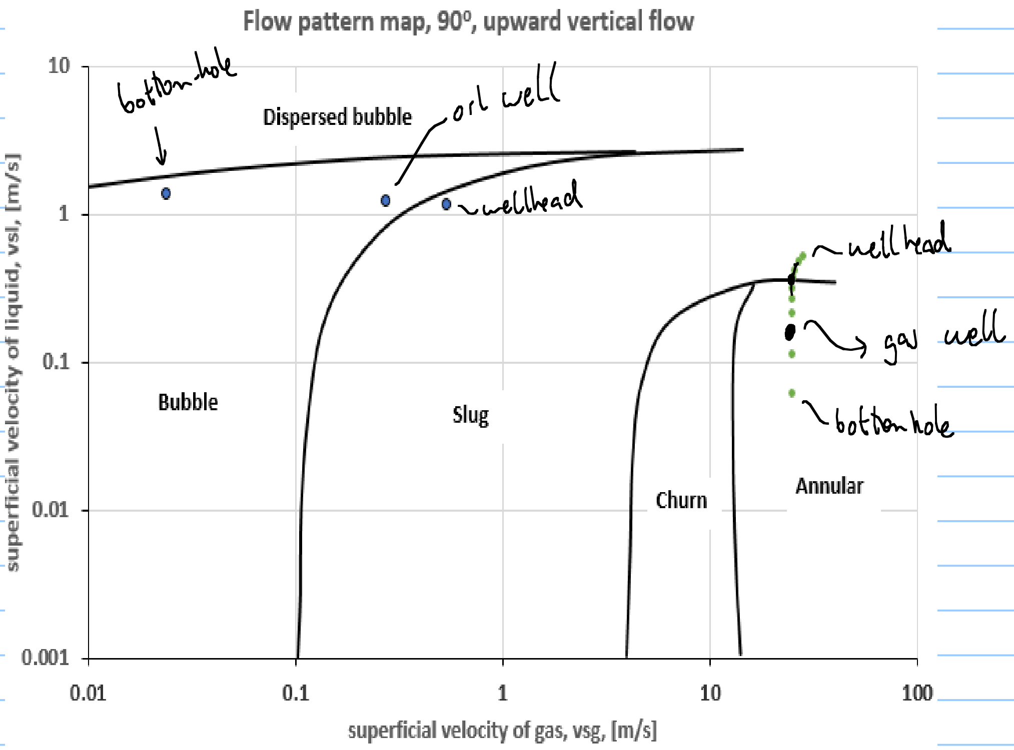
gas well

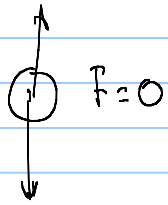


Vertical gas well								
Tubing ID [m]	0.157							
Cross section area [m^2]	0.019							

TVD [m]	mw [kg/s]	mg [kg/s]	ρw [kg/m3]	ρgas [kg/m3]	qw [m3/s]	qg [m3/s]	vsw [m/s]	vsg [m/s]
0	10.2	1.20E+01	997.0	22.0	0.010	0.545	0.53	28.17
284	9.2	1.30E+01	997.0	25.3	0.009	0.514	0.48	26.55
567	8.2	1.40E+01	997.0	28.2	0.008	0.496	0.42	25.63
851	7.2	1.50E+01	997.0	30.9	0.007	0.486	0.37	25.11
1135	6.2	1.60E+01	997.0	33.3	0.006	0.480	0.32	24.81
1418	5.2	1.70E+01	997.0	35.6	0.005	0.478	0.27	24.68
1702	4.2	1.80E+01	997.0	37.7	0.004	0.477	0.22	24.65
1986	3.2	1.90E+01	997.0	39.7	0.003	0.478	0.17	24.69
2269	2.2	2.00E+01	997.0	41.7	0.002	0.480	0.11	24.79
2553	1.2	2.10E+01	997.0	43.5	0.001	0.483	0.06	24.94
2837	0.0	2.22E+01	997.0	45.3	0.000	0.490	0.00	25.32





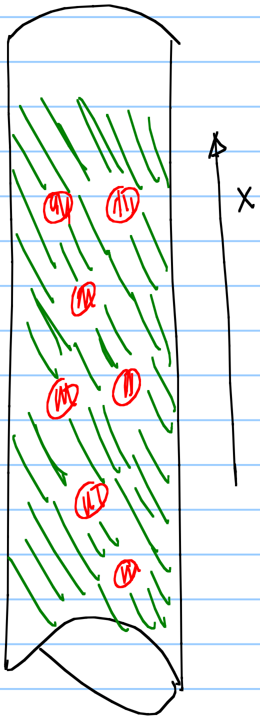


Short comment on liquid loading

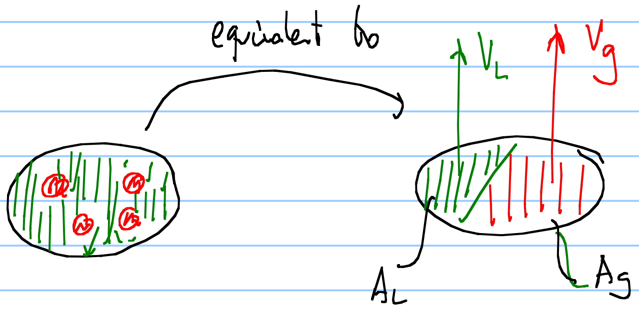
alternative explanation

wall slippage

transition from annular flow to slug flow

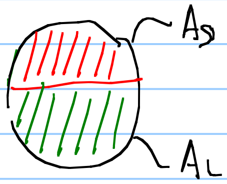


1-D



homogeneous. $V_L = V_g$ non slip condition

non homogeneous → slip $V_L \neq V_g$



gas non-slip void fraction

$$\lambda_g = \frac{A_g}{A}$$

Liquid no-slip holdup

$$\lambda_L = \frac{A_L}{A}$$

no-slip

$$V_g = V_L = V_m$$

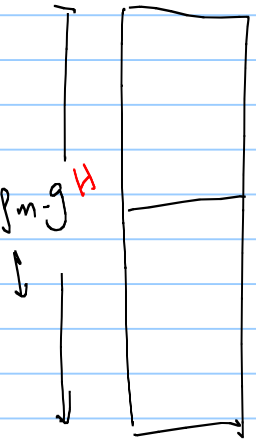
$$q_g = A_g \cdot V_m \quad (1)$$

$$q_L = A_L \cdot V_m \quad (2)$$

$$q_g + q_L = V_m (A_g + A_L)$$

$$V_m = \frac{q_g + q_L}{A} = u_{sg} + u_{sL}$$

$\Delta p = \rho_m \cdot g \cdot H$



λ_g , λ_L ? for $V_L = V_g = V_m$

substitute $V_m = u_{sg} + u_{sL}$ in (1)

$$q_g = A_g \left(\frac{q_g + q_L}{A} \right) \Rightarrow \lambda_g = \frac{q_g}{q_g + q_L}$$

q_L

$$\lambda_L = \frac{q_L}{q_g + q_L}$$

$$\rho_m = \lambda_g \rho_g + \rho_L \lambda_L$$

But often $V_L \neq V_g$!!

void fraction

$$\varepsilon = \frac{A_g}{A}$$

liquid holdup

$$H_L = \frac{A_L}{A}$$

$V_g > V_m$ q_L

$\varepsilon < \lambda_g$

$q_L = \lambda_g \cdot A \cdot V_m = A \cdot \varepsilon \cdot V_g$

V_g V_L real gas and liquid velocities

S .. slip ratio $\frac{V_g}{V_L}$

relative velocity

$u_r = V_g - V_L$

Drift velocity

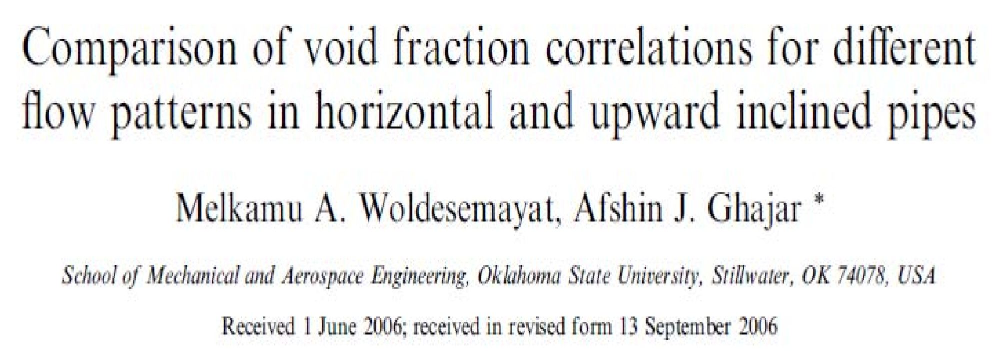
$u_d = V_g - u_m$

$\varepsilon = \frac{A_g}{A}$ $H_L = \frac{A_L}{A}$

$\varepsilon + H_L = \frac{A_g + A_L}{A} = 1$

$H_L = (1-\varepsilon)$

$H_L = f(\theta, \phi, p, \rho_L, \rho_g, u_{sL}, u_{sg})$



Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes

Melkamu A. Woldesemayat, Afshin J. Ghajar *

School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, OK 74078, USA

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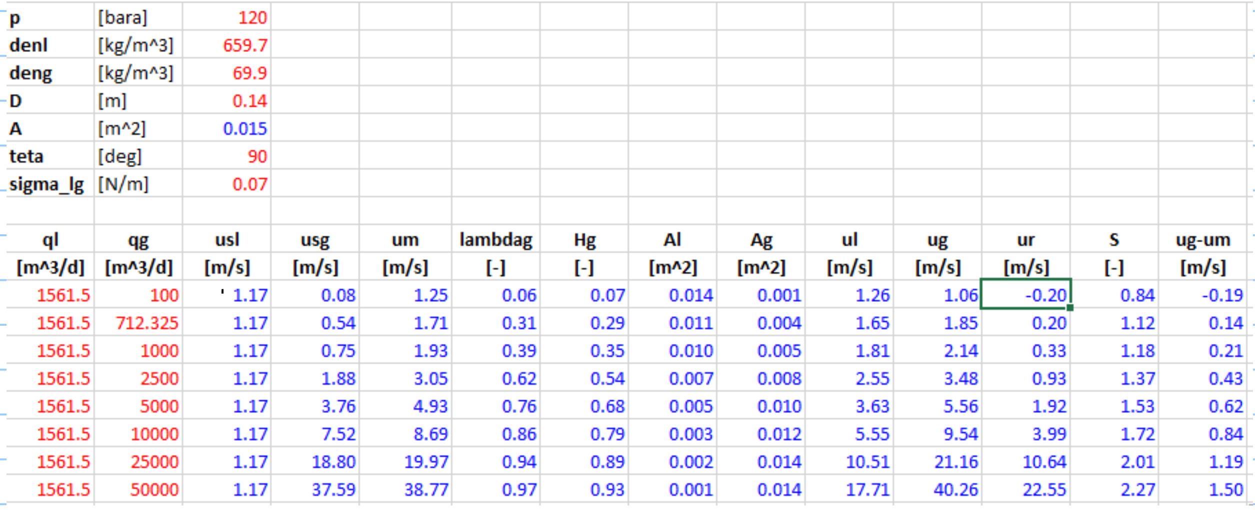
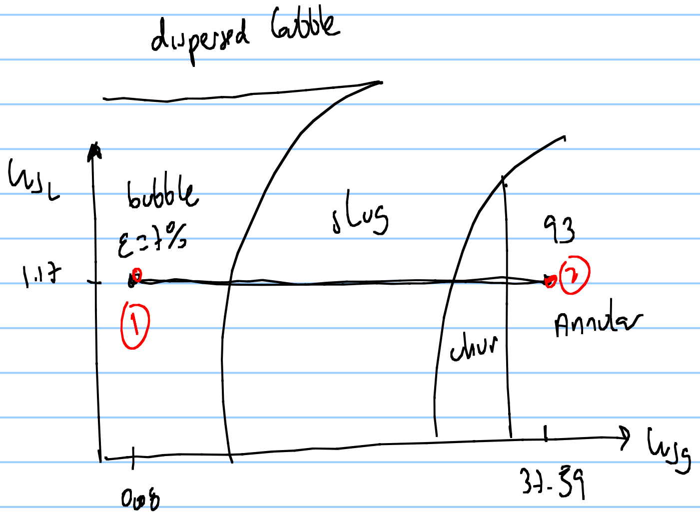
8 parameters.

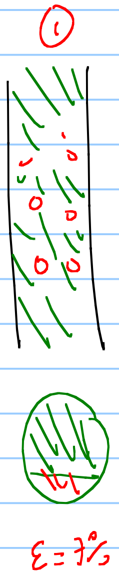
$$\varepsilon = \frac{U_{SG}}{U_{SG}\left(1+\left(\frac{U_{SL}}{U_{SG}}\right)^{\left(\frac{\rho_G}{\rho_L}\right)^{0.1}}\right)+2.9\left[\frac{gD\sigma(1+\cos\theta)(\rho_L-\rho_G)}{\rho_L^2}\right]^{0.25}(1.22+1.22\sin\theta)^{\frac{P_{atm}}{P_{system}}}}$$

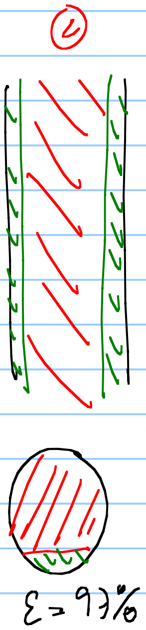


p	[bara]	120
denl	[kg/m^3]	659.7
deng	[kg/m^3]	69.9
D	[m]	0.14
A	[m^2]	0.015
teta	[deg]	90
sigma_lg	[N/m]	0.07

ql	qg	usl	usg	um	lambdag	Hg	Al	Ag	ul	ug	ur	S	ug-um
[m^3/d]	[m^3/d]	[m/s]	[m/s]	[m/s]	[-]	[-]	[m^2]	[m^2]	[m/s]	[m/s]	[m/s]	[-]	[m/s]
1561.5	100	1.17	0.08	1.25	0.06	0.07	0.014	0.001	1.26	1.06	-0.20	0.84	-0.19
1561.5	712.325	1.17	0.54	1.71	0.31	0.29	0.011	0.004	1.65	1.85	0.20	1.12	0.14
1561.5	1000	1.17	0.75	1.93	0.39	0.35	0.010	0.005	1.81	2.14	0.33	1.18	0.21
1561.5	2500	1.17	1.88	3.05	0.62	0.54	0.007	0.008	2.55	3.48	0.93	1.37	0.43
1561.5	5000	1.17	3.76	4.93	0.76	0.68	0.005	0.010	3.63	5.56	1.92	1.53	0.62
1561.5	10000	1.17	7.52	8.69	0.86	0.79	0.003	0.012	5.55	9.54	3.99	1.72	0.84
1561.5	25000	1.17	18.80	19.97	0.94	0.89	0.002	0.014	10.51	21.16	10.64	2.01	1.19
1561.5	50000	1.17	37.59	38.77	0.97	0.93	0.001	0.014	17.71	40.26	22.55	2.27	1.50







Homework

S vs usg

S vs H_L $(1-\varepsilon)$