Day 9 :

- methods to compute multiphase flow $\rightsquigarrow \frac{dp}{dx}$
- the drift flux model $\rightsquigarrow$
- Conversion from local to standard conditions using BO properties
- Exercise
- Pressure integration in multiphase flow
- Exercise
- final comments - end

two approaches to study multiphase flow

→ empirical
- based on adimensional numbers
- experiments

→ mechanistic
- mass balance
- momentum balance
- energy balance
→ correlation exp.
- Considers the flow pattern (distribution of phases)

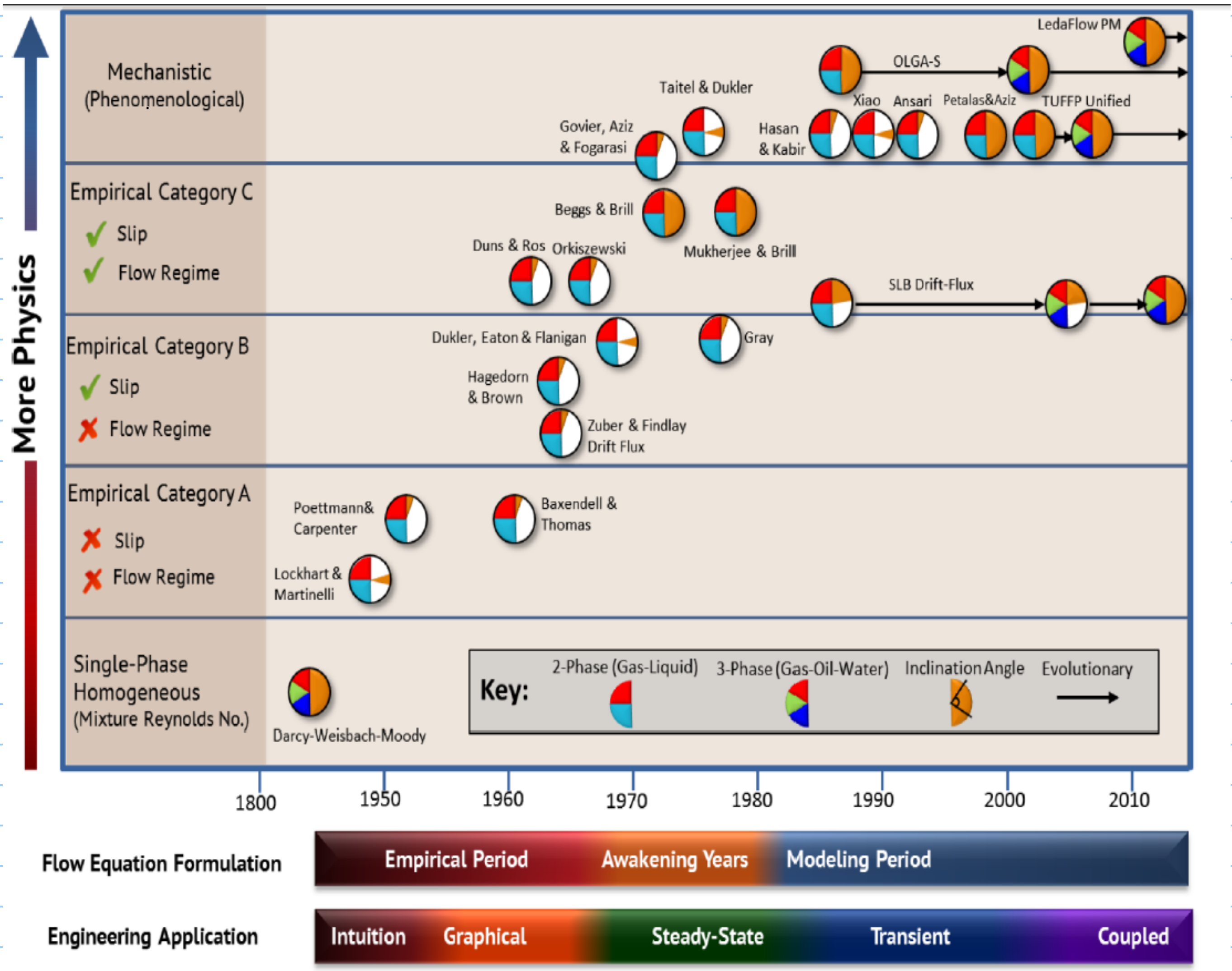
In this course we are interested mainly in $\frac{dp}{dx}$!!
however, there are also some other problems :

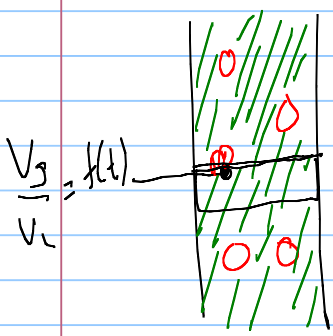
Top of line corrosion

- O+W emulsion
- liquid accumulation and slugging

- Sand erosion
- hydrate and wax - -
- etc

Shippen and Bailey (2012)

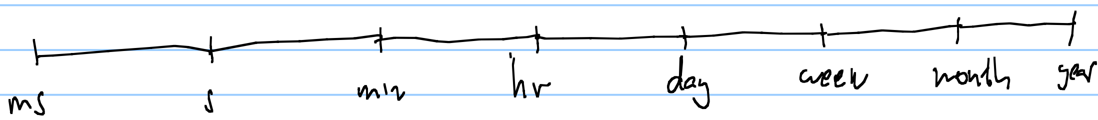


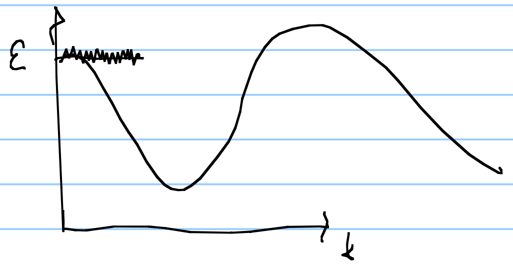


Steady state

transient

slugging !





Drift flux model — 1 momentum equation for mixture using average properties (similar to single phase)

$$\frac{dp}{dl} = -f_{TP} \cdot \rho_{TP} \cdot \frac{V_{TP}^2}{2\phi} - \rho_{TP} \cdot \sin\theta \cdot g - \rho_{TP} V_{TP} \cdot \cancelto{0}{\frac{dV_{TP}}{dl}}$$

$$\rho_{TP} = \varepsilon \rho_g + (1-\varepsilon)\rho_L.$$

slip

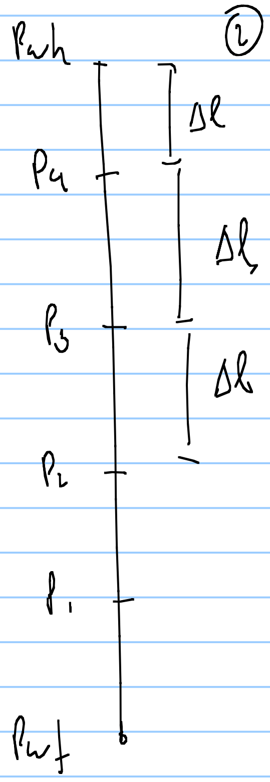
if λ_g is used then homogeneous model

$$V_{TP} = u_m = u_{SL} + u_{sg}$$

$\frac{dV_m}{dl} \approx 0$ ~ neglecting fluid expansion in segment and no change in cross section area.

$$\frac{dp}{dl} = -f_{TP} \cdot \rho_{TP} \frac{V_{TP}^2}{2\phi} - \rho_{TP} \sin\theta \cdot g$$

Pressure integration procedure for steady state multiphase flow in wellbore (T is given)



① • discretize the tubing in segments

② • start for point with pressure known (P_{wh})

• with p, T compute local rate of oil, gas — calculate B_o, R_s, B_g — q_o, q_g

and compute all properties $\{\rho_o, \rho_g, \mu_o, \mu_g, \sigma_{og},$

• compute superficial velocities on that point $u_{so} = \frac{q_o}{A}$ $u_{sg} = \frac{q_g}{A}$

• compute pressure gradient at that point $\frac{dp}{dl}$ → drift flux / → mechanistic model / → empirical model / → multiphase expert.

- integrate numerically the differential equation $\frac{dp}{dl} = C$ $\quad P(TVD=0)$ known.
    - use explicit integration method { euler / runge-kutta
    - use an implicit integration method.

warning ! EULER requires very small intervals

→ use EULER explicit. $\quad P_4 = P_{wh} - \left.\frac{dp}{dl}\right|_{TVD=0} \cdot \Delta l$

- P_4. repeat from point 2

we need to compute q_o q_g from $q_{\bar{o}}$ $q_{\bar{g}}$ using black oil tables

Single phase gas

$$q_g = B_g \cdot q_{\bar{g}}$$

undersaturated oil

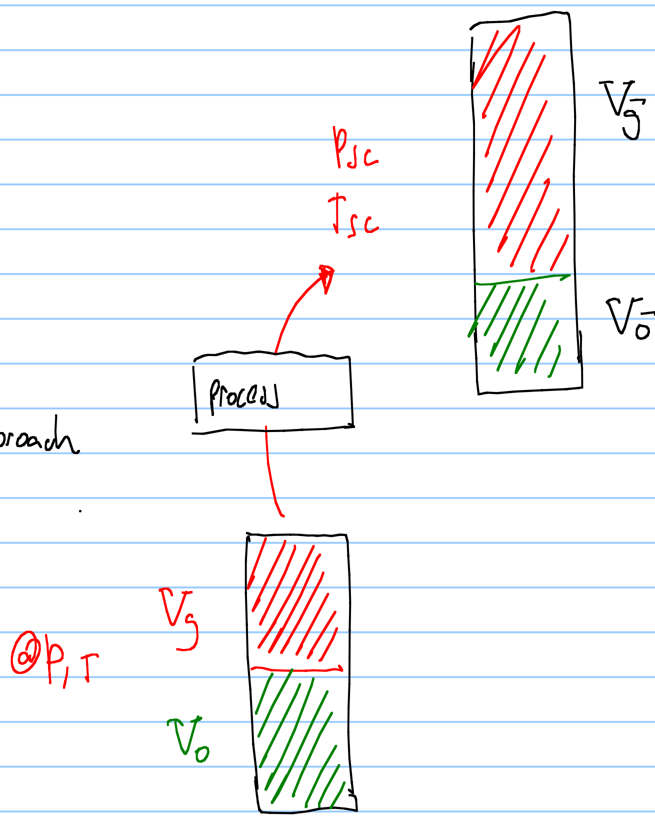
$$q_o = B_o \cdot q_{\bar{o}}$$

assume $r_s = 0$

$$\begin{bmatrix} q_g \\ q_o \\ q_w \end{bmatrix} = \begin{bmatrix} \frac{B_g}{1-R_s \cdot r_s} & \frac{-B_g \cdot R_s}{1-R_s \cdot r_s} & 0 \\ \frac{-B_o \cdot r_s}{1-R_s \cdot r_s} & \frac{B_o}{1-R_s \cdot r_s} & 0 \\ 0 & 0 & B_w \end{bmatrix}_{(p,T)} \cdot \begin{bmatrix} q_{\bar{g}} \\ q_{\bar{o}} \\ q_{\bar{w}} \end{bmatrix}$$

Local conditions calculated from standard conditions

traditional BO-approach



definition

$$B_o(p,T) = \frac{V_o(p,T)}{V_{\bar{o}}}$$

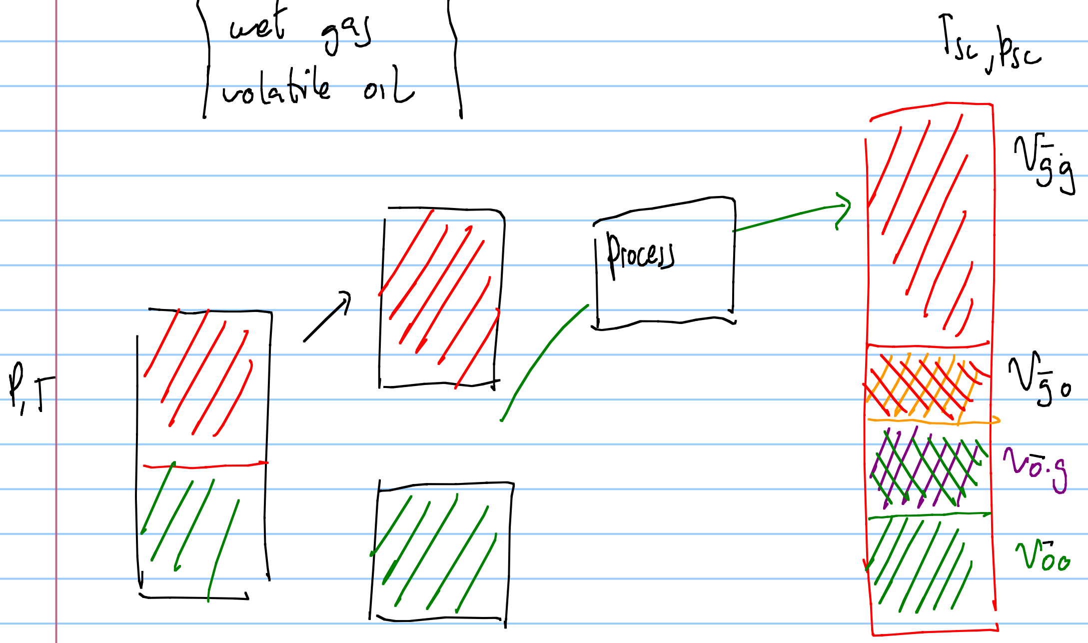
$$B_g(p,T) = \frac{V_g(p,T)}{V_{\bar{g}}}$$

$$R_s(p,T) = \frac{V_{\bar{g}}}{V_{\bar{o}}}$$

$$\boxed{\begin{aligned} q_g &= B_g\, q_{\bar{g}} - B_g R_s\, q_{\bar{o}} \\ q_o &= B_o\, q_{\bar{o}} \end{aligned}}$$

if r_s is important keep track of where surface oil and surface gas is coming from

$\left\{\begin{array}{l}\text{gas condensate} \\ \text{wet gas} \\ \text{volatile oil}\end{array}\right\}$



$$r_s = \frac{V_{\bar{o}g}}{V_{\bar{g}g}}$$

$$R_s = \frac{V_{\bar{g}o}}{V_{\bar{o}o}}$$

BO Variable	Definition
Oil Volume Factor	$B_o(p,T) = \dfrac{V_o(p,T)}{V_{\bar{o}o}}$
Gas Volume Factor	$B_g(p,T) = \dfrac{V_g(p,T)}{V_{\bar{g}g}}$
Solution Gas Oil Ratio	$R_s(p,T) = \dfrac{V_{\bar{g}o}}{V_{\bar{o}o}}$
Solution Oil Gas ratio	$r_s(p,T) = \dfrac{V_{\bar{o}g}}{V_{\bar{g}g}}$

$$\begin{bmatrix} q_g \\ q_o \\ q_w \end{bmatrix} = \begin{bmatrix} \frac{B_g}{1-R_s \cdot r_s} & \frac{-B_g \cdot R_s}{1-R_s \cdot r_s} & 0 \\ \frac{-B_o \cdot r_s}{1-R_s \cdot r_s} & \frac{B_o}{1-R_s \cdot r_s} & 0 \\ 0 & 0 & B_w \end{bmatrix}_{(p,T)} \cdot \begin{bmatrix} q_{\bar{g}} \\ q_{\bar{o}} \\ q_{\bar{w}} \end{bmatrix}$$

Local conditions calculated from standard conditions

qg [Sm^3/d]	60000		qg [m^3/d]	6.29E+02		
qo [Sm^3/d]	500		qo [m^3/d]	620.4		
					Conversion matrix fo	
p	**Bo**	**Bg**	**Rs**	**rs**		
[bara]	**[m^3/Sm^3]**	**[m^3/Sm^3]**	**[Sm^3/Sm^3]**	**[Sm^3/Sm^3]**	1.65E-02	-7.22E-01
160	1.44	8.17E-03	105.22	3.92E-05	-2.10E-05	1.24E+00
120	1.33	1.09E-02	72.47	2.40E-05		
80	1.24	1.65E-02	43.74	1.69E-05		

	qg [Sm^3/d]	60000		qg [m^3/d]	6.29E+02		
	qo [Sm^3/d]	500		qo [m^3/d]	621.2		
						Conversion matrix f	
T = 120 C							
	p	**Bo**	**Bg**	**Rs**	**rs**		
	[bara]	**[m^3/Sm^3]**	**[m^3/Sm^3]**	**[Sm^3/Sm^3]**	**[Sm^3/Sm^3]**	1.65E-02	-7.21E-01
	160	1.44	8.17E-03	105.22	3.92E-05	0.00E+00	1.24E+00
	120	1.33	1.09E-02	72.47	2.40E-05		
	80	1.24	1.65E-02	43.74	1.69E-05		

assuming $r_s = 0$

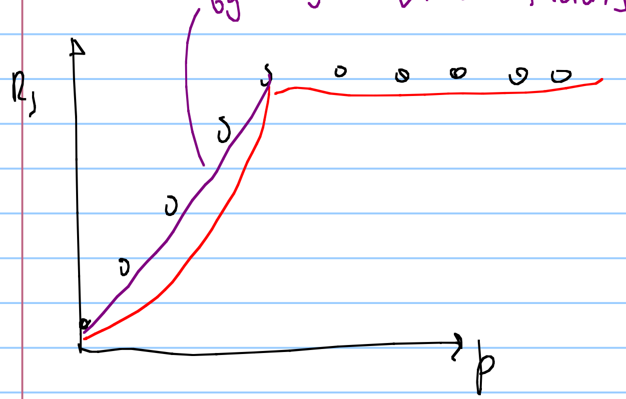
Class exercise: $\frac{dp}{dx}$ calculations in tubing → BO properties come from correlations

$f\{p, T, \gamma_o, GOR, \gamma_g\}$

tuning BO correlations $\left\{ \begin{array}{l} FO1, FO2, FO3, FO4, FO5 \\ FO6 \end{array} \right.$

in field units

by tuning with FO factors

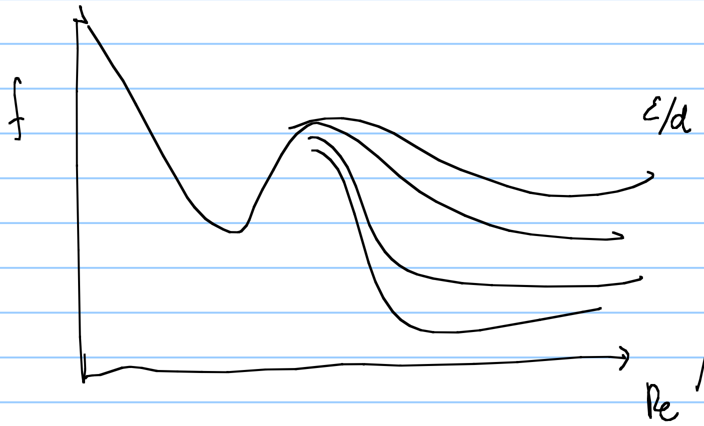


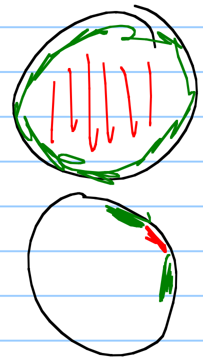
Pwh known and calculate Pwf for $q_{\bar{o}} = 1000$ stb/d

$$\frac{dp}{dx} = -\rho_m \cdot \sin\theta\, g - \frac{1}{2\phi} f_{TP} \, v_m^2 \rho_m$$

$$\rho_m = \varepsilon \rho_g + (1-\varepsilon)\rho_o$$

$$u_m = u_{so} + u_{sg}$$





u_m ρ_m

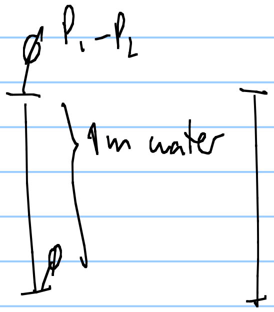
$$\frac{V \cdot \rho \cdot \phi}{\mu}$$

$$\mu_m = \varepsilon(\mu_g) + (1-\varepsilon)\mu_o$$

$$q_o = q_{\bar{o}} \cdot B_o(P,T)$$

$$q_g = q_{\bar{g}} B_g - q_{\bar{o}} R_s \cdot B_g$$

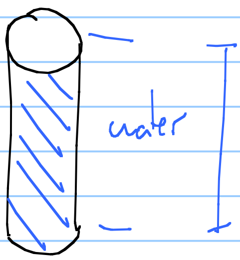
QC quality control



$$\Delta p = \rho \cdot g \cdot \Delta h = 1000 \cdot 10 \cdot 1 \text{ Pa}$$

$$10.000 \text{ Pa}$$

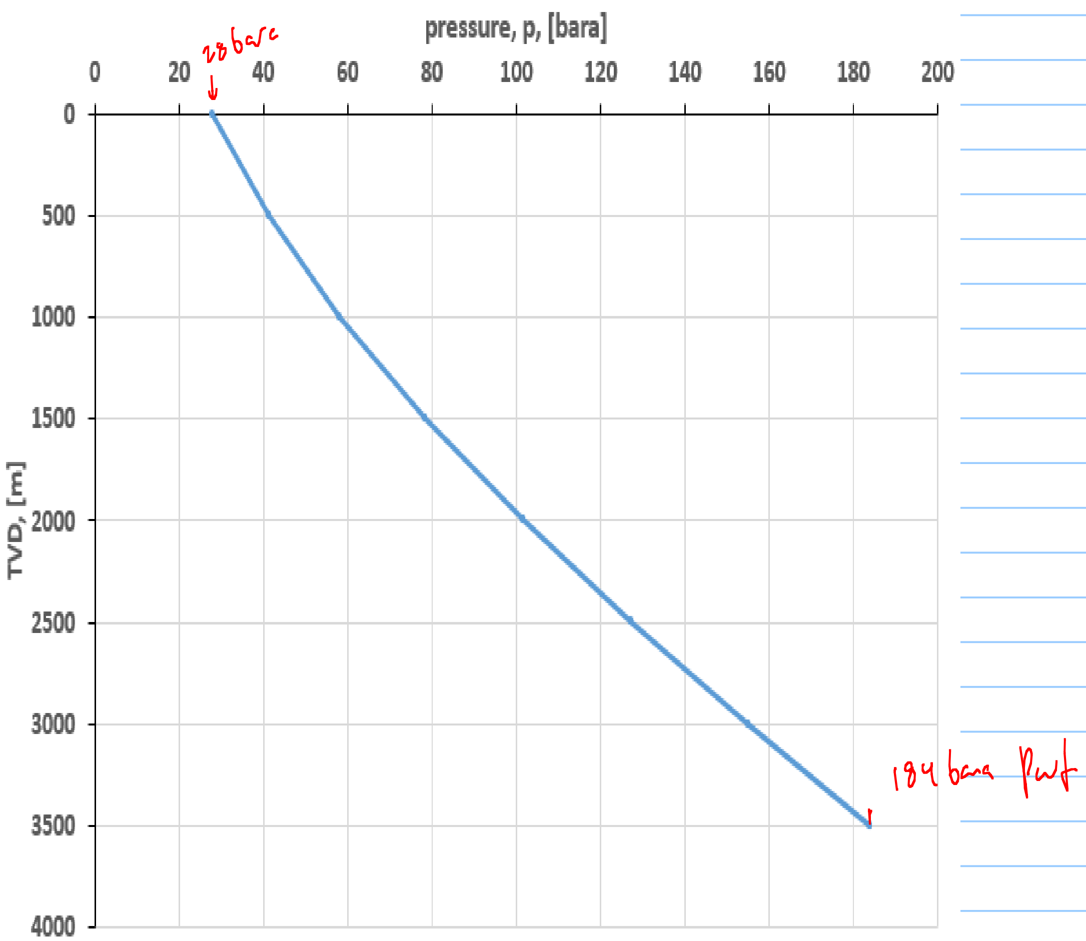
$$\approx 0.1 \text{ bar}$$



$$\Delta p = \rho_w \cdot \Delta L \cdot g = 10 \cdot 1 \cdot 1000 = 10000 \text{ Pa} \; \frac{1 \text{ bar}}{10^5 \text{ Pa}} = 0.1 \text{ bar}/m$$

we are getting $0.0267 \frac{\text{bar}}{m} \approx 20\%$ water

Bg [m^3/Sm^3]	deng [kg/m^3]	viscg [cp]	deno [kg/m^3]	viso [cp]	sigma_o_g [N/m]	qo [m^3/d]	qg[m^3/d]	uso [m/s]	usg [m/s]	lambdag[-]	e[-]	dp/dx [bara/m]
3.229E-02	40.3	0.011	794.4	2.518	1.624E-02	1083.4	4.210E+03	0.710	2.757	0.80	0.69	0.0267
2.163E-02	60.1	0.012	770.6	1.295	1.279E-02	1137.2	2.560E+03	0.745	1.676	0.69	0.60	0.0335
1.528E-02	85.1	0.013	744.6	0.813	9.500E-03	1202.6	1.582E+03	0.788	1.036	0.57	0.50	0.0404
1.142E-02	113.8	0.015	717.5	0.575	6.668E-03	1279.3	9.867E+02	0.838	0.646	0.44	0.40	0.0467
9.100E-03	142.9	0.018	690.4	0.440	4.515E-03	1364.9	6.143E+02	0.894	0.402	0.31	0.30	0.0517
7.711E-03	168.6	0.020	664.8	0.356	3.044E-03	1455.7	3.701E+02	0.953	0.242	0.20	0.21	0.0552
6.867E-03	189.3	0.022	641.4	0.301	2.097E-03	1547.5	1.986E+02	1.014	0.130	0.11	0.12	0.0575
6.334E-03	205.2	0.024	620.5	0.263	1.493E-03	1637.0	6.988E+01	1.072	0.046	0.04	0.05	0.0589

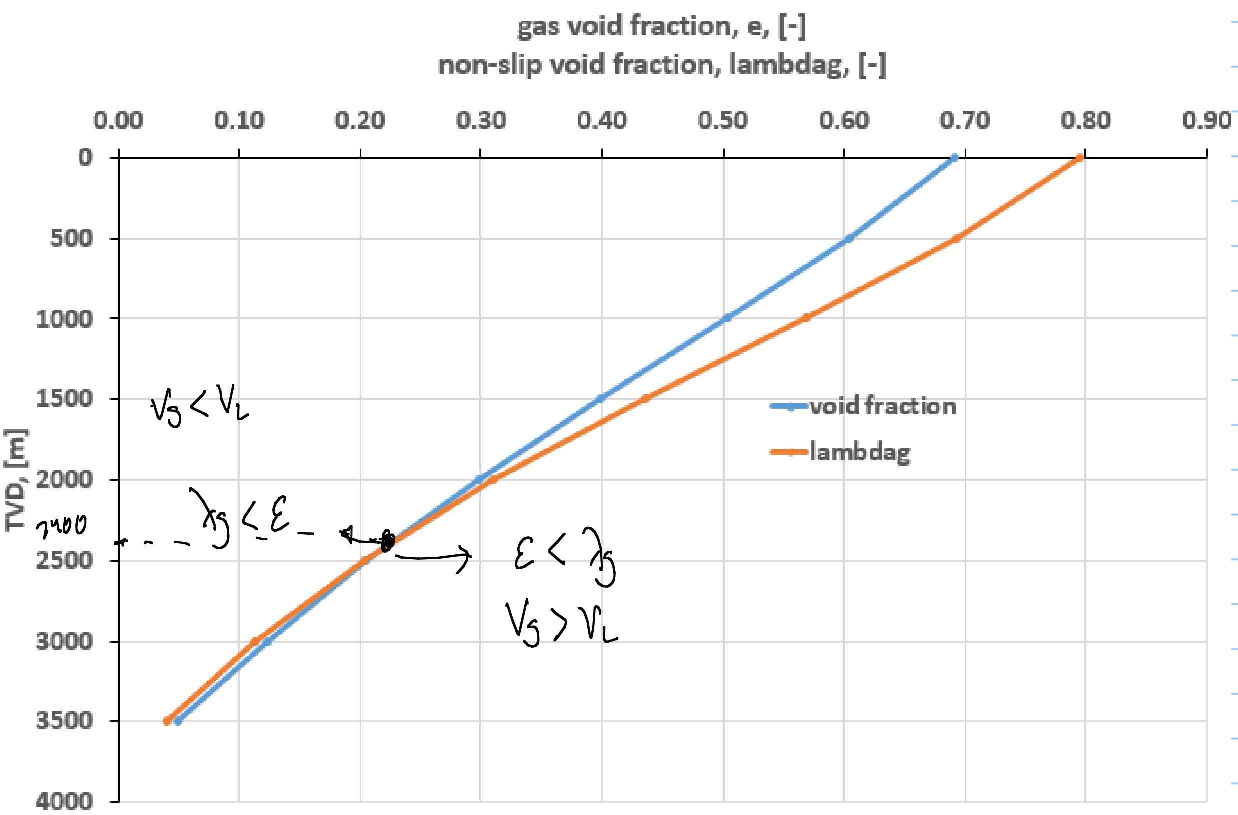


$\varepsilon = \frac{A_g}{A}$

slip

$\lambda_g = \frac{q_g}{q_o + q_g}$

assuming $V_L = V_g = V_m$



Home exercise · Case 2 $P_{wf} = 200$ bara, $q_o = 1000$ stb/d

P_{wh} ?

$P_1 <$

$100 + \frac{dP}{dx} \cdot \Delta x < 0$

THANK YOU FOR YOUR ACTIVE PARTICIPATION!

--THE END--