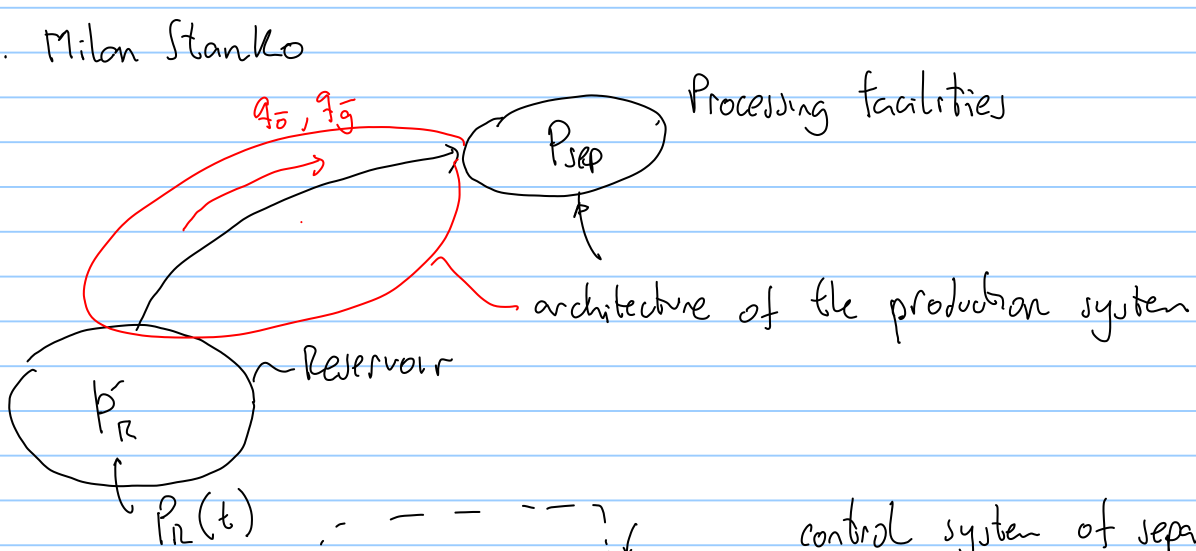
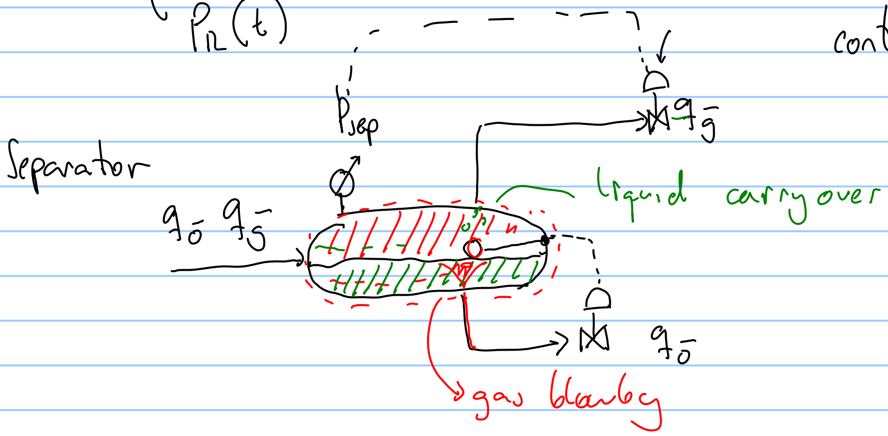
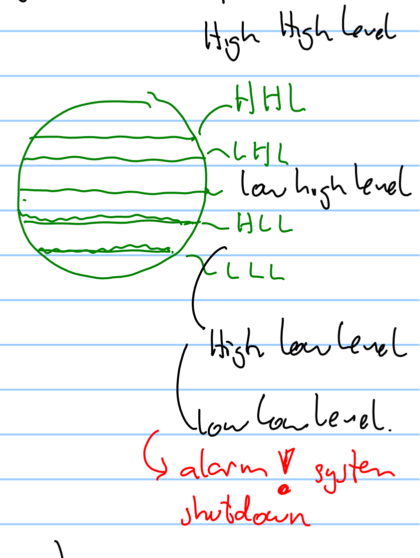
Prof. Milan Stanko



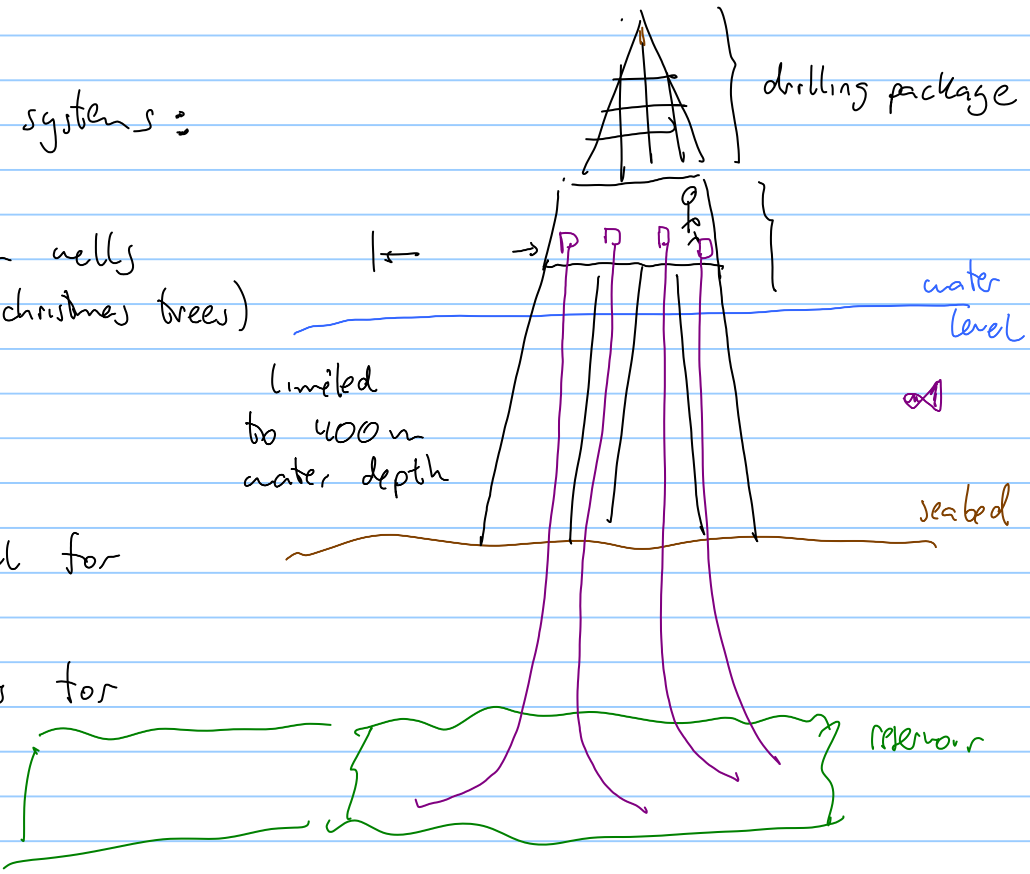
control system of separator



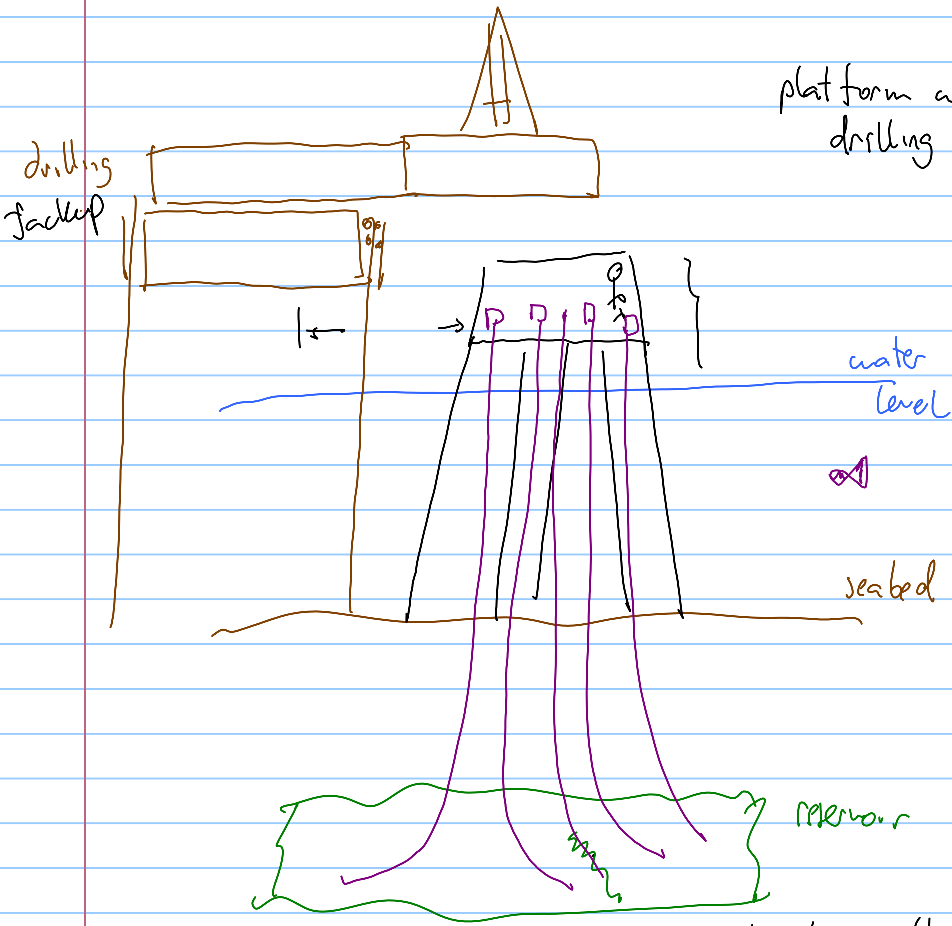


layout of production systems:

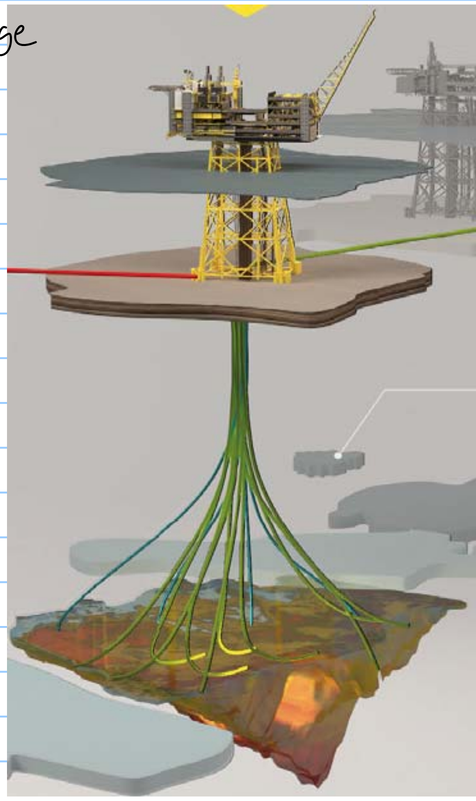
- offshore { platform wells (dry christmas trees)



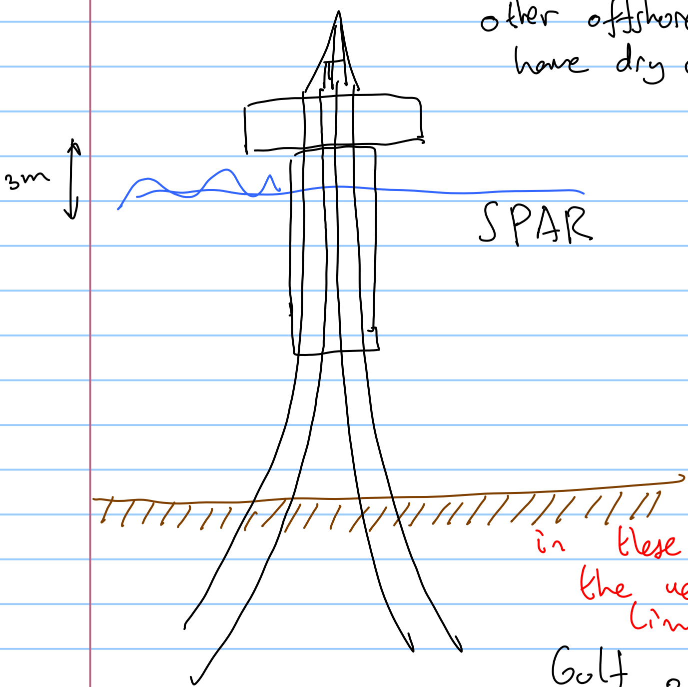
- Easy access to well for intervention
- Limited well slots for in fill drilling



platform without
drilling package

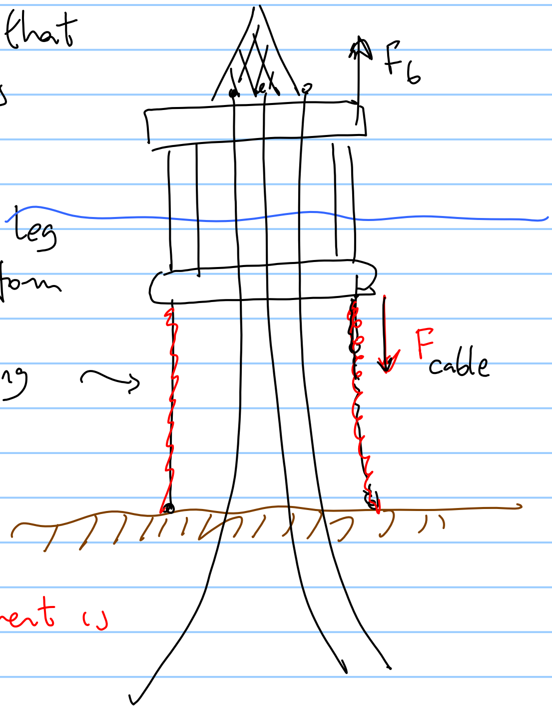


other offshore structures that
have dry christmas trees



TLP
tension leg
platform

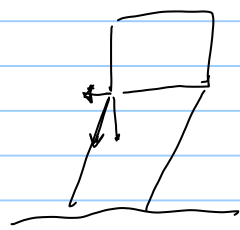
tensioning
cable



in these structures
the vertical movement is
limited

Gulf of Mexico

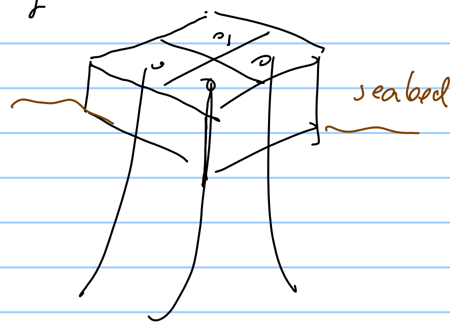
≈ 1700 m water depth max



- Subsea wells

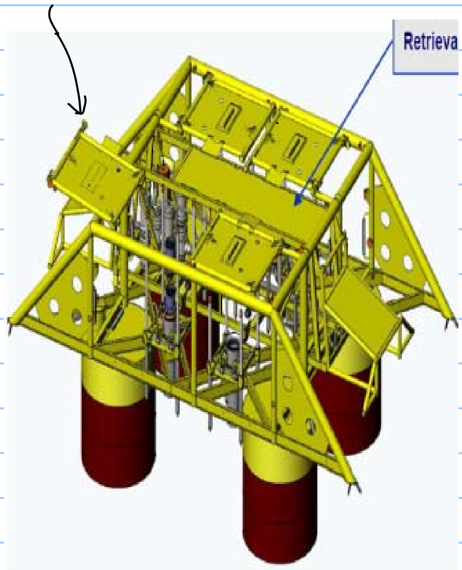
  wet christmas trees

template drilled wells — wells are deviated

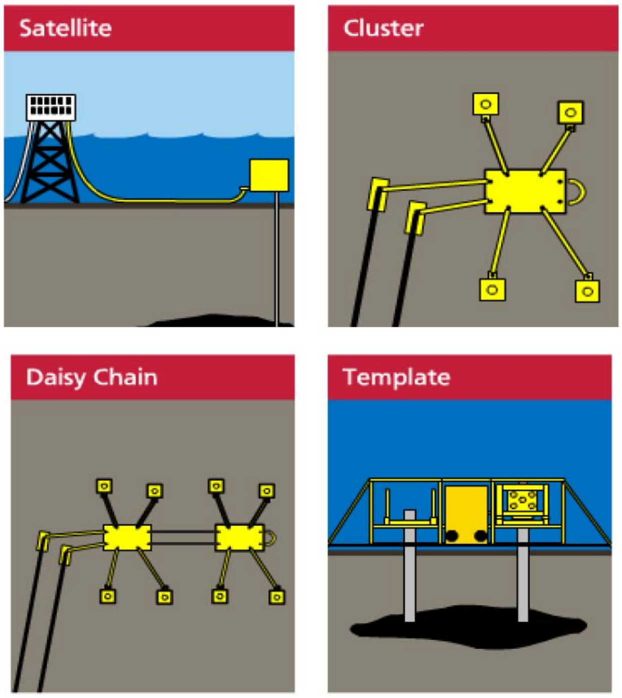


Satellite wells
well are usually drilled above target.

well slot

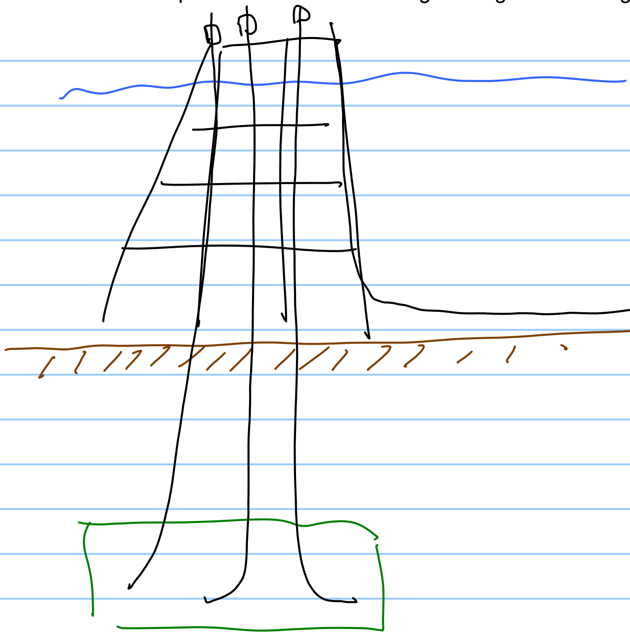


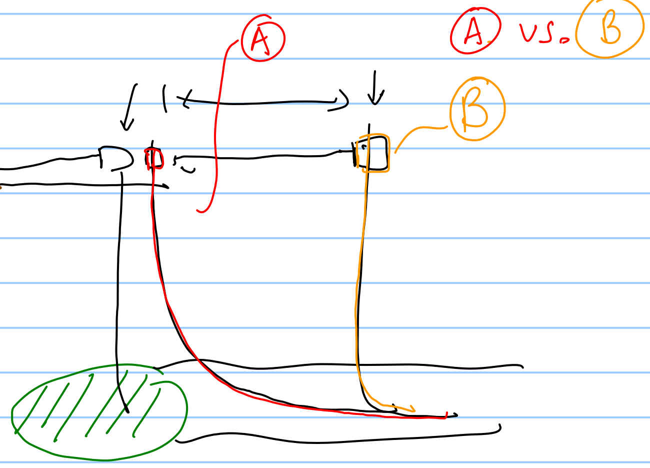
subsea template



subsea well producing to existing facilities.

Ⓐ vs. Ⓑ

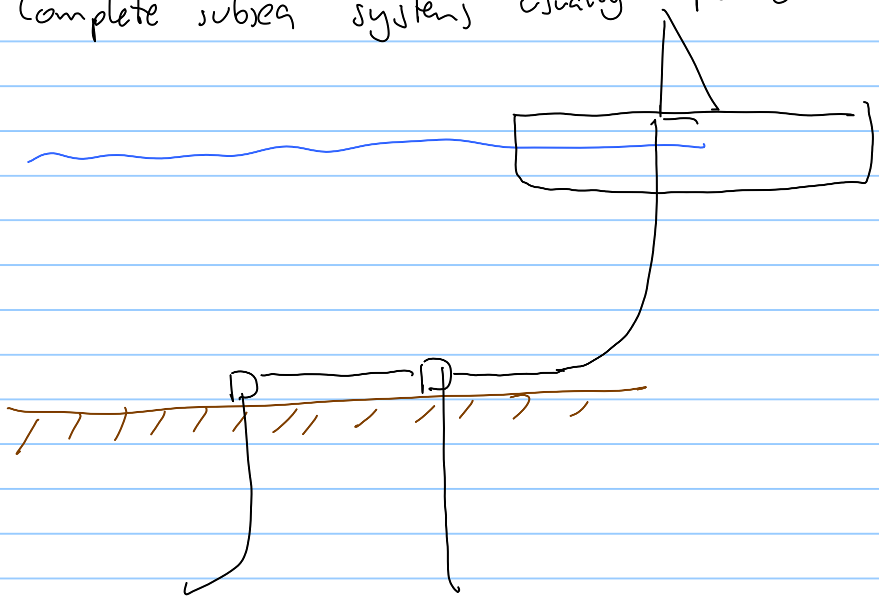




Complete subsea systems usually produce to { FPSO, Semi Sub

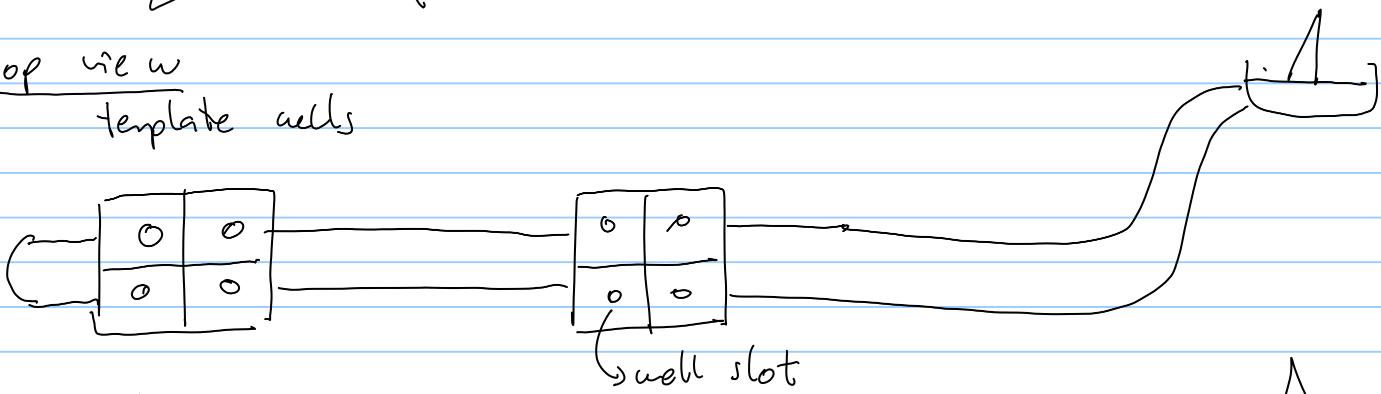
Semi Sub → similar to TLP without the tensioning cables.

(FPSO) floating production storage offloading

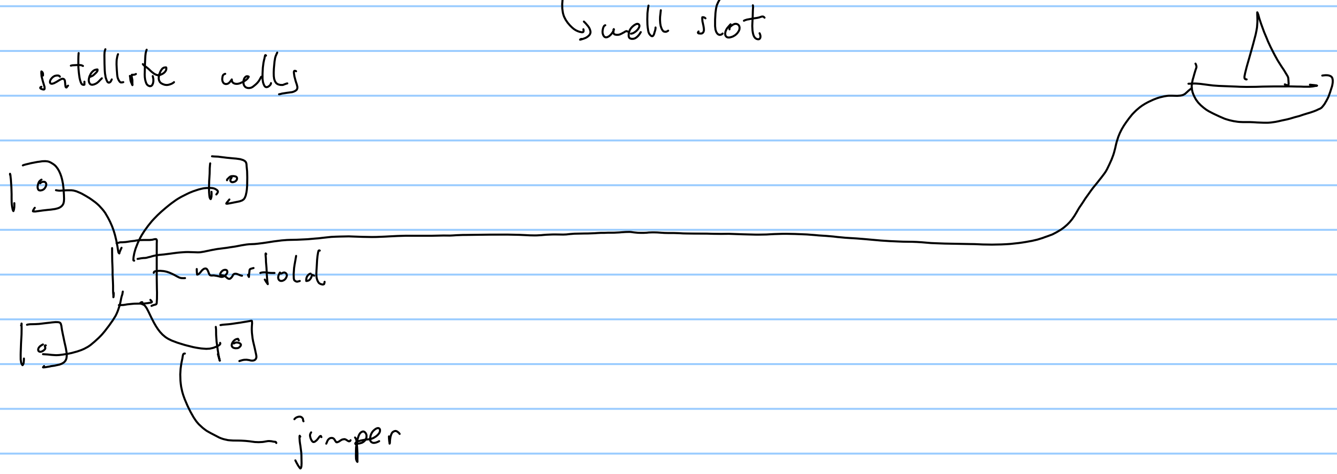


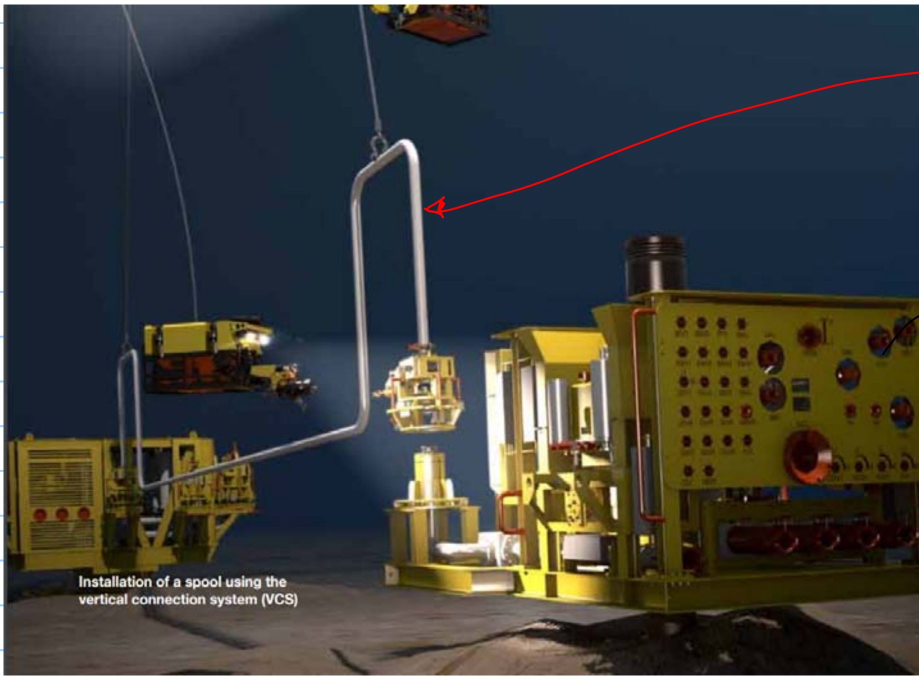
Top view

template wells



satellite wells

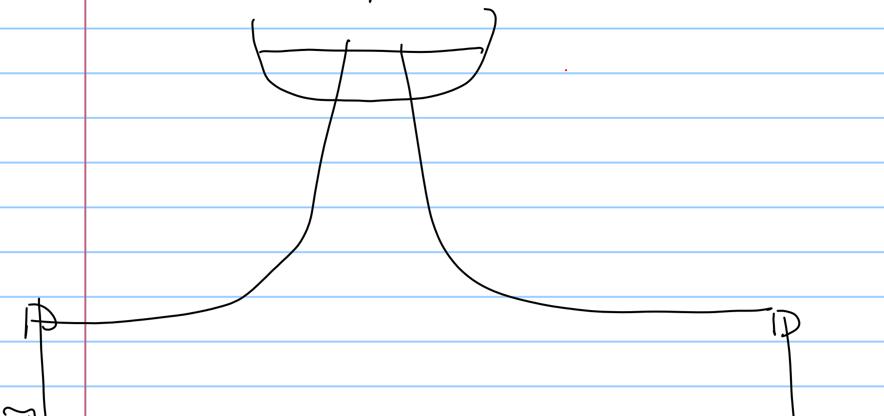


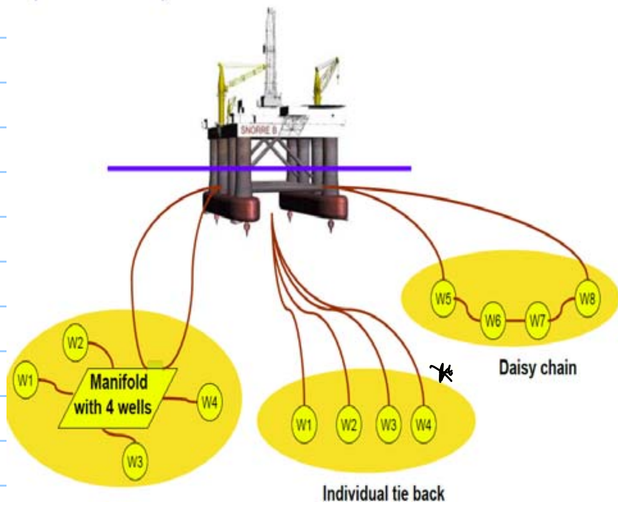


jumper

x-mas tree

* for example

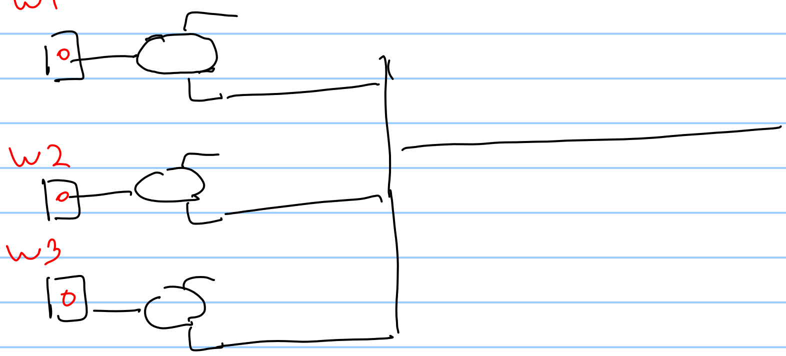




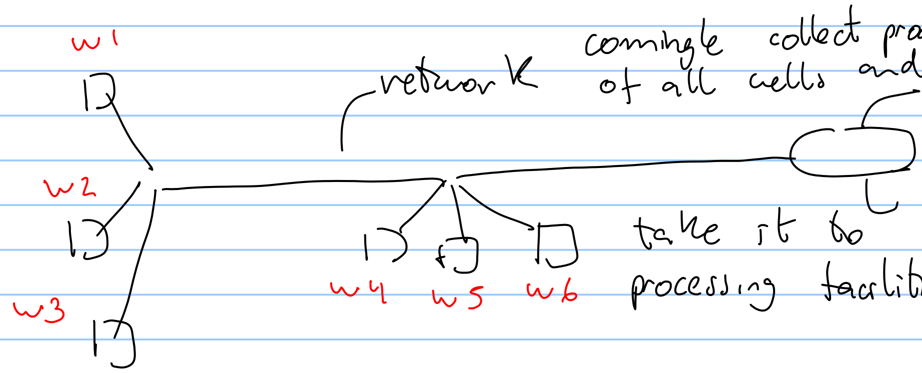
*

Onshore systems

- Standalone wells

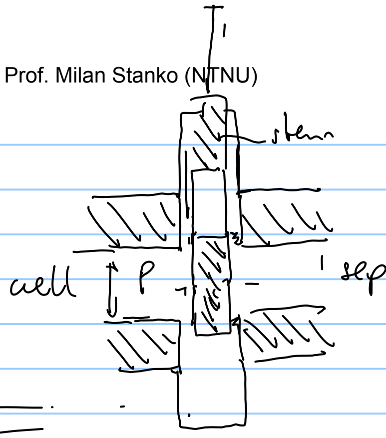


- network

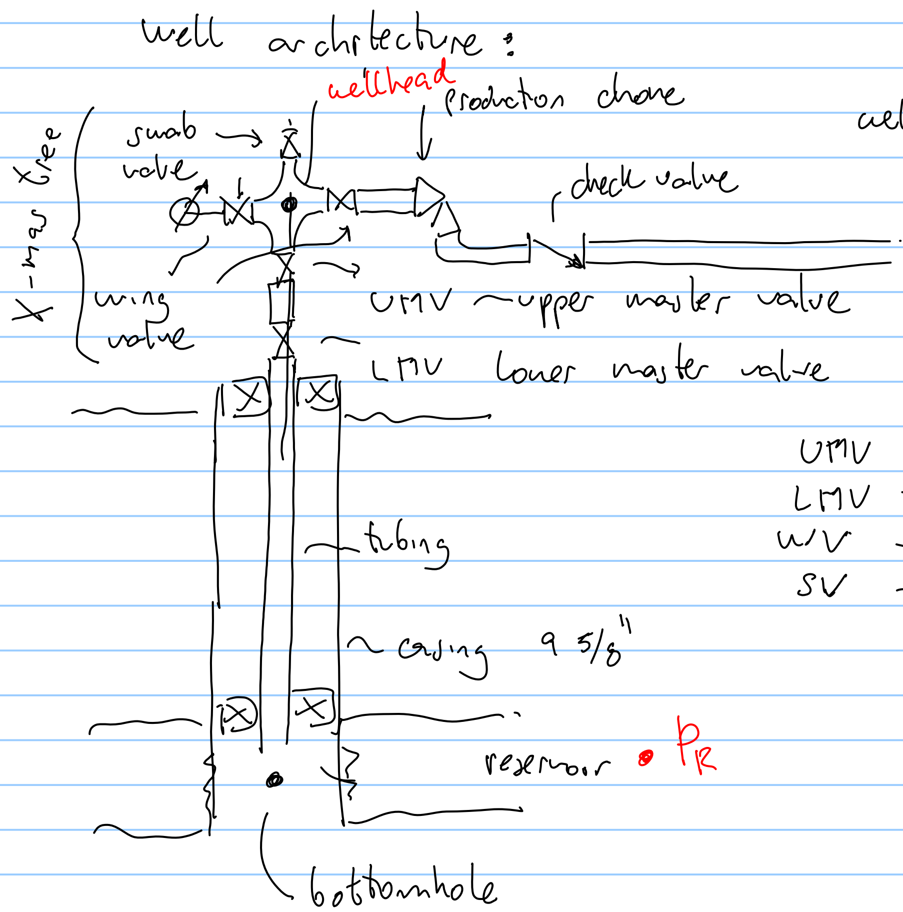


commingle collect production of all wells and take it to processing facilities

//



well architecture:

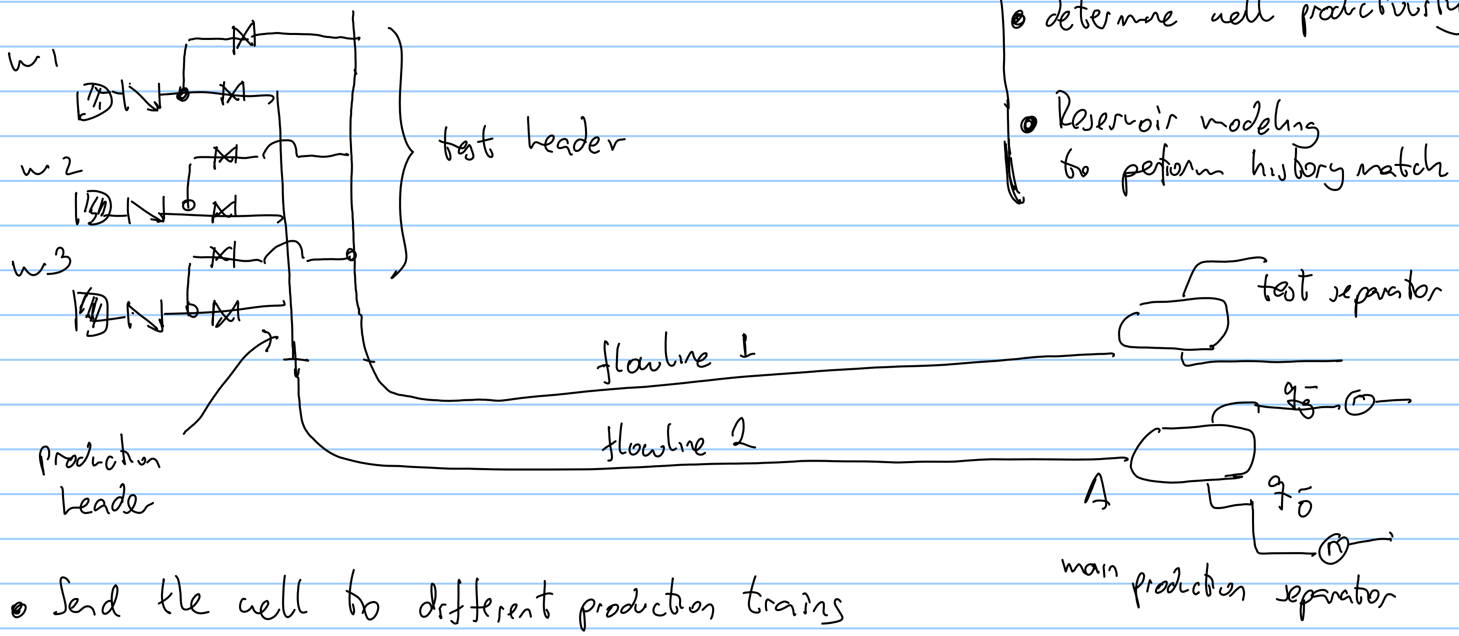


UMV – on-off valves
LMV – on-off valves
WV – on-of valve
SV – on off valve

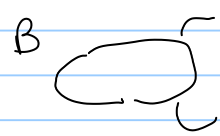
Production manifold:

- commingle the production of several wells
- test the well — measure q_o, q_g, P_{wh}

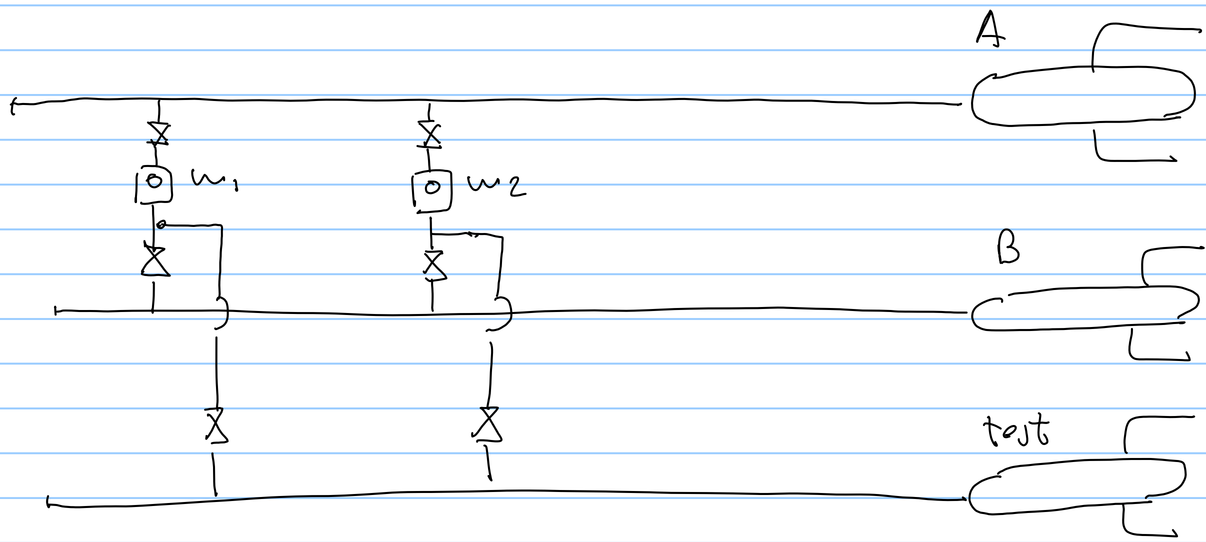
- allocation — split production to different (USD $)
- determine well productivity
- Reservoir modeling to perform history match



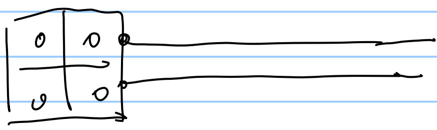
- Send the well to different production trains

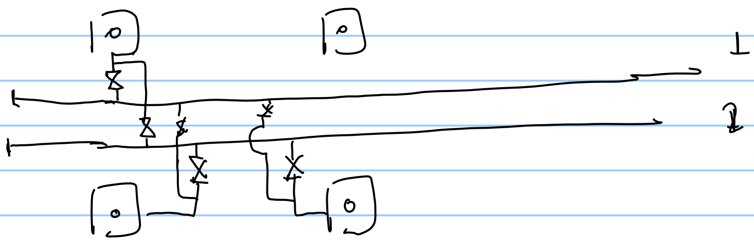


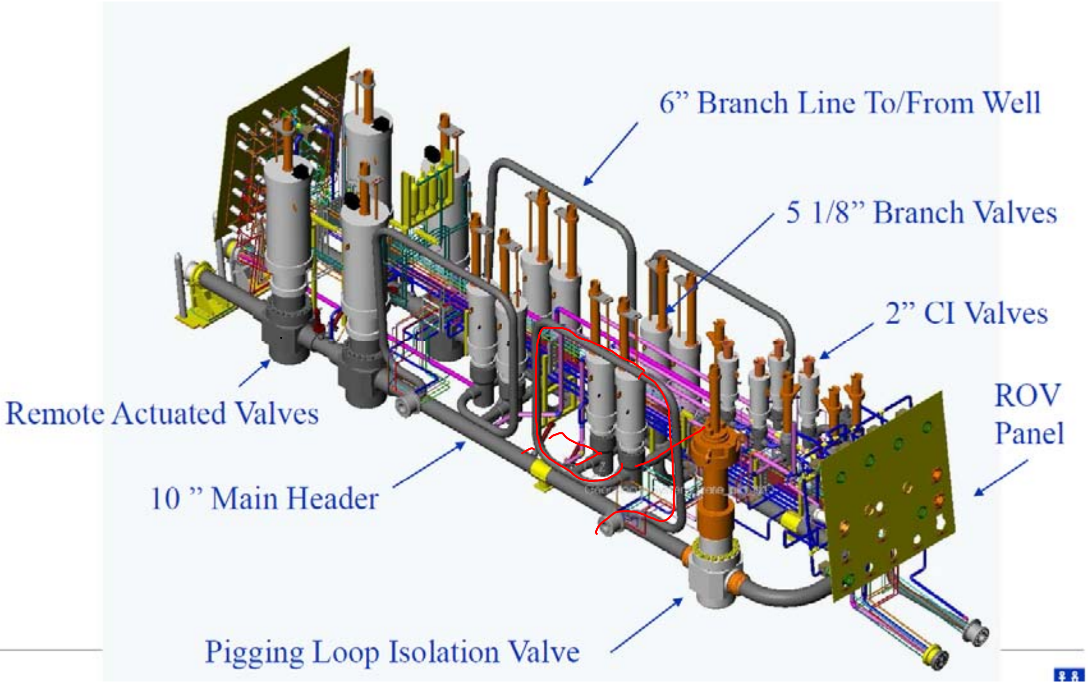
Class exercise 3 wells to 3 separators



Subsea wells arranged in template. Subsea manifold



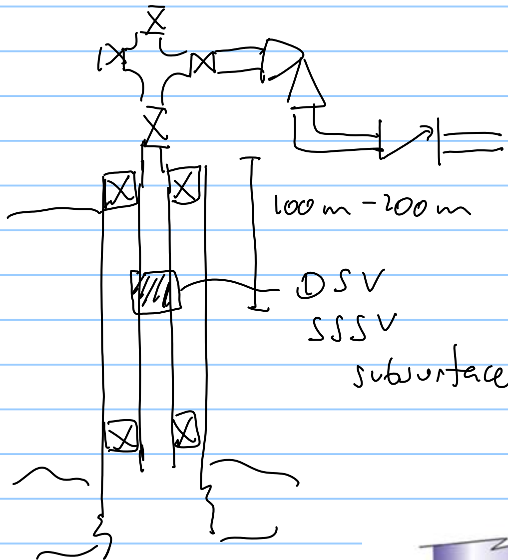




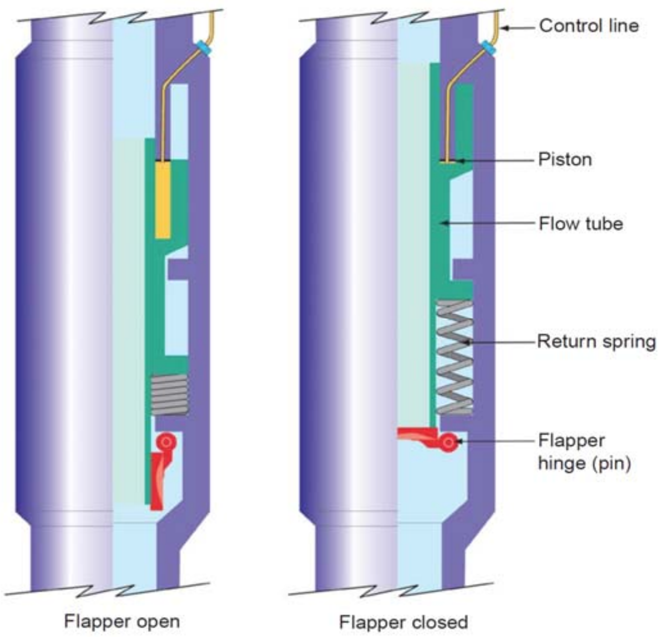
valves of a well DSV downhole safety valve

Barrier philosophy

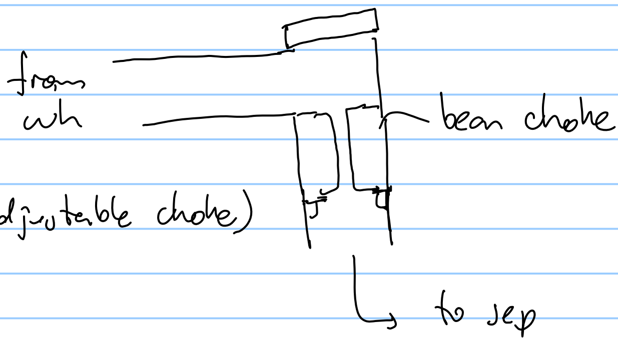
- always 2 barriers between reservoir and environment
- barriers must be physically in different places
- action mechanism must be independent



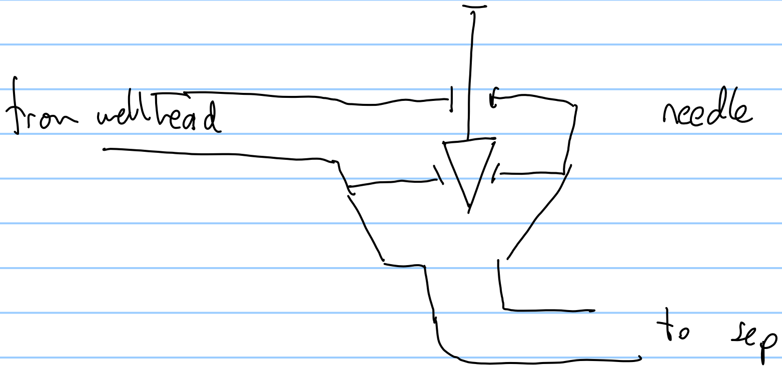
SSSV
subsurface safety valve



onshore system

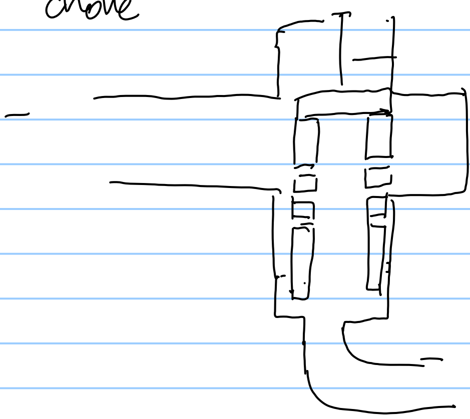


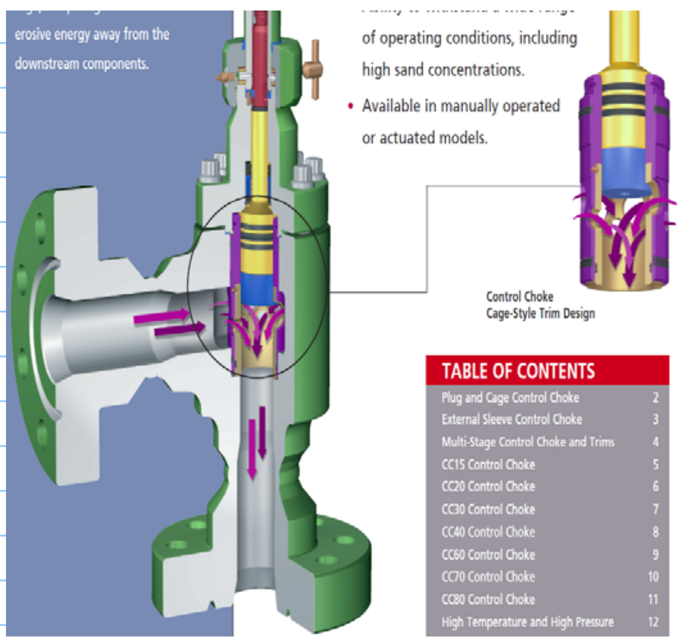
production choke { Fixed opening / variable opening (adjustable choke)



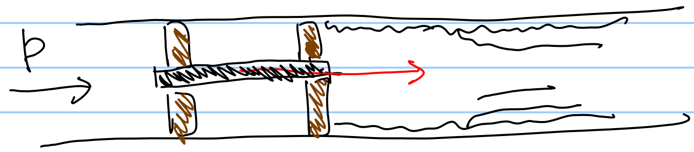
needle choke

Cage choke





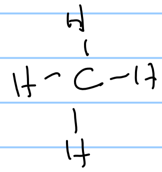
Need for pigging.



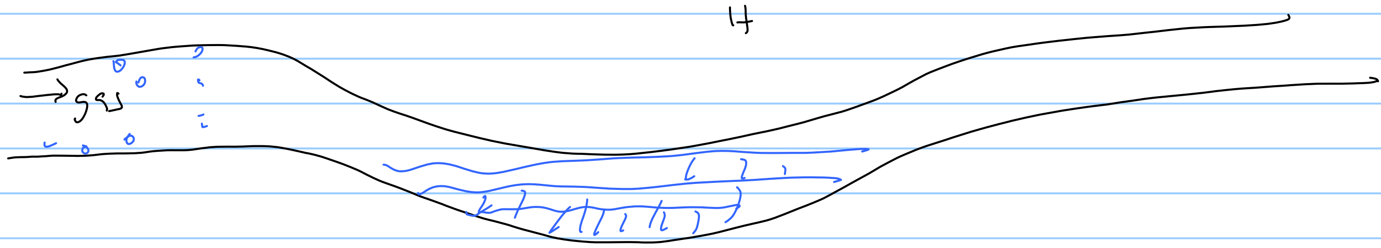
- remove accumulations on the pipe wall

wax — heavy hydrocarbon fraction

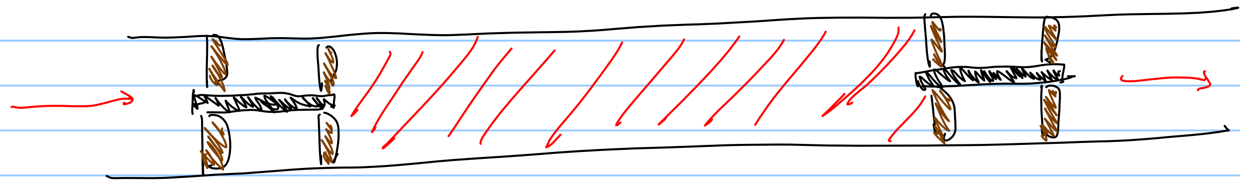
$C_1, C_2, \ldots C_{11}, C_{20}$



- remove liquid accumulation

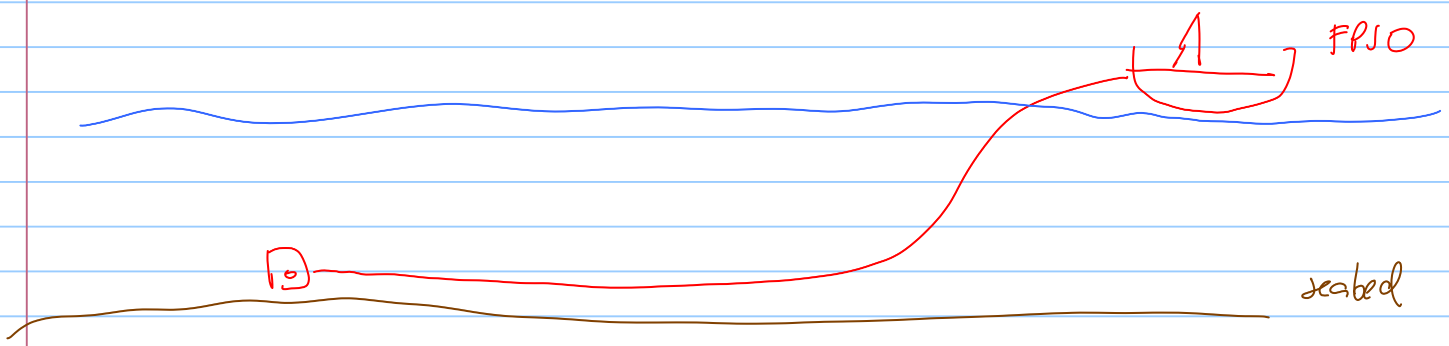


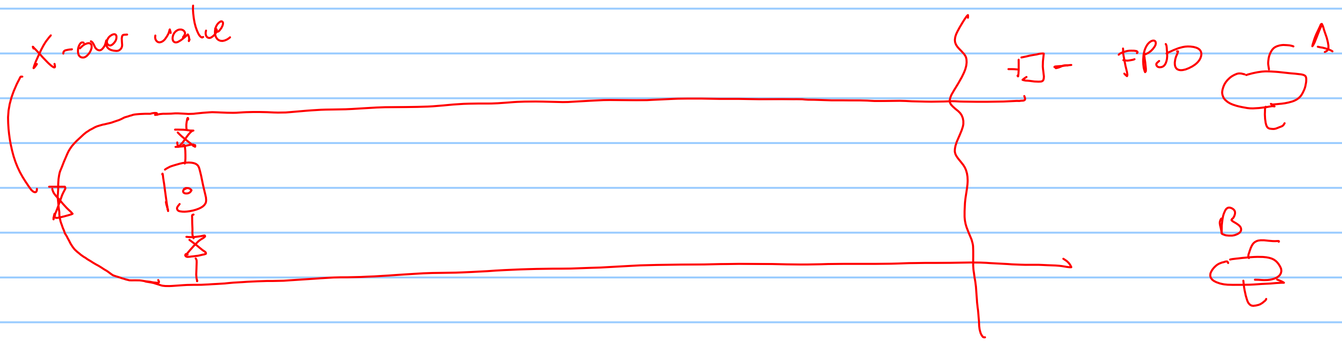
- inspection of pipeline integrity (corrosion) thickness, etc
- treatment of inner pipe wall

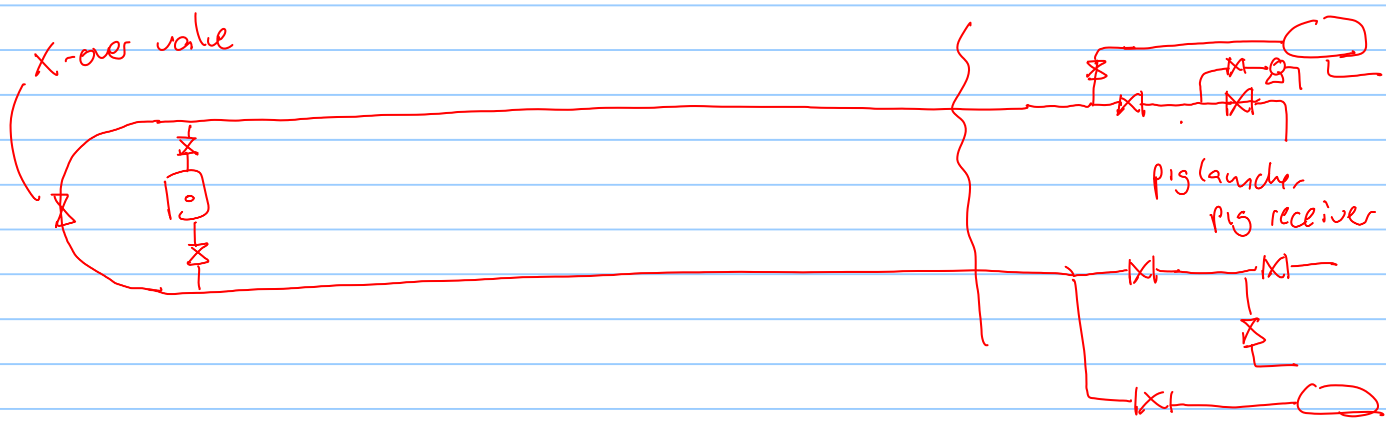


Various pig types

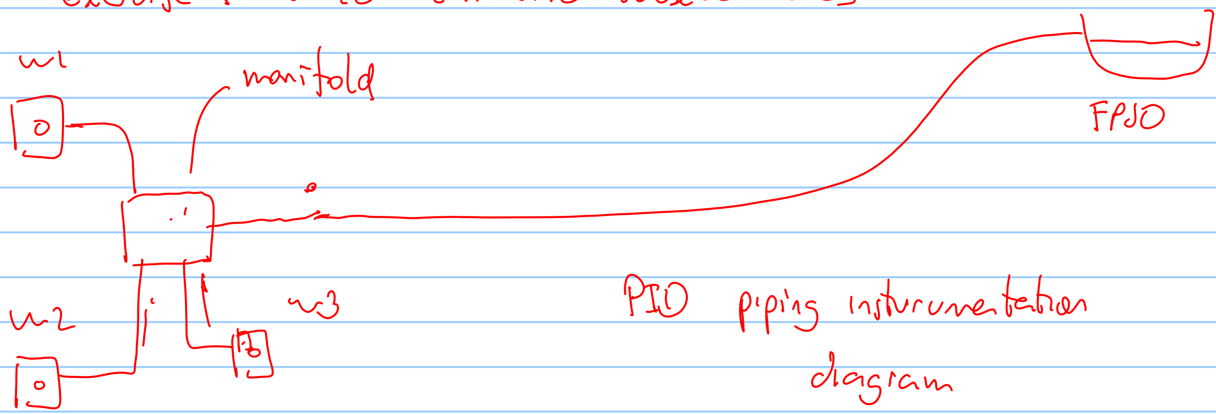
Wax plug-North Sea line pigging


FPSO
seabed


X-over valve
FPSO
A
B


X-over valve
pig launcher
pig receiver

- Home exercise: three satellite subsea wells



PID piping instrumentation diagram

1 multiphase meter inside the manifold

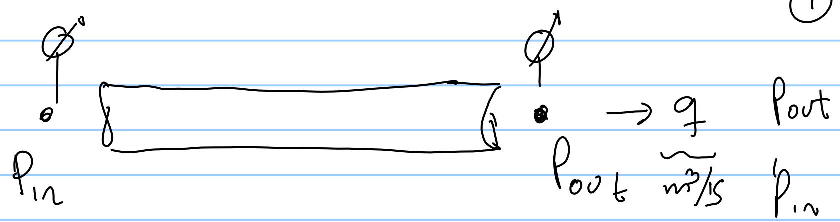
please provide a solution (flow diagram) to be able to test individually each well

---

flow equilibrium: NODAL Analysis

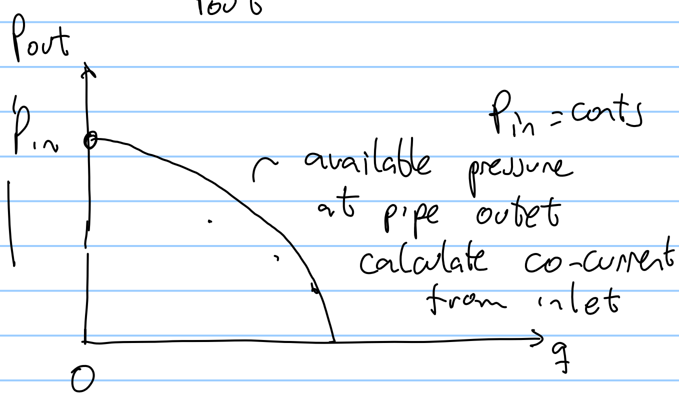
Inflow-outflow balance

Horizontal pipe



$$P_{out} = P_{in} - \left|\Delta P_{friction}(q)\right|$$

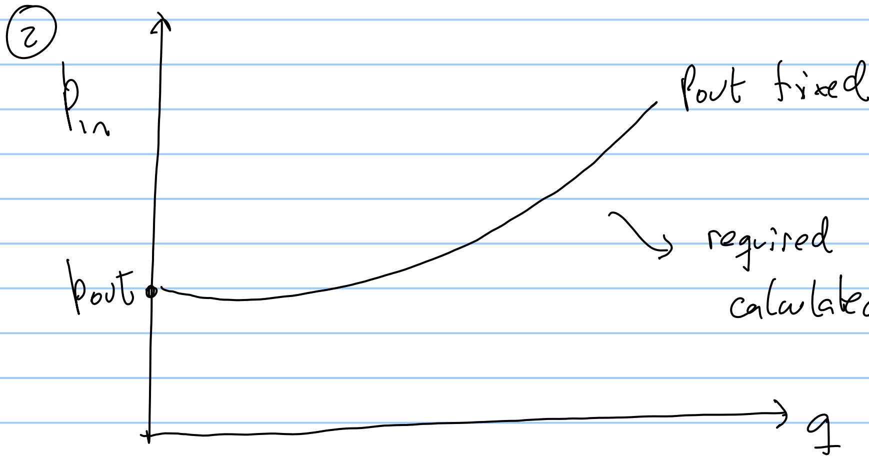
① fix P_{in}, change q, obtain P_{out}



available pressure at pipe outlet calculate co-current from inlet

fix P_{out}, change q obtain P_{in}

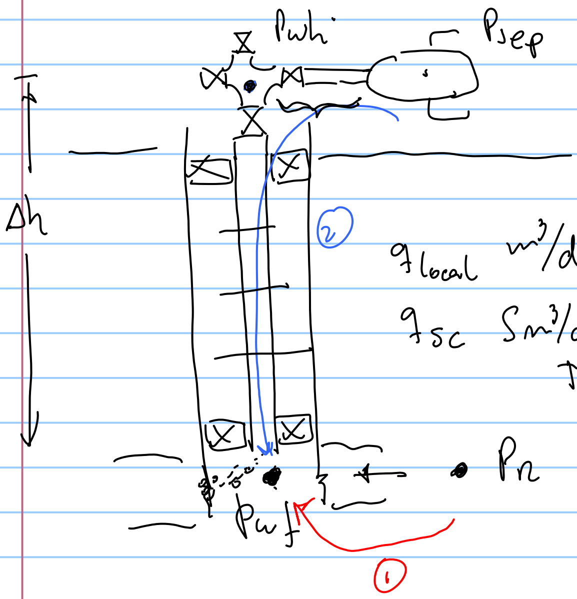
②

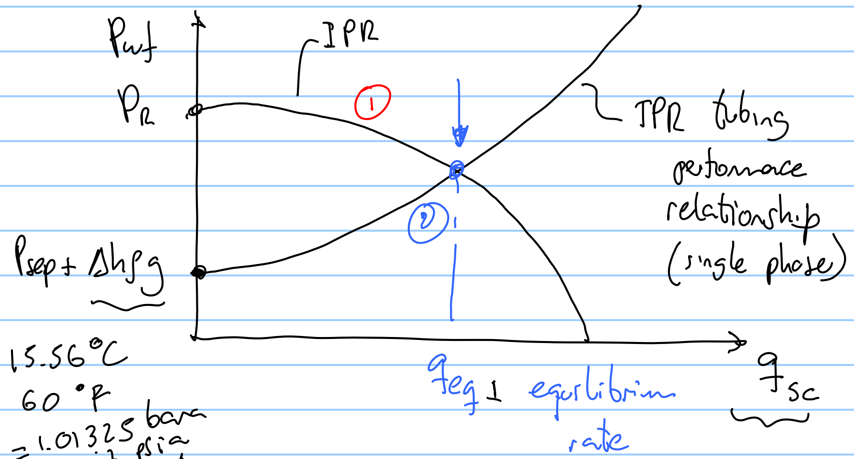


$$P_{in} = P_{out} + \left|\Delta p(q)\right|$$

required pressure at pipe inlet calculated counter-current from pipe outlet

③ give P_{in}, P_{out} $\xrightarrow{\text{calculate}}$ q





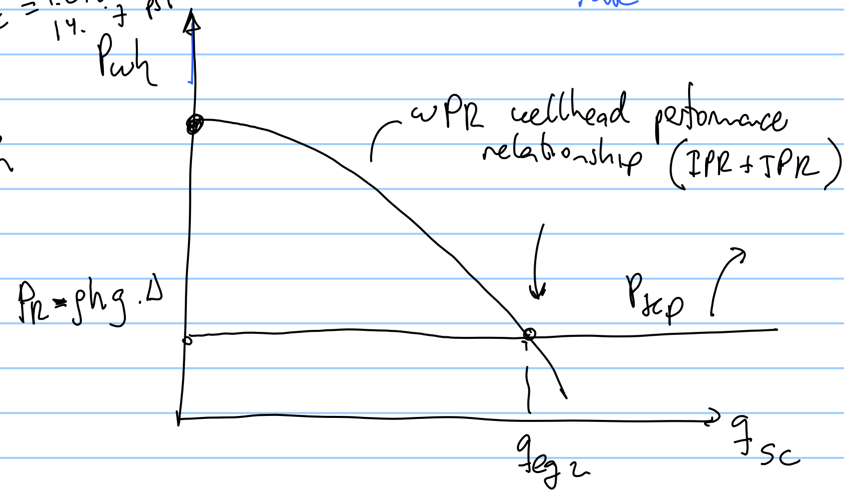
q_{local} m^3/d

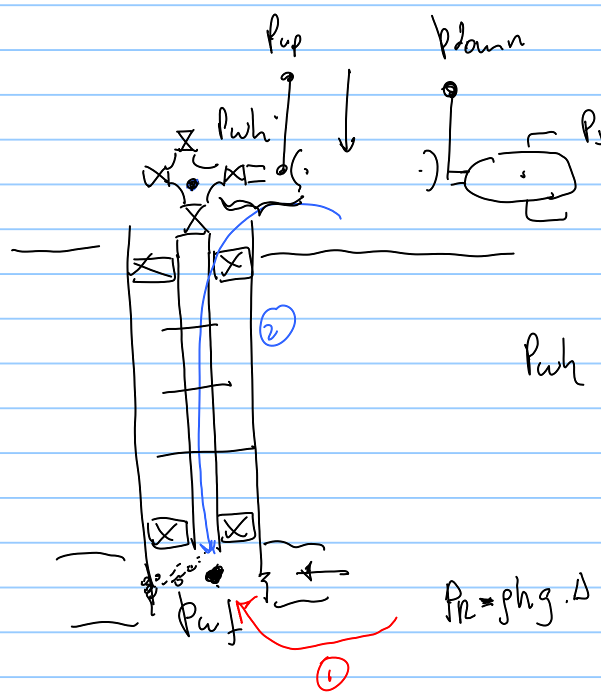
q_{sc} Sm^3/d

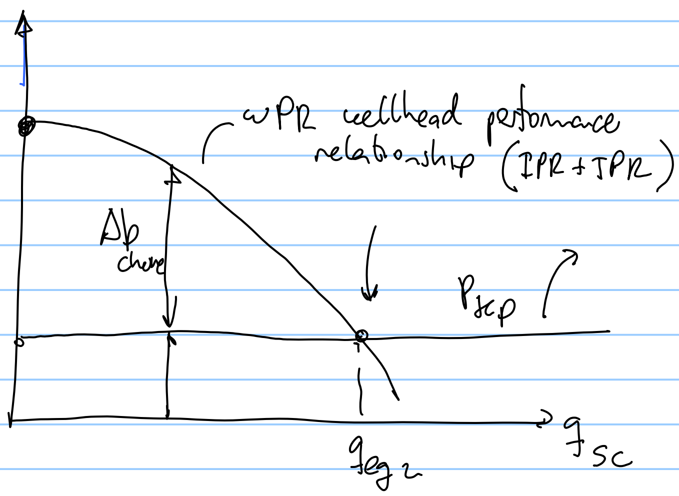
$T_{sc} = 15.56°C$
60 °F

$p_{sc} = 1.01325$ bara
14.7 psia

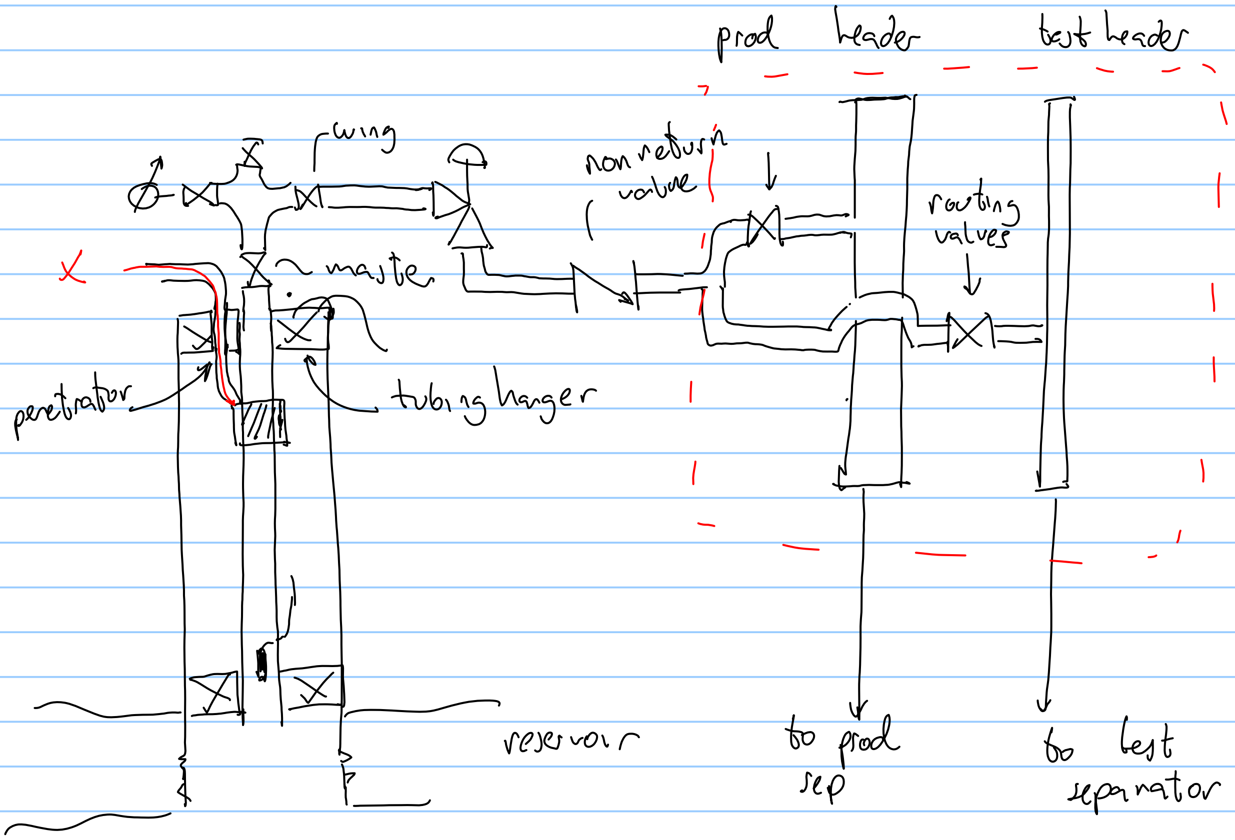
$q_{sc} \propto \dot{m}$







Day 2:

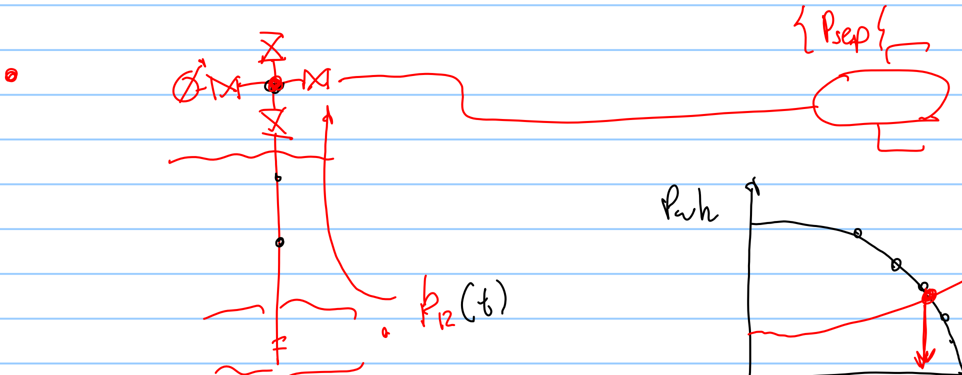


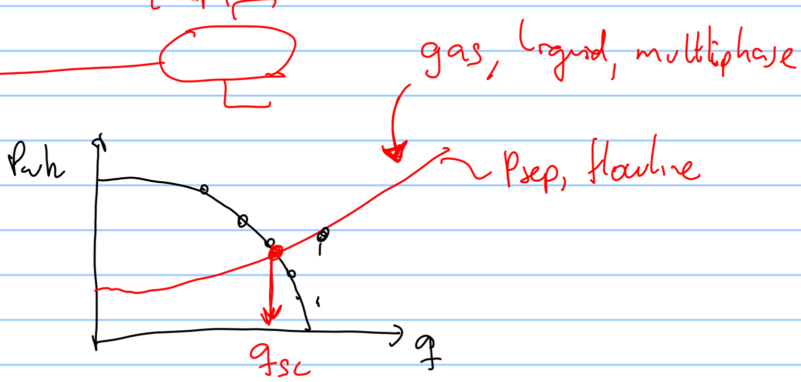
Christmas Tree Systems


Onshore tree


Offshore tree

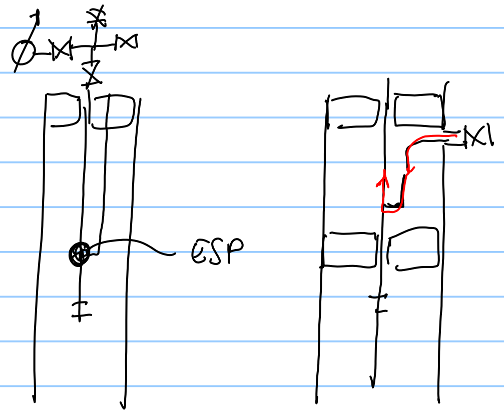
Subsea tree





Selection of equilibrium point → bottom hole
- Design artificial lift
  - ESP
  - gas lift
- Study IPR

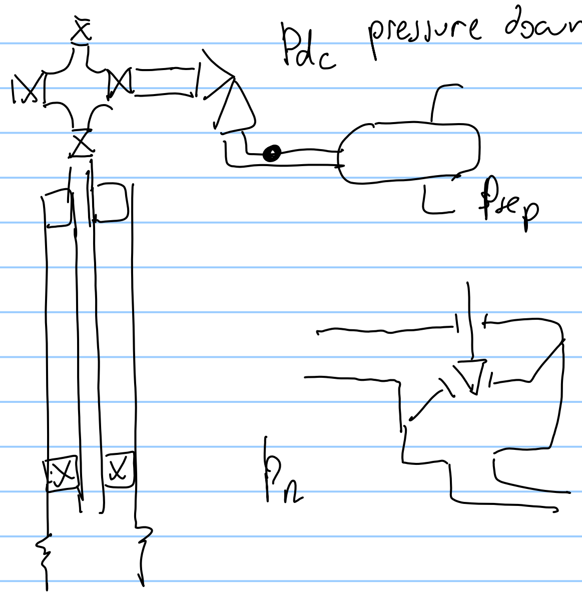
→ wellhead
- choke design
- well test

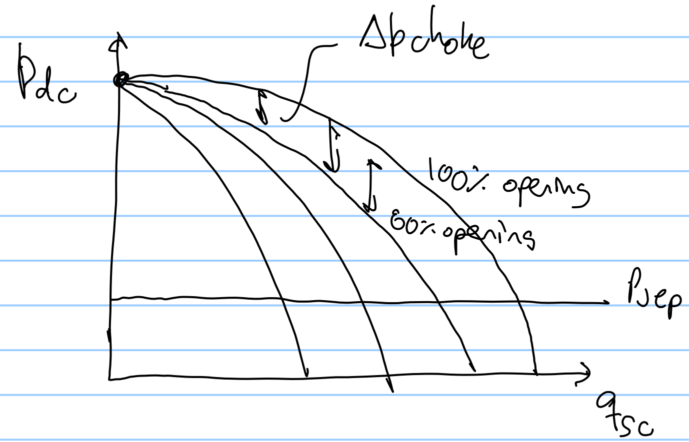


$\rho_o + \rho_g$

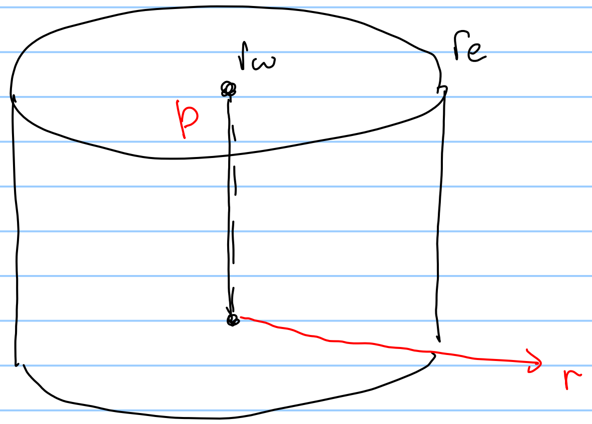
Δp

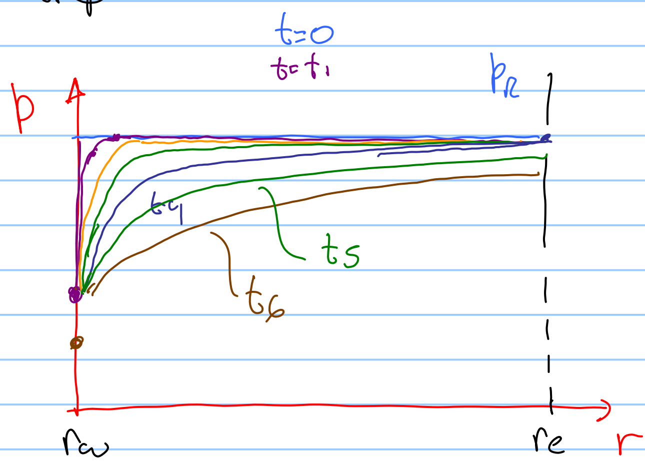
Flow equilibrium including the choke





- IPR Inflow performance relationship





$t_0 \rightarrow t_4$ transient, infinite acting

$t_4 \rightarrow$ forward → pseudo steady state (PSS)

$t_0 \rightarrow t_4$ t_{pss} time to pseudo steady state

C_f, C_R, μ, K } tight formation $\downarrow K \rightsquigarrow t_{pss}$ is in order of months years

normal formation $\uparrow K \rightsquigarrow t_{pss} \rightarrow$ hours days

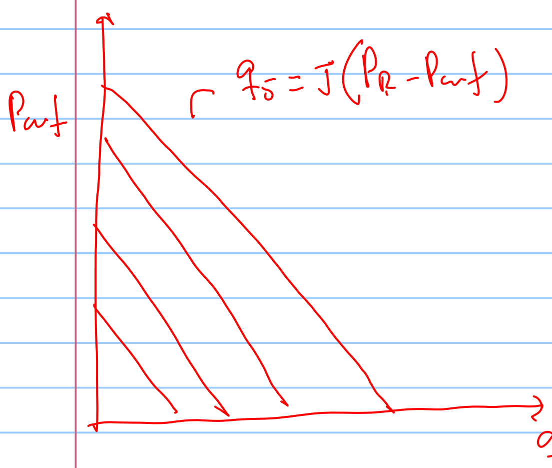
if t_{pss} is short { then I use IPR for pss } * for this course

If t_{pss} is long { then use IPR for transient regime

$IPR = f(t)$

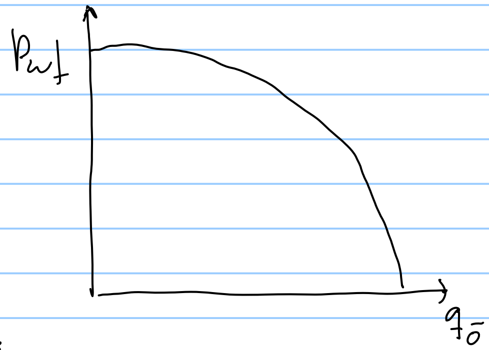
PSS IPRs

single phase Oil



GAS

Saturated oil (mixture oil + gas)



Vogel

$$q_g = C\left(P_R^2 - P_{wf}^2\right)^n$$

$$\frac{q_o}{q_{o\,max}} = 1 - 0.2\frac{P_{wf}}{P_R} + 0.8\frac{P_{wf}^2}{P_R^2}$$

$0.5 \leq n \leq 1$

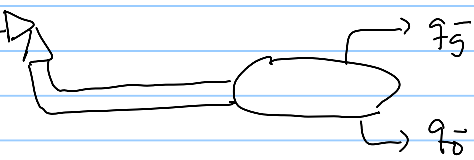
turbulent — Darcy

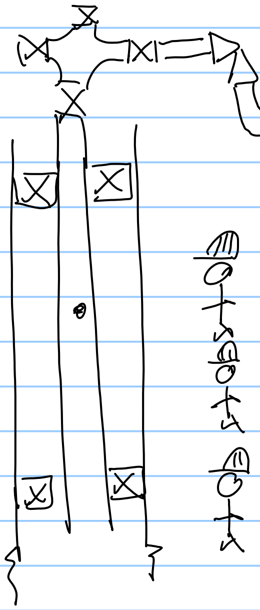
for low pressure $p \leq 100$ bara

$$m(p) = 2\int_0^p \frac{p}{\mu z}\,dp$$

for medium → high pressure

$$q_g = C\left[m(P_R) - m(P_{wf})\right]^n$$ } for the whole pressure range!





mechanical eng. — kg/s mass flow $\qquad n = \frac{m}{Mw}$

chemical eng. — $kmol/s$ molar flow

petroleum eng. — Sm^3/d, scf/d, stb/d standard conditions rate

$\Delta p_{friction} \simeq v$

- Case: dry gas

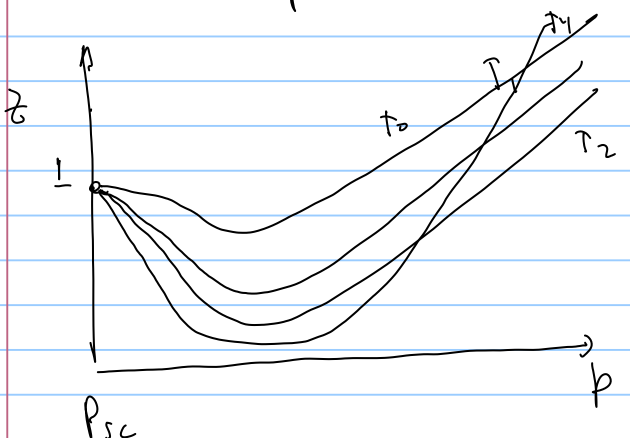
Ideal gas law $\underbrace{p\,V = n\,R\,T}$ → Boyle → Hooke

0.7 → 2

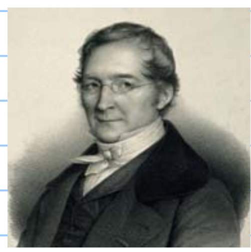
Charles

insert a correcting factor in the ideal gas eq.

$$pV = Z\,n\,R\,T \checkmark$$



Gay Lussac

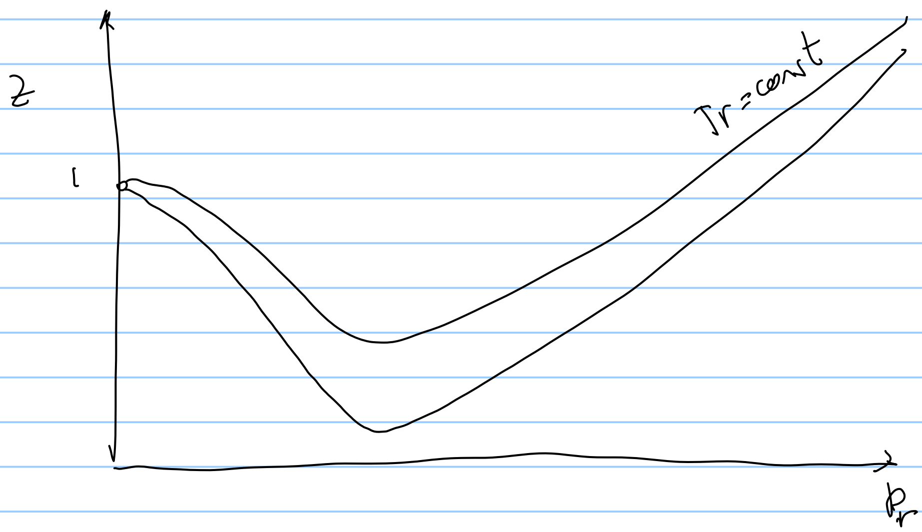


Avogadro

Van der Waals corresponding states principles

pseudo-reduced pressure $p_r = \frac{p}{p_c}$ — psi

pseudo reduced T $T_r = \frac{T}{T_c}$ use absolute units only! K, °R !



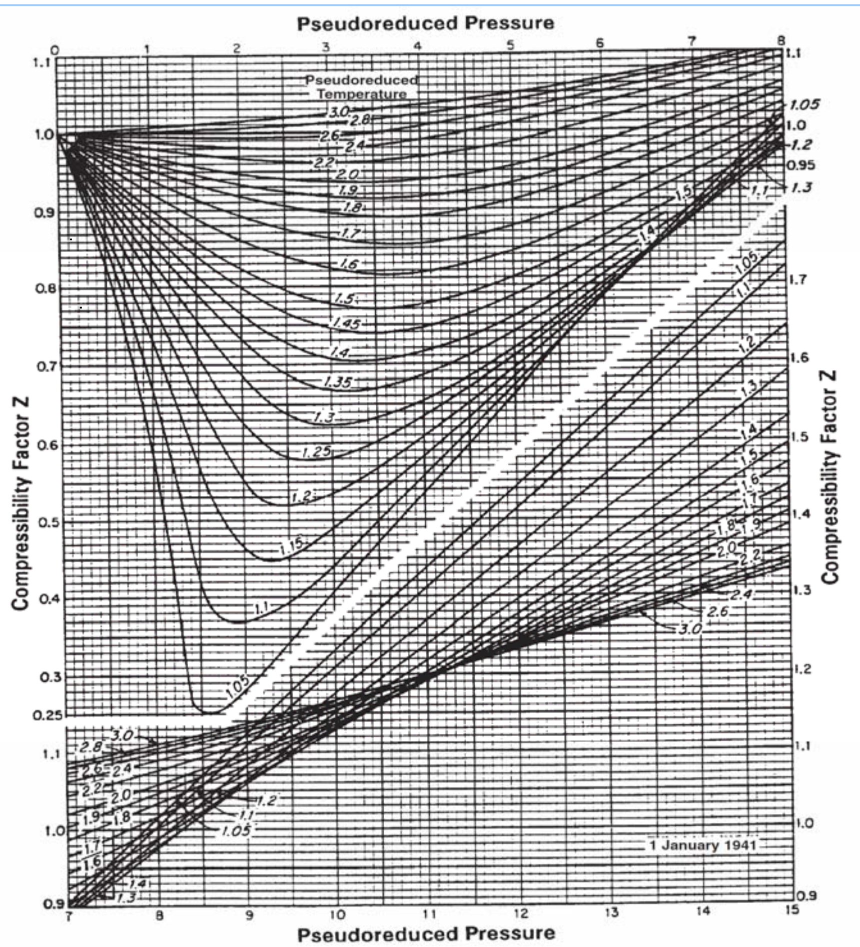


Fig. 3.6—Standing-Katz[4] Z-factor chart.

$p_r = 12$

$T_r = 1.4$

Production gas is usually a mixture of several gases (components)

C_1	N_2	C_1	0.80
C_2	CO_2	C_2	0.10
C_3	H_2S	C_3	0.03
C_4		↓	
C_5			
C_7+ ↓		Σ 1	

y_i ~ mole fraction

components

$$MW_{mix} = \sum_{i=1}^{N} y_i \, MW_i$$

Specific gravity of gas

$$\gamma_g = \frac{MW_{mix}}{MW_{air}} \quad MW_{air} \to 28.97$$

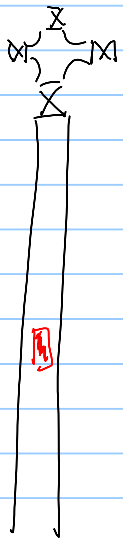
$$P_{c_{mix}} = \sum_{i=1}^{N} y_i P_{ci}$$

$$T_{c_{mix}} = \sum_{i=1}^{N} y_i T_{ci}$$

Correlation Sutton

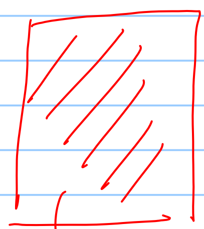
$$P_{c_{mix}} = f(\gamma_g)$$

$$T_{c_{mix}} = f(\gamma_g)$$



n_1, P_1, T_1

V_{sc} T_{sc} P_{sc}



n_1

$pV = nRTz$ in S.C

$z \simeq 1$

$P_{sc} V_{sc} = n R T_{sc}$

$$R = 8314.3 \frac{J}{Kmol\,K}$$

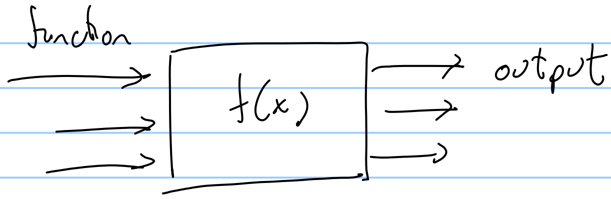
$$V_{sc} = n \cdot \frac{R T_{sc}}{P_{sc}}$$

$$V_{sc} = n \; 23.67 \frac{Sm^3}{Kmol}$$

↳ $n \cdot 379.7 \frac{Scf}{lbmol}$

Excel VBA access the VBA module $\boxed{\text{alt}}$ + $\boxed{\text{F11}}$

function



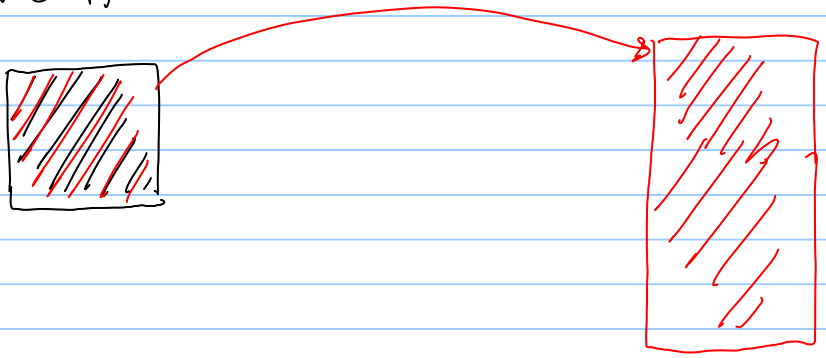
options → trust center → trust center options → macro settings

↳ enable all.

at any point in the production system

V @ p,T

V_{sc} @ P_{sc}, T_{sc}



no liquid is condensed

dry

gas volume factor $$B_{g_d} = \frac{V@p,T}{V_{sc}} = \frac{\frac{n z R T}{p}}{\frac{n\, 1\, R\, T_{sc}}{P_{sc}}} = \frac{z\, T}{p} \left(\frac{P_{sc}}{T_{sc}}\right)$$

if $T = T_R$
$p = p_R$

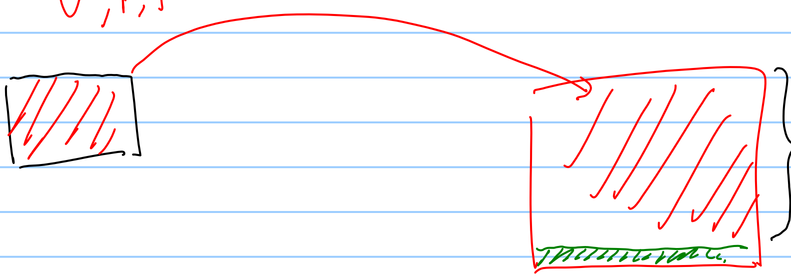
gas formation volume factor

if I give you q_g @ sc

find $q_{g@p,T}$

$$q_{g@p,T} = B_{g@p,T} \cdot q_{sc}$$

V, p, T

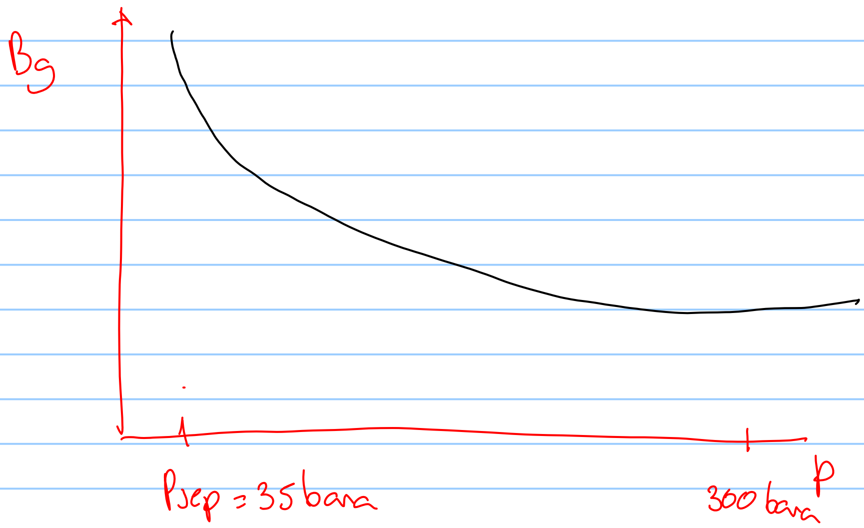


V_{sc}, P_{sc}, T_{sc}

B_{g_w} ← wet

$\gamma_s = 0.55$

$T = 80\,°C$



* homework 2:

plot B_g for

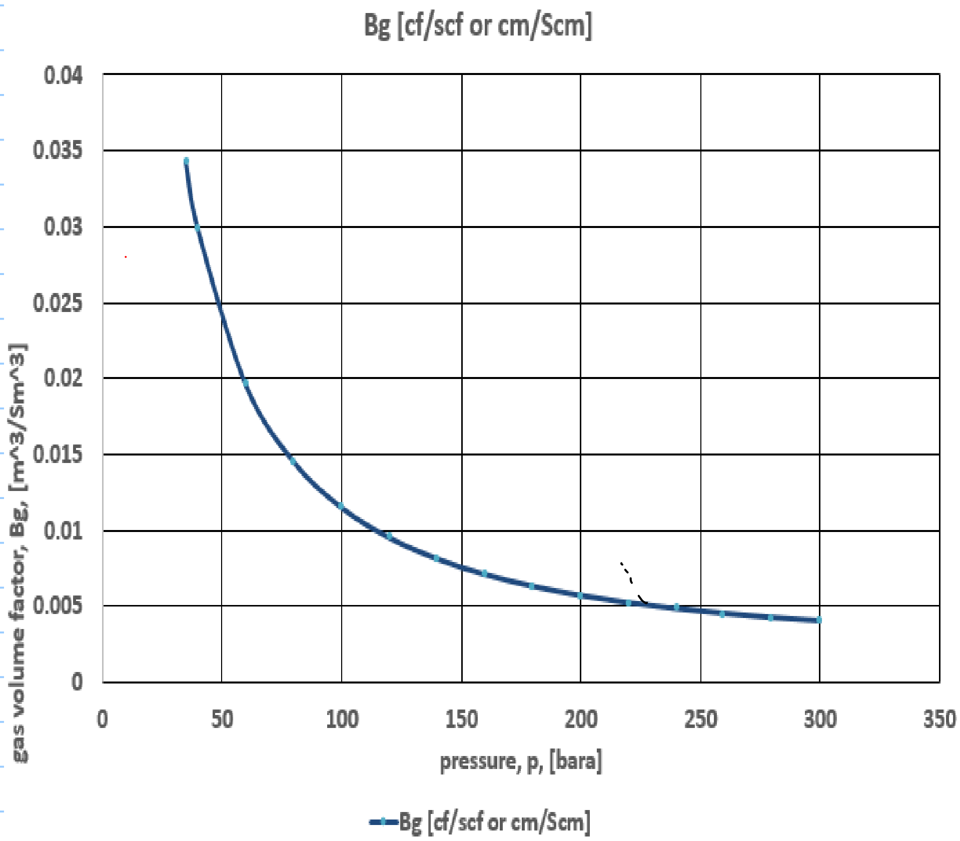
$T = 120\,°C$

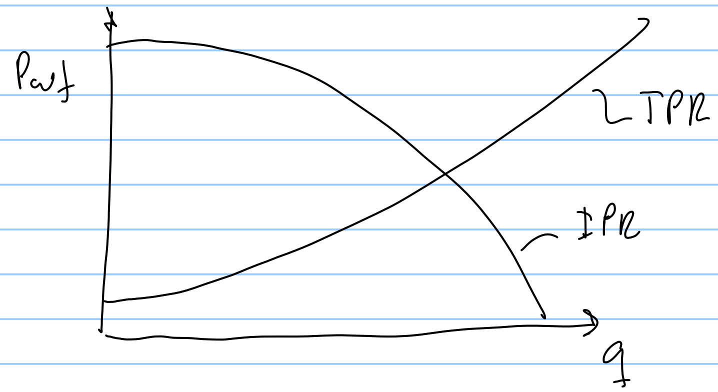
$T = 60\,°C$

$T = 80\,°C$

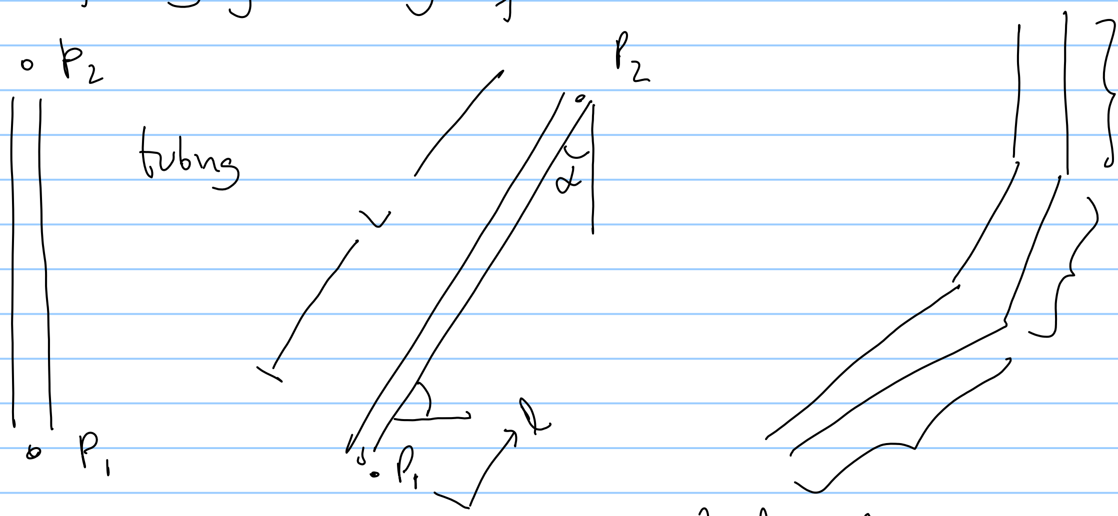
$p \in [35 \text{ bara} - 300 \text{ bara}]$

$\gamma_s = 0.55$





Development of Dry gas tubing equation ⇝ flowlines (also applicable for)



divide and conquer

$$\frac{dp}{dl} = \underbrace{-\rho \cdot g \cos\alpha}_{\text{hidrostatic}} - f \rho \frac{u^2}{2\underset{\text{ID}}{\phi}}$$

p changes along tubing

T " " "

$$\rho = f(p, T)$$

$$\rho = \frac{p\, M_w}{zRT}$$

$$\frac{dp}{dl} = -\left(\frac{p M_w}{zRT}\right) g \cdot \cos\alpha - f \frac{p M_w}{zRT} \frac{u^2}{2\phi}$$

$$u = \frac{\dot{m}}{\rho \cdot A} \quad \frac{kg/s}{kg/m^3 \cdot m^2} = \frac{m}{s}$$

$$A = \pi \cdot \phi^2 \cdot 0.25$$

$$u = \frac{\dot{m} \cdot zRT\; 4}{p M_w \cdot \pi \phi^2}$$

$$\frac{dp}{dl} = -\frac{p M_w}{zRT} g \cos\alpha - f \frac{\cancel{p}\cancel{M_w}}{\cancel{zRT}\; \cancel{2}\phi} \frac{\overset{8}{\cancel{16}}\, \dot{m}^2 (zRT)^{\cancel{2}}}{p^{\cancel{2}} M_w^{\cancel{2}} \pi^2 \phi^4}$$

$$\frac{dp}{dl} = -\frac{p M_w}{zRT} g \cos\alpha - f \frac{\dot{m}^2\, zRT\, 8}{\phi^5 \cdot \pi^2 p M_w}$$

Constant $B = \dfrac{M_w \cdot g \cos\alpha}{\bar{Z} R \bar{T}}$

$$D = \frac{f \bar{Z} R \bar{T} \, 8 \, \dot{m}^2}{\Phi^5 \pi^2 M_w}$$

$$\frac{dp}{dl} = -B \cdot p - \frac{D}{p} \qquad - \frac{dp}{Bp + \frac{D}{p}} = dl$$

B and D are constant and equal to

$$B = \frac{M_w g \cos\alpha}{\bar{Z} R \bar{T}}$$

$$\bar{Z} = f(\bar{p}, \bar{T}) \qquad \bar{T} = \frac{T_1 + T_2}{2}$$

$$D = \frac{\bar{f} \bar{Z} R \bar{T} \, 8 \, \dot{m}^2}{\Phi^5 \pi^2 M_w}$$

$$\underbrace{\int_1^2 \frac{dp}{Bp + \frac{D}{p}}}_{} = \int_1^2 -dl$$

$$= -L$$

$$\int_1^2 \frac{p \, dp}{B p^2 + D}$$

change variable $U = Bp^2 + D$

$dU = 2pB \, dp$

$$\frac{1}{2B} \int_1^2 \frac{dU}{U} = \frac{1}{2B} \ln\left(\frac{U_2}{U_1}\right)$$

return the variable change

$$\frac{1}{2B} \ln\left(\frac{B p_2^2 + D}{B p_1^2 + D}\right) = -L$$

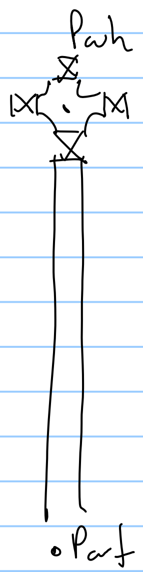
$$\frac{B P_2^2 + D}{B P_1^2 + D} = e^{-L\,2\,B}$$

elevation factor

$S = 2LB$

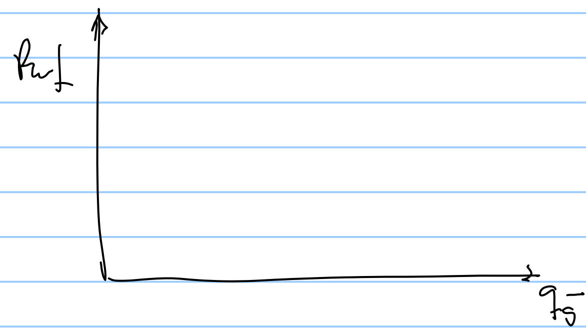
$$\frac{B P_2^2 + D}{B P_1^2 + D} = e^{-S}$$

$$P_1^2 = P_2^2 e^{S} + \left(\frac{B}{D}\right) e^{S} - 1$$



$P_2 = P_{wh}$

$P_1 = P_{wf}$



$$\frac{B}{D} = \frac{\dot{m}^2\, \bar{Z} R \bar{T}\;\; 8 \cdot f\;\; \bar{Z} R \bar{T}}{M_w\, \pi^2 \phi^5\, M_w\, g \cos\alpha}$$

$\dot{m} = \rho_{sc} \cdot q_{sc}$

$\frac{kg}{m^3} \cdot \frac{m^3}{d}$

$$\frac{B}{D} = \frac{q_{sc}^2 \left(\bar{Z} R \bar{T}\right)^2 8 \cdot f}{\pi^2 \phi^5 \cos\alpha\, R^2 g} \left(\frac{p_{sc}}{T_{sc}}\right)^2$$

$$\rho_{sc} = \frac{p_{sc} \cdot M_w}{\cancel{Z}\, R\, T_{sc}}$$

$$P_1^2 = P_2^2 e^{S} + q_{sc}^2 \underbrace{\left(\text{constant}\right)}_{\frac{1}{C_T^2}}$$

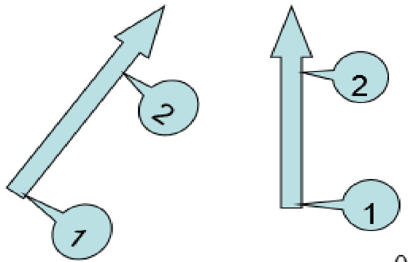
$$P_1^2 = P_2^2 e^{S} + \frac{q_{sc}^2}{C_T^2}$$

Tubing flow Equation-Dry gas

$$\boxed{q_{sc} = \left(\frac{\pi}{4}\right)\left(\frac{R}{M_{air}}\right)^{0.5}\left(\frac{T_{SC}}{P_{SC}}\right)\left[\frac{D^5}{\gamma_g f_M Z_{av} T_{av}\, L}\right]^{0.5}\left(\frac{s e^S}{e^S - 1}\right)^{0.5}\left(\frac{p_1^2}{e^S} - p_2^2\right)^{0.5}}$$

$$\boxed{\frac{s}{2} = \frac{M_g g}{Z_{av} R T_{av}} H = \frac{(28.97)\gamma_g g}{Z_{av} R T_{av}} H}$$

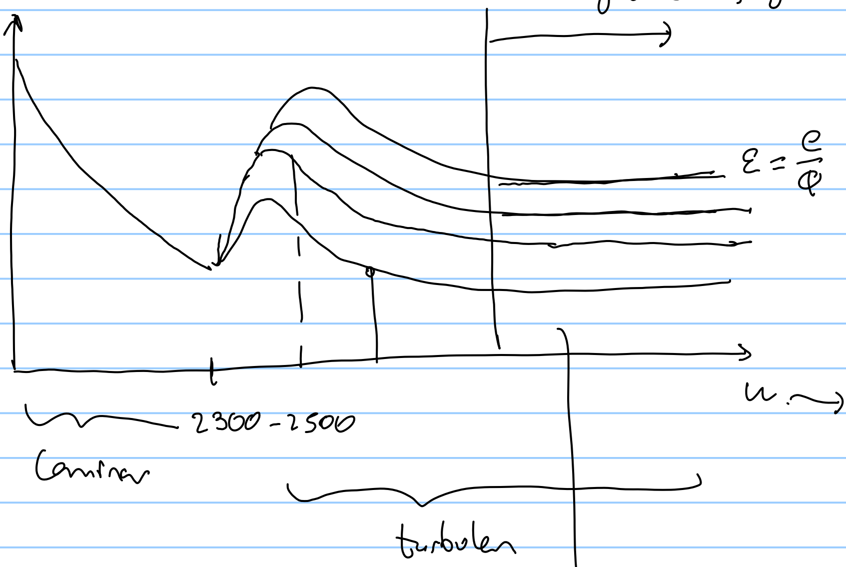
$$q_{gsc} = C_T \left(\frac{p_1^2}{e^s} - p_2^2\right)^{0.5}$$



$$p_{\text{inlet}} = p_1 = e^{s/2}\left(p_2^2 + \frac{q_g^2}{C_T^2}\right)^{0.5} \qquad p_{wh} = p_2 = \left(\frac{p_1^2}{e^s} - \frac{q_g^2}{C_T^2}\right)^{0.5}$$

Reynolds of gas flow

$$f = \frac{\frac{\Delta p\, \Phi}{L}}{\left(\frac{v^2}{2}\right)}$$



$u \rightarrow$ $Re = \frac{u \cdot \Phi \cdot \rho}{\mu}$

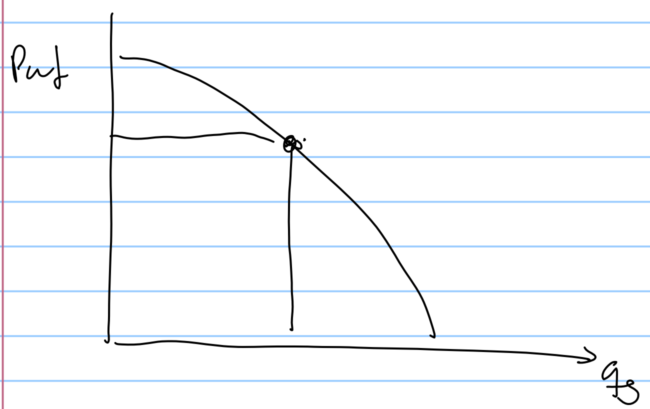
100m

$e = f(\Phi)$

$$f = \frac{0.0777}{\Phi^{0.224}}$$

Φ in m
inch

IPR



Check tubing constant calculator spreadsheet. Class exercise.

CALCULATION OF TUBING FLOW CONSTANT		
height difference	[m]	3000
Internal Diameter	[m]	0.15
Gas gravity	[-]	0.55
Line length	[m]	3000
Inlet temperature	[K]	378
Outlet temperature	[K]	360
Inlet pressure	[bara]	303
Outlet pressure	[bara]	275
Ave. Temperature	[K]	369
Ave. Pressure	[bara]	289
Ave. Compressibility factor	[-]	0.981
Friction factor	[-]	0.012
Elevation Coeff, S		0.156
Tubing flow constant	[Sm^3/bar]	3.58E+04

Note Title 12.01.2017

Day 3

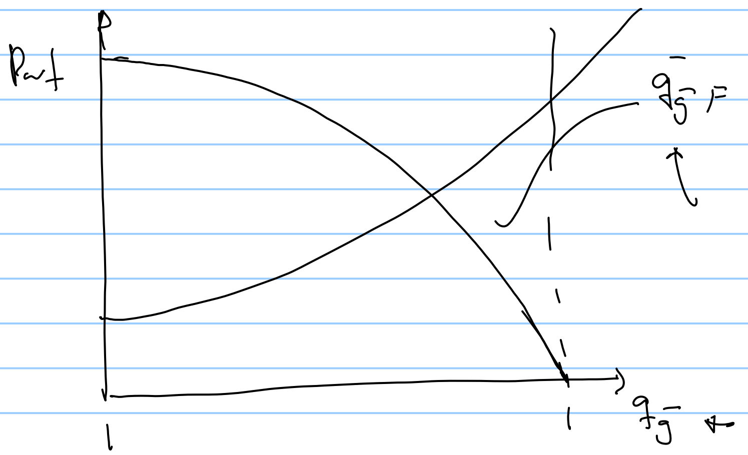
http://folk.ntnu.no/stanko/Courses/POFE_UEM/2017/

- IPR - TPR equilibrium downhole

tubing equation $p_2^2 = \frac{p_1^2}{e^s} - \frac{q_g^2}{C_T^2}$

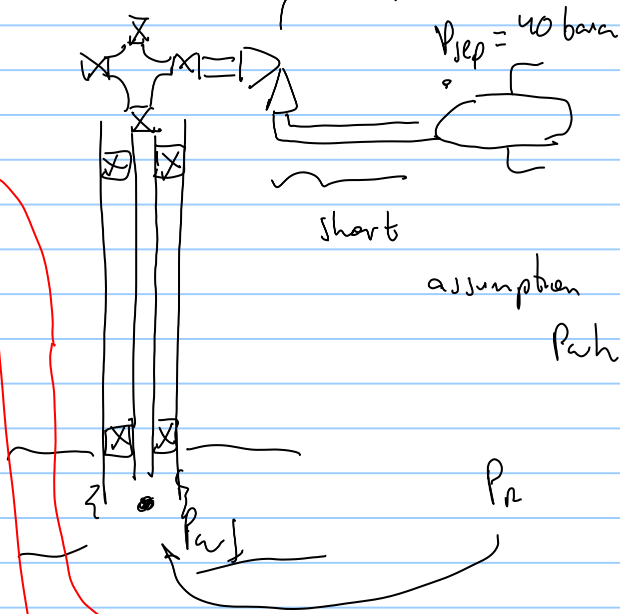
$q_g = C_R\left(P_R^2 - P_{wf}^2\right)^n$

check



Single_dry_gas_well_flow_equilibrium.xls - Compatibility Mode - Excel

Eva No 3		
p_R, Res pressure	304	bara
C_R	104	~~Sm3/d/bar^2n~~
n, exponent	0.9	
C_t, tubing	4.25E+04	Sm³/d/bar
s, elevation	0.155	
C_{fl}, flowline	1.25E+05	4.00E+04 Sm³/d/bar
p_{sep}	40	bara



assumption

$P_{wh} = const = P_{sep}$

available / independent variable

P_{wf} (bara)	IPR q_g [Sm³/d]	TPR P_{wf} (bara) required
P_R	$q_g = C_R\left(P_R^2 - P_{wf}^2\right)^n$	$p_1 = e^{s/2}\left(p_2^2 + \frac{q_g^2}{C_T^2}\right)^{0.5}$
$P_2 = P_R - 20$ bar		
$P_3 \to P_2 - 20$		
$P_4 \to P_3 - 20$		
0		

$P_2^2 = \frac{P_1^2}{e^s} - \frac{q_g^2}{C_T^2}$

to freeze cells in excel [F4]

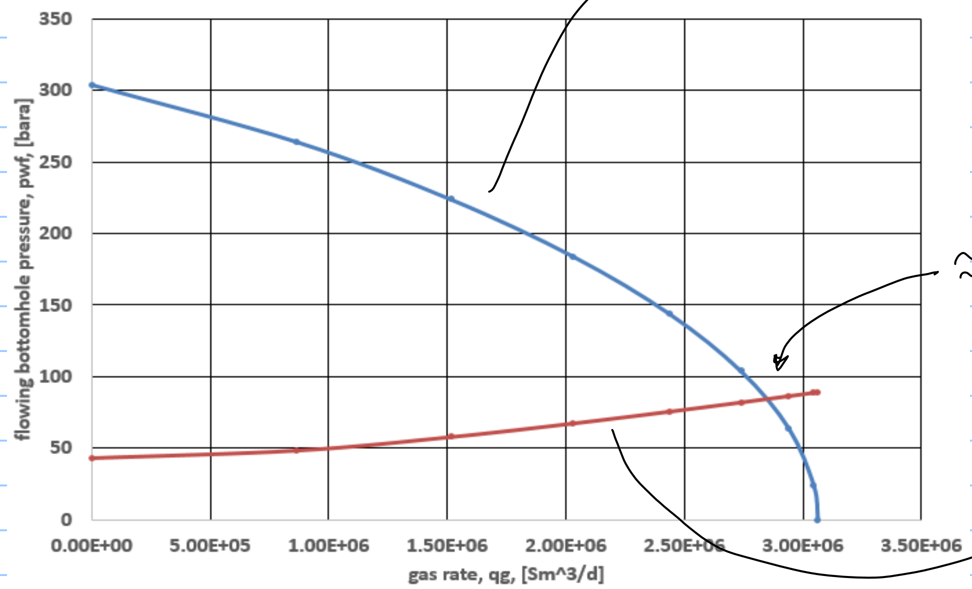
\$E\$4

	IPR	TPR
pwf_avail	qg	pwf_req
[bara]	[sm^3/d]	[bara]
(304)	0	43.2
264	866564	48.5
224	1514206	57.9
184	2031769	67.4
144	2437202	75.6
104	2738763	82.0
64	2940942	86.4
24	3046225	88.7
0	3063415	89.1

Pwf_avail − Pwf_req

304 − 43.2

$f_1(q_g)$



≈ 2.8 E6 Sm^3/d

$f_2(q_g)$

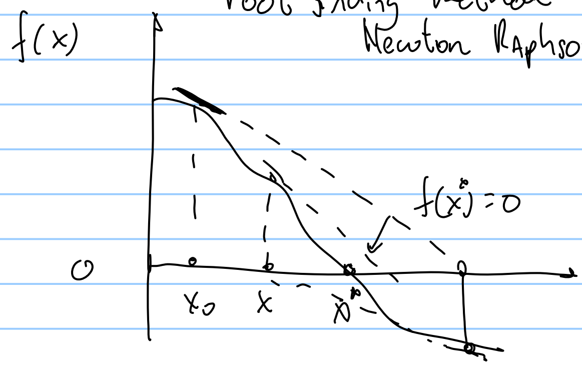
find $q_{g\,eq}^{*}$ that makes

$f_1(q_g^*) = f_2(q_g^*)$

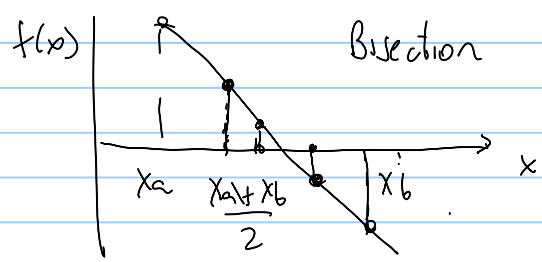
$$\underbrace{f_3(q_g)} = f_1(q_g) - f_2(q_g)$$

root finding method

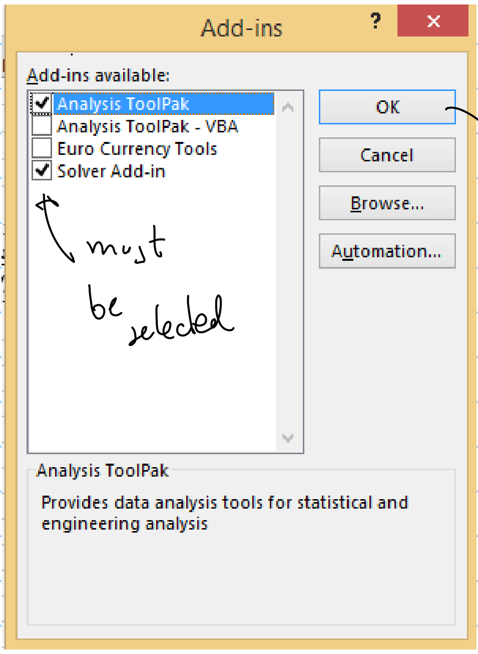
Newton Raphson



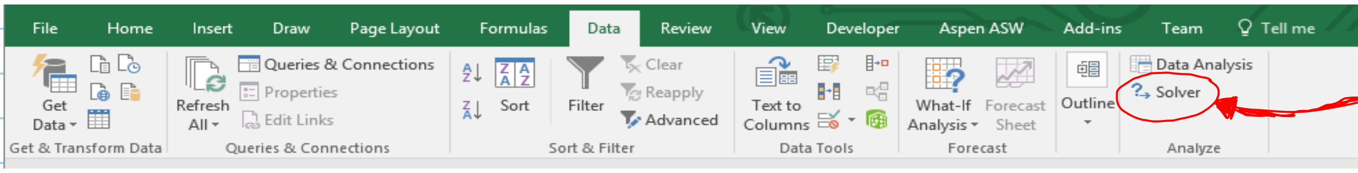
Bisection

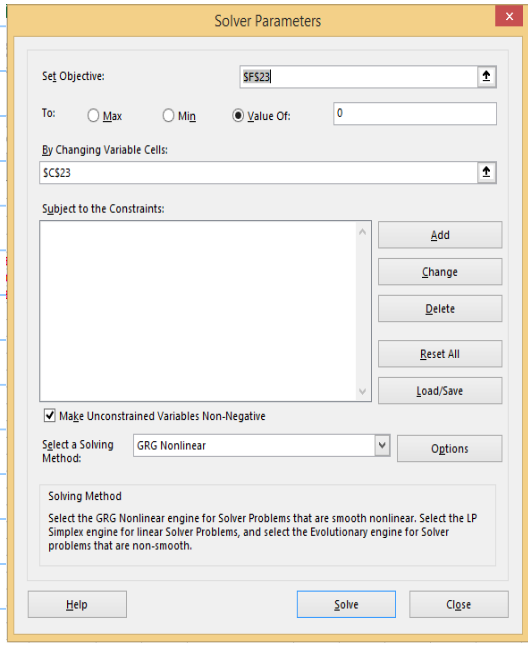


activate the solver in excel options, Add-in, go . . .



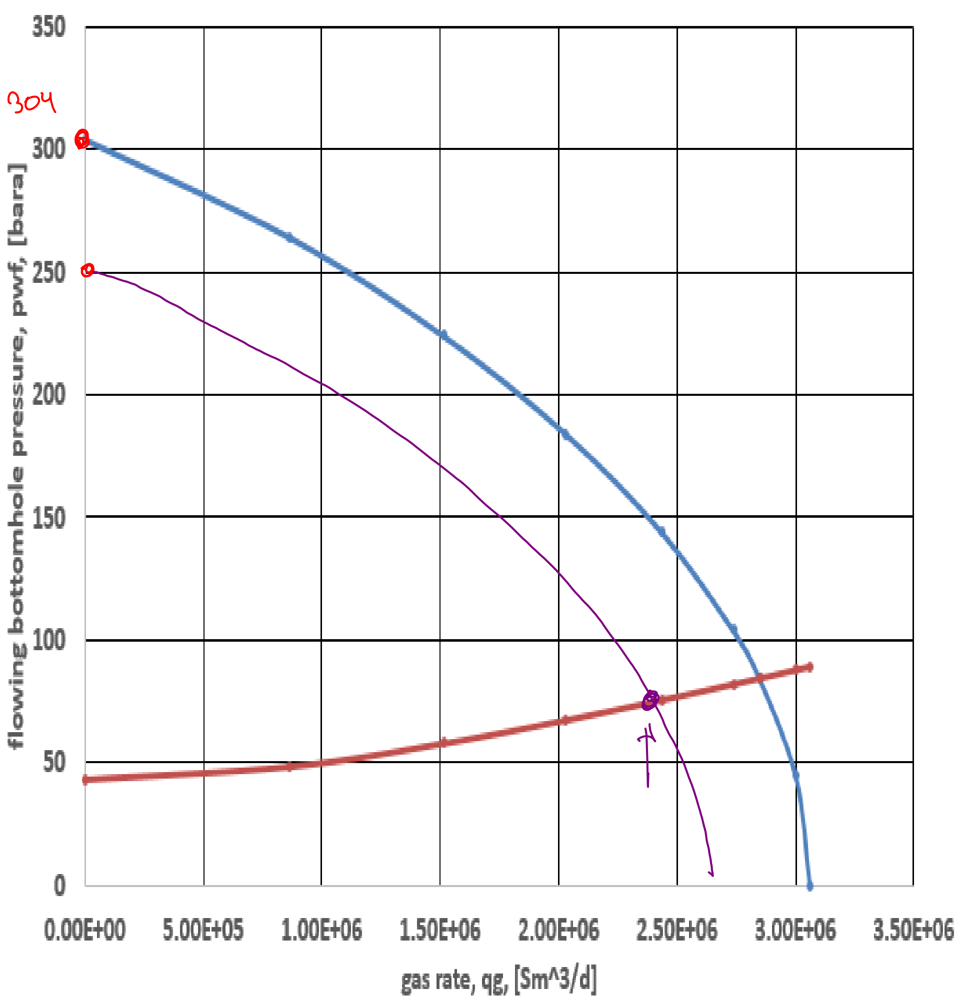
click "ok"





	IPR	TPR	
pwf_avail	qg	pwf_req	pwf_avail_pwf_requ
[bara]	[sm^3/d]	[bara]	[bara]
304	0	43.2	260.8
264	866564	48.5	215.5
224	1514206	57.9	166.1
184	2031769	67.4	116.6
144	2437202	75.6	68.4
104	2738763	82.0	22.0
84.4	2850168	84.4	0.0
44.4	3004597	87.8	-43.4
0	3063415	89.1	-89.1

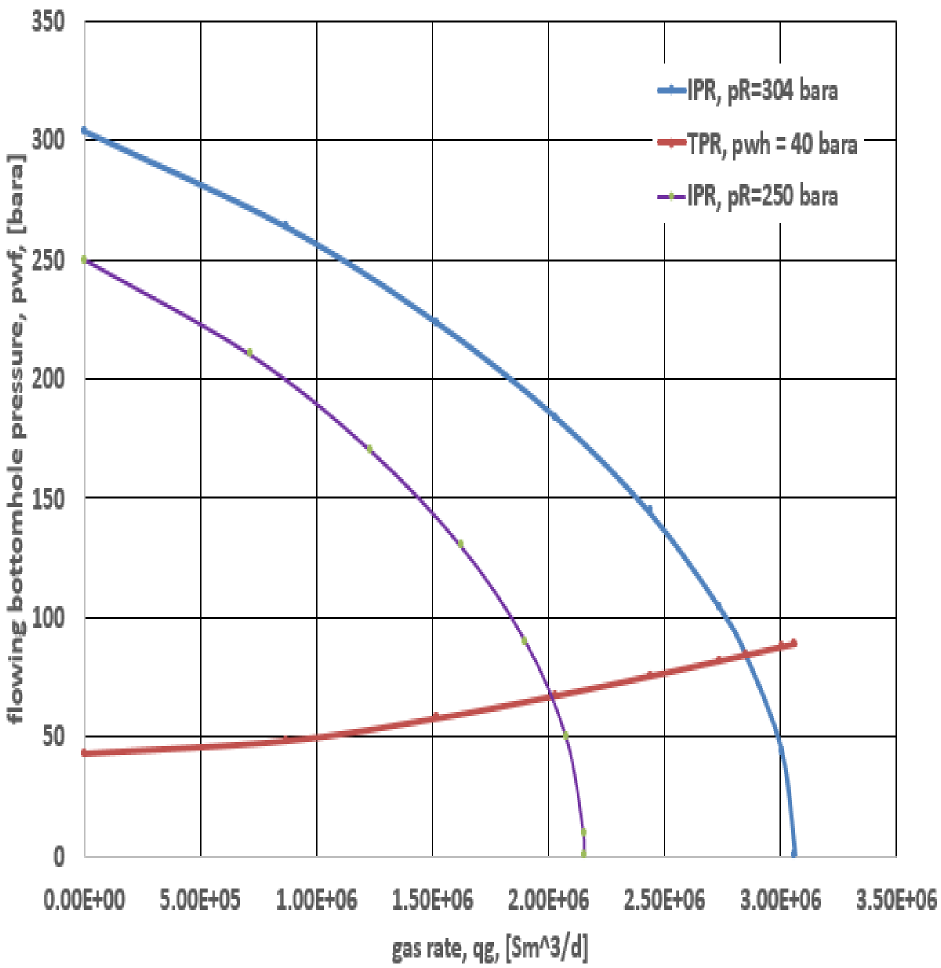
solution ☺



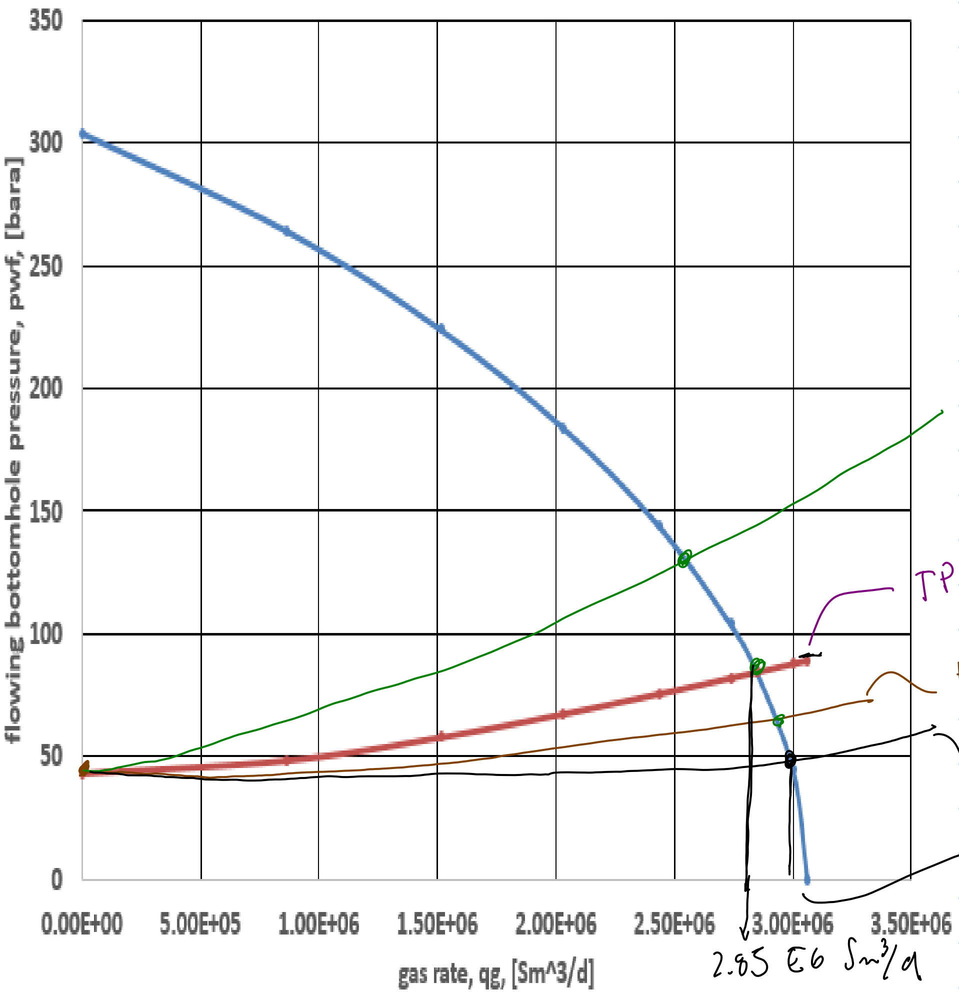
effect of depletion (P_R is reduced)

C n

on the equilibrium rate



changing tubing size (ID).



$$\text{relative difference} = \frac{(-\overset{2.85}{q_{g\,orig}} + \overset{3}{q_{g\,new}})}{q_{g\,original}} \times 100$$

≈ 2.85

5% increase in the rate of well.

Our well is NOT tubing-restricted

$$p_2^2 = \frac{p_1^2}{e^S} - \frac{q_g^2}{C_T^2}$$

$$C_T = \frac{\pi}{4}\left(\frac{R}{M_{air}}\right)^{0.5} \frac{T_{sc}}{p_{sc}} \left[\frac{\phi^5}{\gamma_g \cdot f \cdot \bar{z}\,\bar{T}\,L}\right]^{0.5} \left[\frac{S\ e^S}{e^S - 1}\right]^{0.5}$$

an increase in $\phi \longrightarrow$ increase C_T

by increasing C_T we can assess what would be the effect of a bigger or smaller diameter if only diameter changes then

$$C_{T_1} = f(\Phi_1)$$

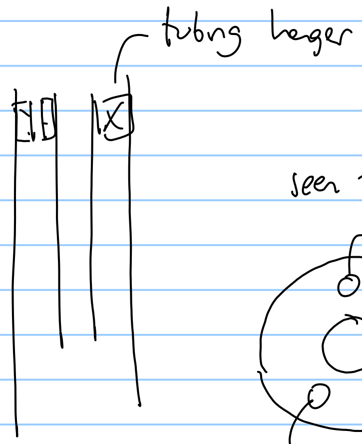
$$C_{T_2} = f(\Phi_2)$$

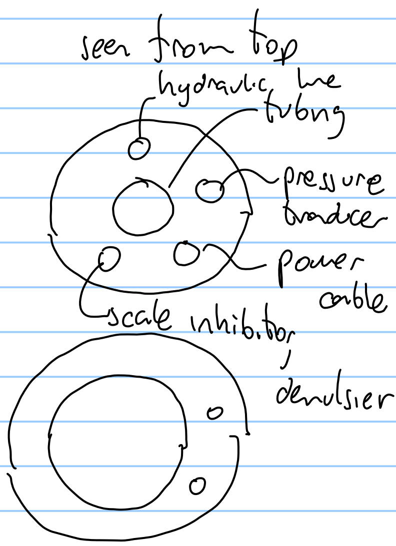
$$\frac{C_{T_1}}{C_{T_2}} = \left(\frac{\Phi_1^{5}}{\Phi_2^{5}}\right)^{0.5} = \frac{\Phi_1^{2.5}}{\Phi_2^{2.5}}$$

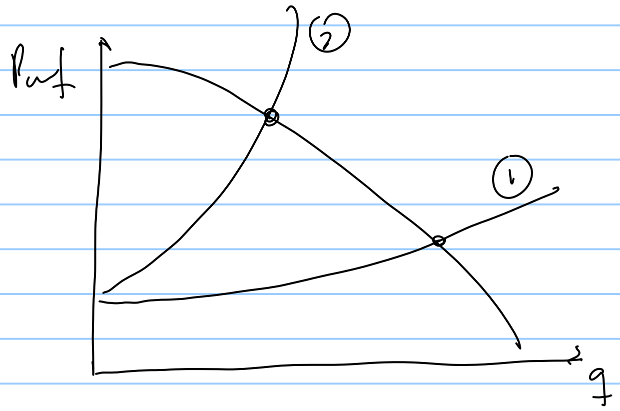
$$C_{T_2} = C_{T_1}\frac{\Phi_2^{2.5}}{(\Phi_1)^{2.5}}$$

tubing sizing.

- ID of production casing
- size and amounts of holes on the tubing hanger
- reduce Δp tubing and increase production





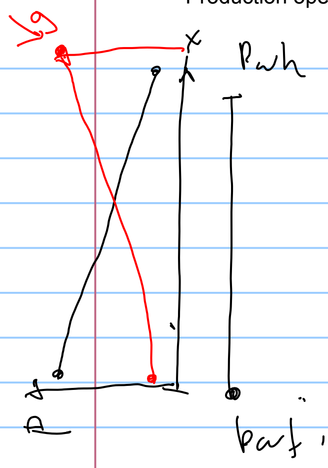


1 is better than nr 2

- Erosion $V_{gas} \leq V_{erosional}$ velocity → API 14 E

$$\text{Limit } V_{erosional} = \frac{C}{\sqrt{\rho_m}} \quad C \begin{cases}100\\120\end{cases}$$

$[ft/s]$ $\quad [lb/ft^3]$



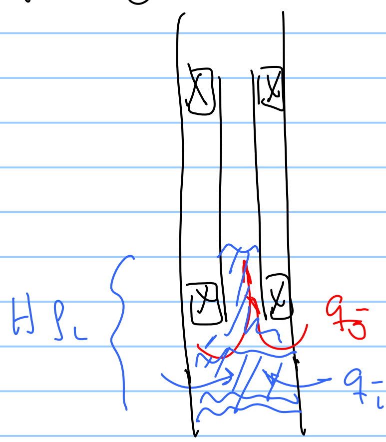
$$V_{gas} = \frac{q_g @ p,T}{A} = \frac{q_{\bar g} \cdot B_g(p,T)}{A}$$

if wellhead $V_g \geq V_{erosional}$ velocity ⇒ I might have erosion in tubing

- avoid liquid loading $V_g \leq V_{erosional}$ velocity

  $V_{gas} \geq V_{Turner}$

- if producing with liquid then

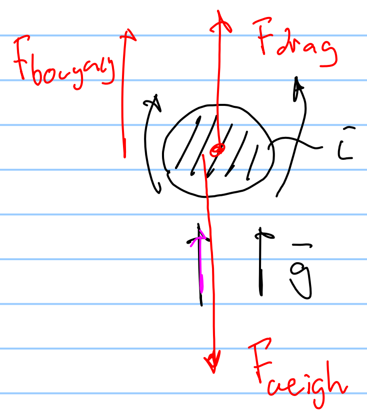


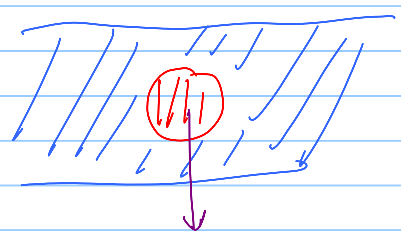
$q_{\bar g} \uparrow$ such it can carry $q_{\tilde l}$

liquid accumulation in wellbore

↳ liquid loading

Force balance on a droplet





$$F_{drag} = F_{weigh}$$

$$(\rho_l - \rho_g) g \cdot V_d$$

$$\frac{\pi \phi^2}{4}$$

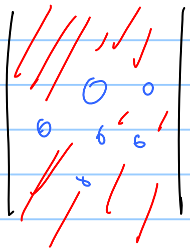
$$\frac{1}{2} C_D \rho_g \cdot V_g^2 A_d = (\rho_l - \rho_{\bar g}) g \cdot \frac{\pi \phi^3}{6}$$

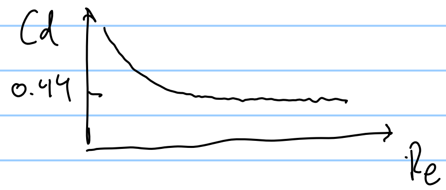
$\rho_L \approx$ cont $PV = ZnRT$

$$V = \sqrt{\frac{\Phi\, g\, (\rho_L - \rho_g)}{C_d\, \rho_g} \frac{4}{3}} \qquad (1)$$

Hinze

C_d in the turbulent region is 0.44





$$\text{Weber number} = \frac{\rho_g\, u_g^2\, \Phi}{\sigma}$$

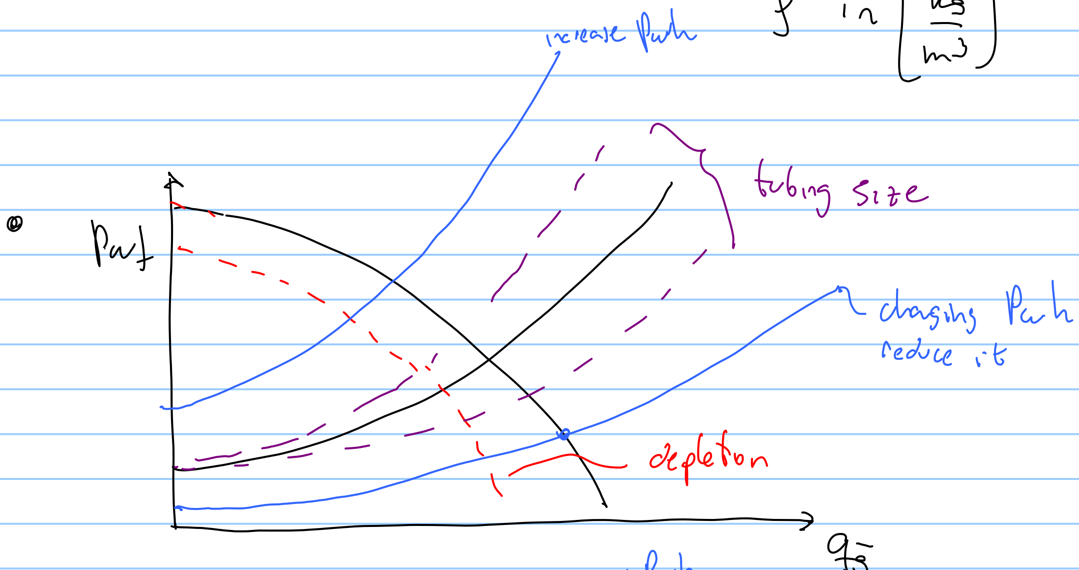
when $We = 30$ that gives you Φ_{max}

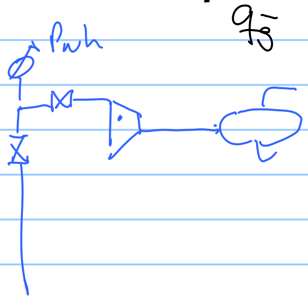
$$\frac{u_g^2\, \rho_g\, \Phi_{max}}{\sigma} = 30 \qquad (2)$$

substitute eq (2) in (1)

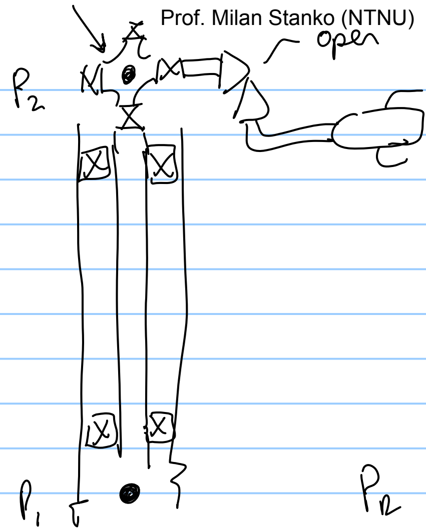
Turner equation : $V = 5.46 \left[\frac{\sigma^{0.25} (\rho_L - \rho_g)^{0.25}}{\rho_g^{0.5}} \right]$

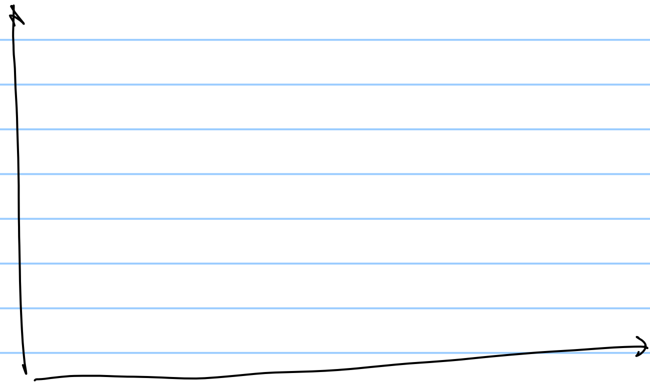
ρ in $\left[\frac{kg}{m^3}\right]$ σ in $\left[\frac{N}{m}\right]$

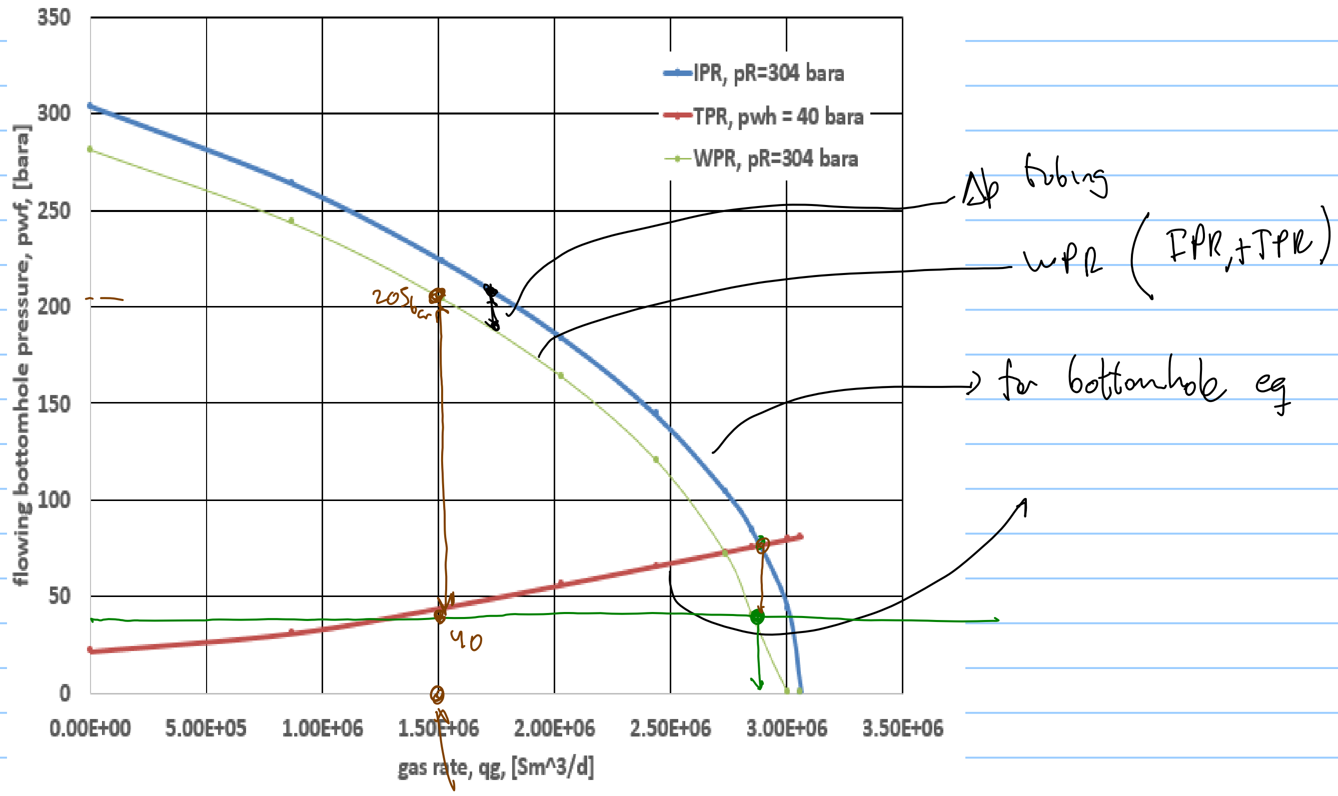




Perform wellhead equilibrium







$\Delta p_{choke} = 205 - 40 = 165$ bar

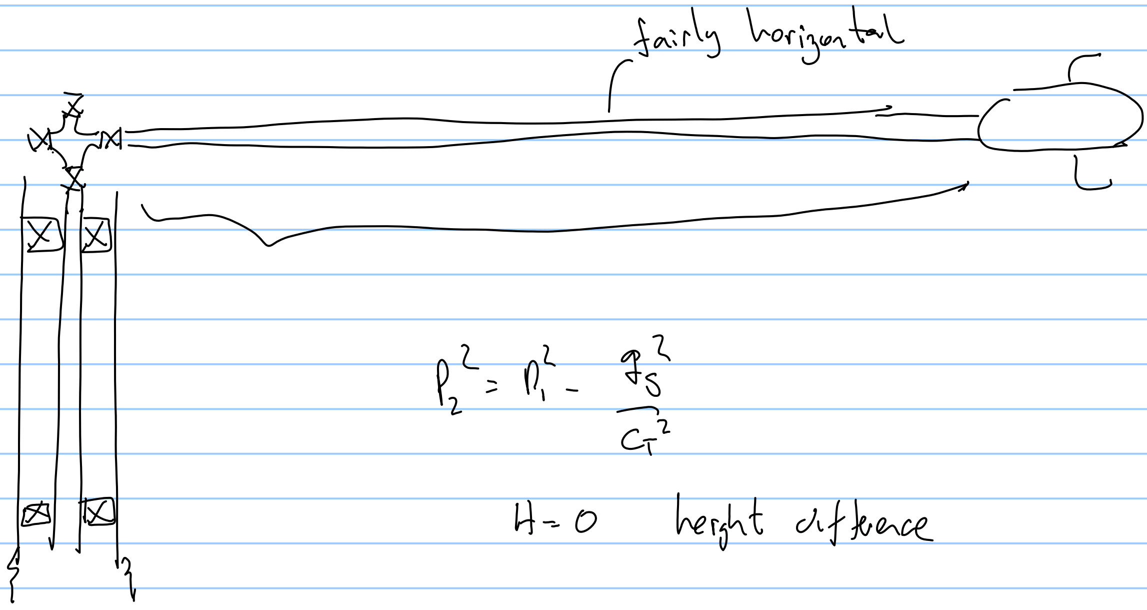
(3) Homework.

Perform flow equilibrium for this class exercise but using the wellhead as the equilibrium point.

- Compute WPR
- WPR − psep
- find q_g such as WPR − P_{sep} = 0
- make plot

find Δp choke such as q_g = 2.E06 Sm^3/d

Day 4:



$$p_2^2 = p_1^2 - \frac{q_g^2}{C_T^2}$$

$H = 0$ height difference

Tubing flow Equation-Dry gas

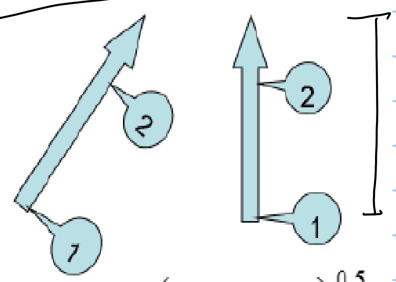
$$\boxed{q_{sc} = \left(\frac{\pi}{4}\right)\left(\frac{R}{M_{air}}\right)^{0.5}\left(\frac{T_{SC}}{P_{SC}}\right)\left[\frac{D^5}{\gamma_g f_M Z_{av} T_{av} L}\right]^{0.5}\left(\frac{se^S}{e^S - 1}\right)^{0.5}\left(\frac{p_1^2}{e^S} - p_2^2\right)^{0.5}}$$

$Z_{av} = f(p_{av}, T_{av})$

$C_T = f(p_{av})$

$$\boxed{\frac{s}{2} = \frac{M_g g}{Z_{av} R T_{av}} H = \frac{(28.97)\gamma_g g}{Z_{av} R T_{av}} H}$$

$$q_{gsc} = C_T \left(\frac{p_1^2}{e^s} - p_2^2\right)^{0.5}$$



$z_2 - z_1 = H$

z

$H = 0$

$$p_{inlet} = p_1 = e^{s/2}\left(p_2^2 + \frac{q_g^2}{C_T^2}\right)^{0.5} \qquad p_{wh} = p_2 = \left(\frac{p_1^2}{e^s} - \frac{q_g^2}{C_T^2}\right)^{0.5}$$

if H $S = 0$

$$p_2^2 = \frac{p_1^2}{e^0} - \frac{q_g^2}{C_T^2}$$

1

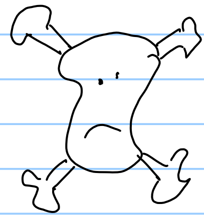
$$C_T = \frac{\pi}{4}\left(\frac{R}{M_{air}}\right)^{0.5} \cdot \frac{T_s}{P_{sc}}\left[\frac{D^5}{\gamma_g f \bar{z} \bar{T} L}\right]^{0.5}\left[\frac{\cancel{S}\cdot e^S}{\cancel{e^S} - 1}\right]^{0.5}$$

0

1

$$\sqrt{p_1^2 - p_2^2} = q_g$$

$$\lim_{s \to 0} \left[\frac{s\, e^s}{e^s - 1} \right]^{0.5} \quad \frac{0}{0}$$



l'Hopital

$$\lim_{s \to 0} \frac{\left(\cancelto{1}{e^s} + \cancelto{1}{e^s} \cdot \cancelto{0}{s}\right)}{\cancelto{1}{e^s}} = 1$$

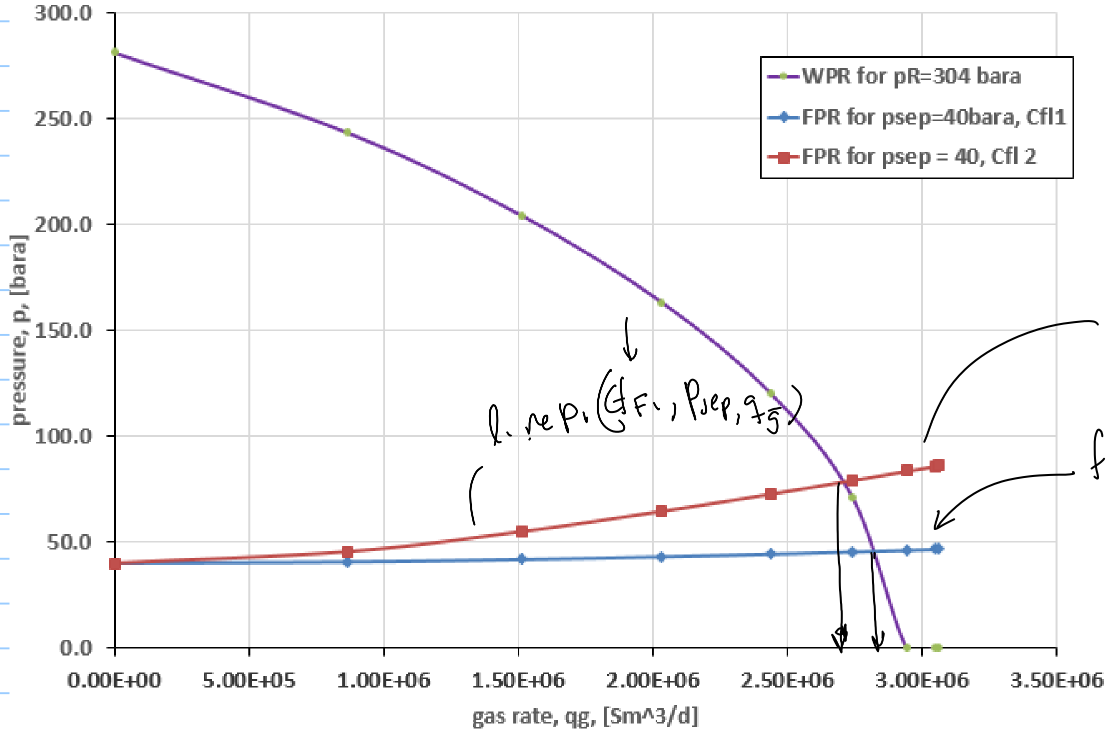
C_T for horizontal flowline is:

$$C_T = \underbrace{\frac{\pi}{4} \left(\frac{R}{M_{air}} \right)^{0.5} \cdot \frac{T_s}{p_{sc}} \left[\frac{D^5}{\gamma_g\, f\, \bar{z}\, \bar{T}\, L} \right]^{0.5}}$$

flowline performance relationship

Class exercise WPR vs FPR

	IPR	TPR			WPR	PPR for Cfl1	PPR for Cfl2
pwf_avail	qg	pwf_req	pwf_avail-pwf_req		pwh_avail	pwh_req	pwh_req
[bara]	[Sm^3/d]	[bara]	[bara]		[bara]	[bara]	[bara]
304	0.00E+00	43.2	260.8		281.3	40.00	40.0
264	8.67E+05	48.5	215.5		243.5	40.60	45.5
224	1.51E+06	57.9	166.1		204.2	41.79	55.1
184	2.03E+06	67.4	116.6		163.4	43.18	64.7
144	2.44E+06	75.6	68.4		120.3	44.50	72.9
104	2.74E+06	82.0	22.0		71.5	45.61	79.3
64	2.94E+06	86.4	-22.4		#VALUE!	46.41	83.7
24	3.05E+06	88.7	-64.7		#VALUE!	46.84	86.0
0	3.06E+06	89.1	-89.1		#VALUE!	46.91	86.4

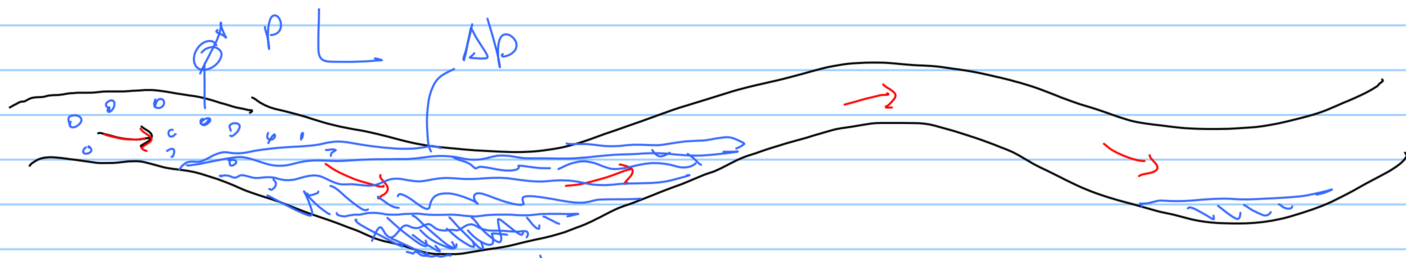


flowline with small diameter

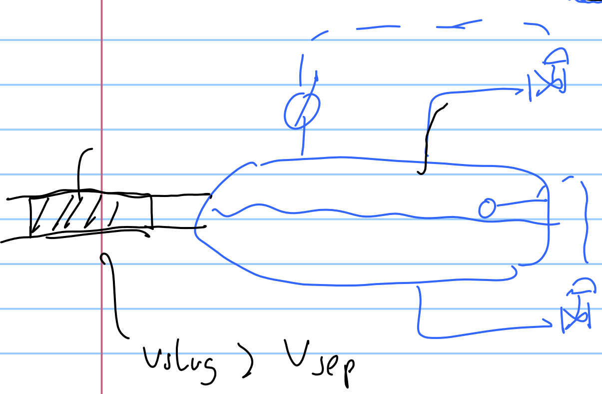
flowline with big ϕ

factors that affect the sizing of gas flowlines:

- Cost ↑ ϕ ↑ Cost, ↑ USD
- pressure drop ↓ pressure drop ↑ ϕ
- liquid transportation



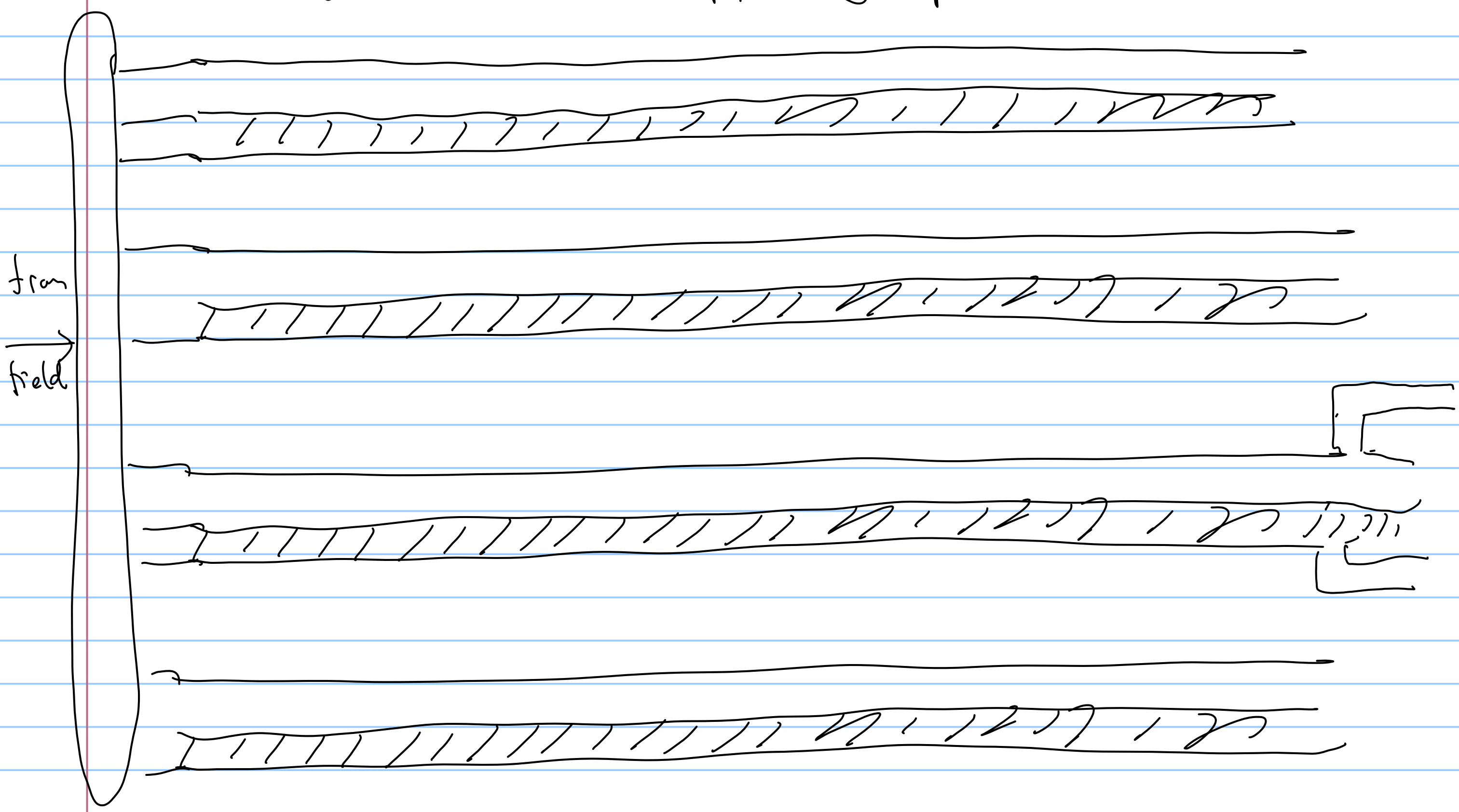
- increased Δp
- pipe blockages
- Corrosion
- Hydrates
- Slugging intermittent production of batches of liquid and gas



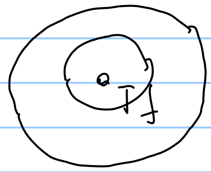
V_{gas} should be high enough to carry liquids and avoid accumulation.

- If slugging cannot be avoided { Snøhvite ~ subsea gas field 146 km from cast
  Block-2 Tanzania
  Canal

Slug catcher a multi pipe long separator

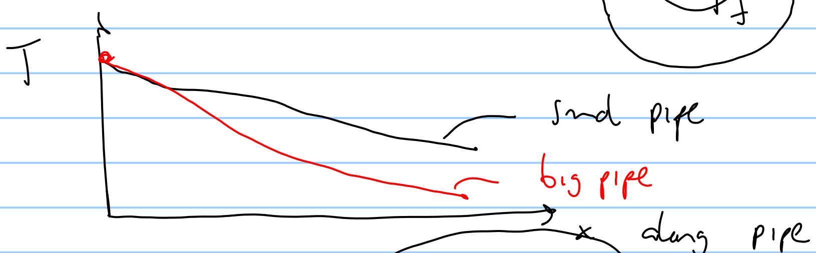


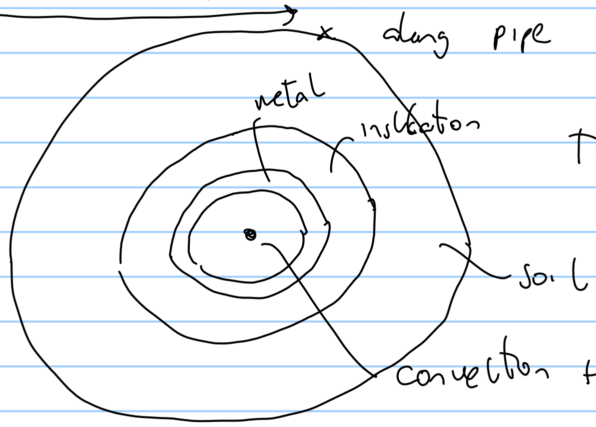
- Cooling of fluid



pipe cross section

Tamb





Tamb

convection + inner conduction in pipe
+ conduction in the insulating layer

$$A \cdot U \,(T_{fluid} - T_{amb}) = q$$

universal heat transfer coefficient (includes conduction, convection, radiation)

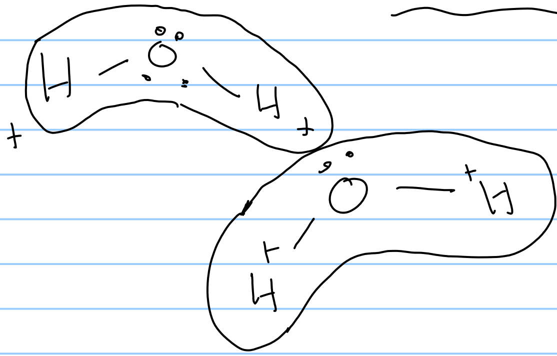
Lower Temperature → more condensation of liquid

Risk forming Hydrates

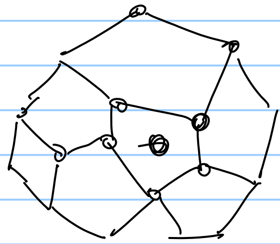
Short comment on Hydrates

at $p = 12$ bara

$T = 4\,°C$



Ice with HC



CH_4

C_2H_6

C_3H_8

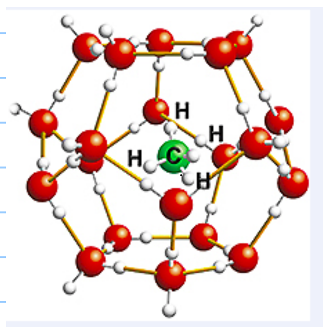
C_4H_{10}

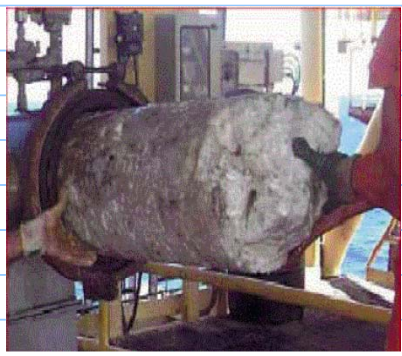
CO_2

N_2

necessary conditions:

- low T
- liquid water (free water)
- Small HC molecules

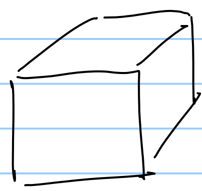




$4\,CH_4 \; 23\,H_2O$ ~ $MW = 478 \frac{kg}{kmol}$

$\rho \approx 900\ kg/m^3$

$1\ m^3$



How much methane in a 1 m^3 of Hydrate methane clathrate

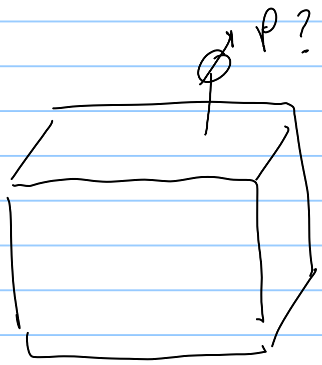
$$Mass = \rho \cdot Vol = 900 \cdot 1 = 900 \text{ kg}$$

$$n = \frac{900 \text{ kg}}{478} = 1.88 \text{ kmol Hydrate}$$

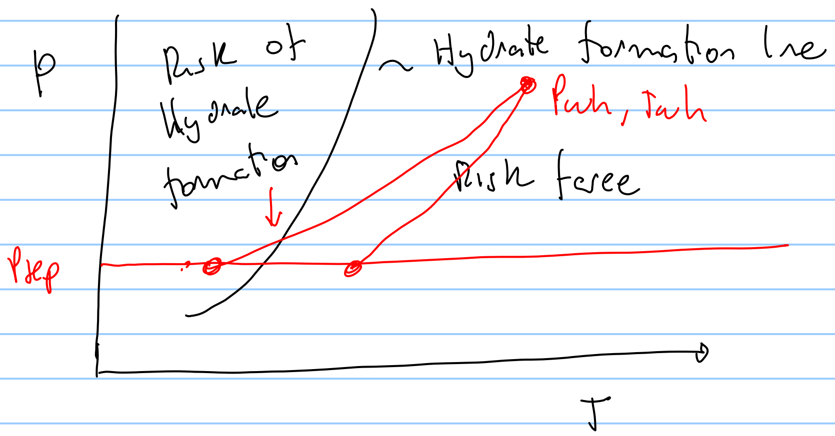
$$n_{CH_4} = 7.53 \text{ kmoles}$$

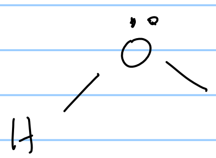
$$V_{sc} = n \cdot 23.67$$

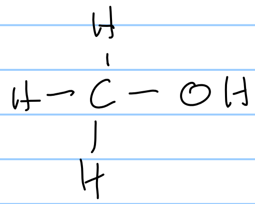
$$V_{sc} = 178 \text{ Sm}^3 \text{ of } CH_4$$



$$p = \frac{7.53 \cdot R \, T_{sc}}{1 \, m^3} \simeq 180 \text{ bara}$$

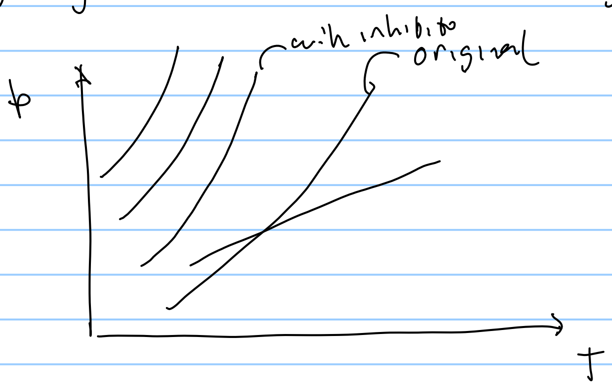




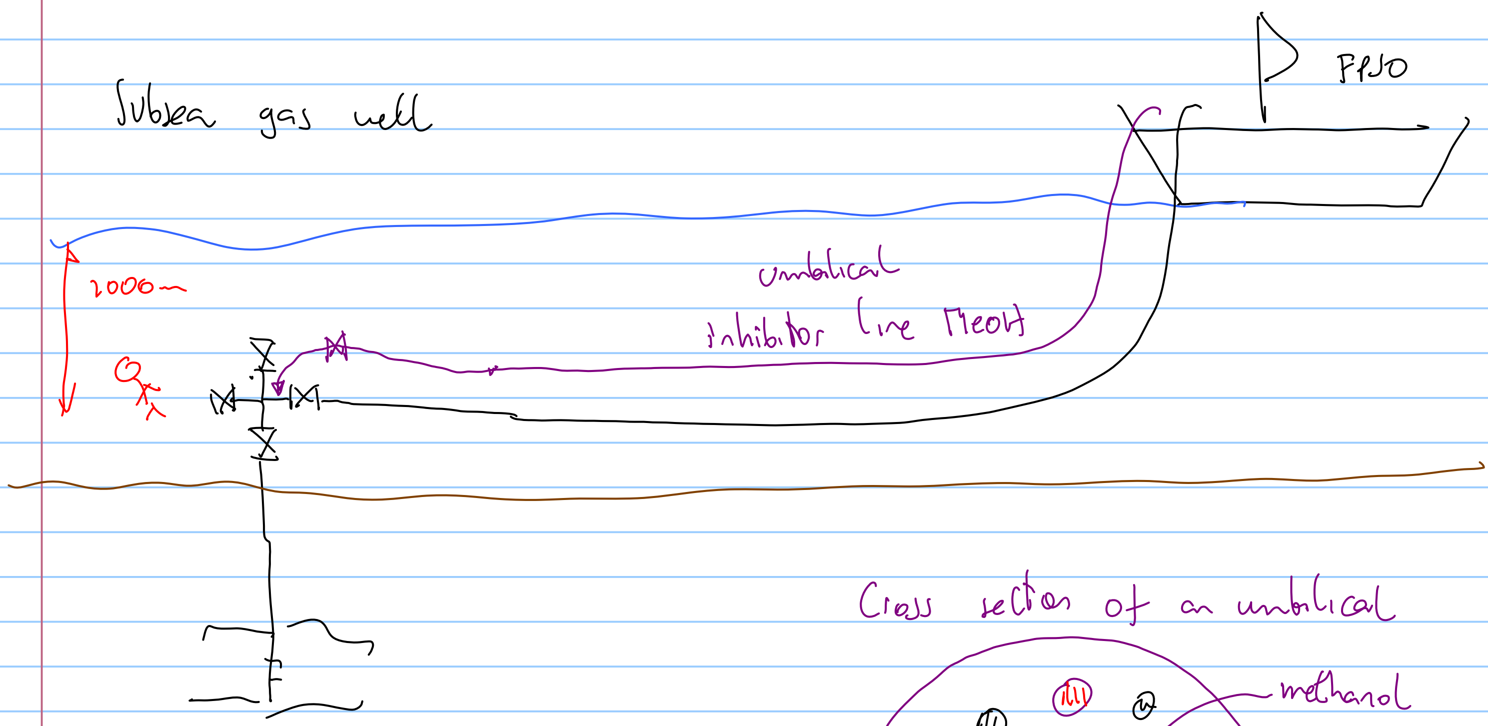


methanol
TEG
MEG

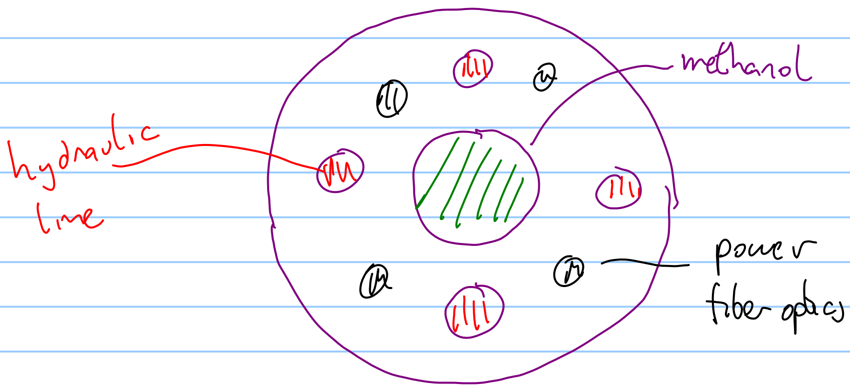
Using hydrate inhibitors to change the hydrate formation line



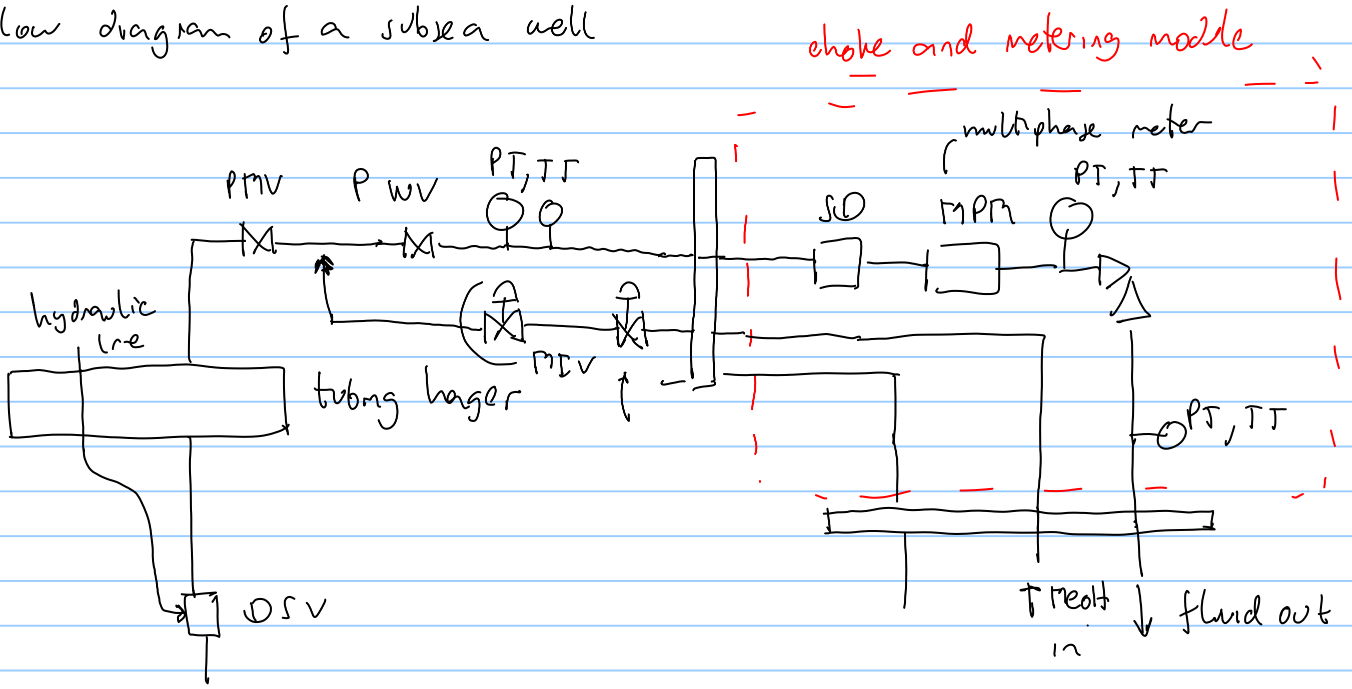
Subsea gas well



Cross section of an umbilical



flow diagram of a subsea well



PWV production wing valve

PT pressure transducer

TT temperature transducer

SD .. Sand detection

PMV ... production master valve

MIV .. Methanol injection value

- Better estimation of C_T

when using P_R and P_{in} to estimate P_{av}, $\frac{304+40}{2}$

I obtain $C_T = 42500$ Sm³/d/bara

$S = 0.153$

the equilibrium P_{wf} is actually 84.378 bara way different than $P_R = 304$ bara.

Using this $P_{av} = \frac{84.378+40}{2}$ I obtain $C_T = 41900$ Sm³/d/bara

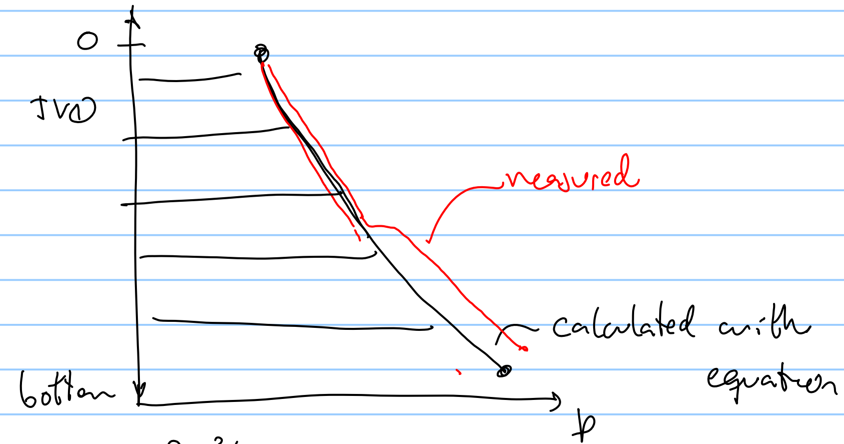
$S = 0.151$

However the equilibrium point is not affected dramatically!

Pressure traverse calculation

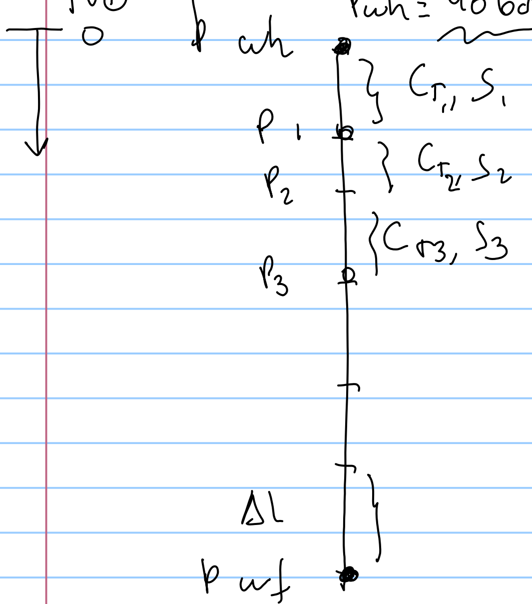
example.. traverse calculation can help diagnose a well with scaling.

pressure distribution along tubing



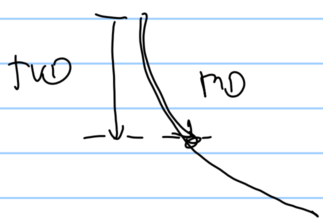
(true vertical depth

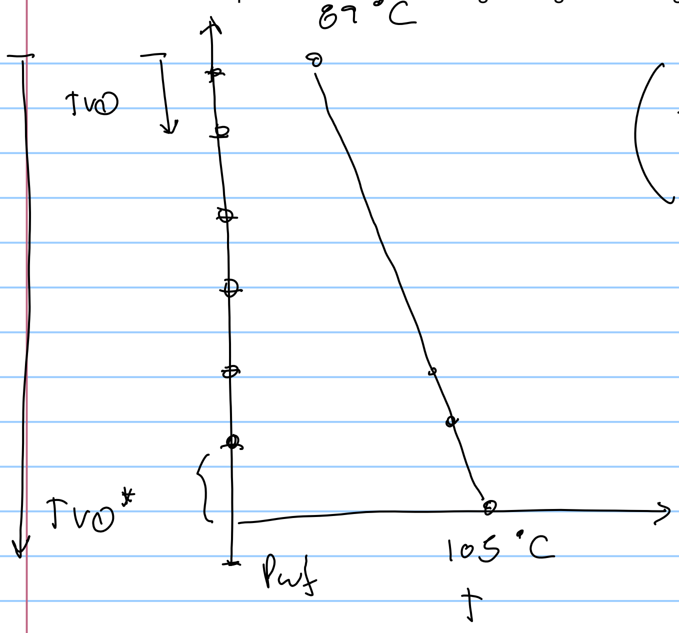
TVD



Calculate p distribution along tubing for equilibrium rate

MD measured depth





$$\left(\frac{105^\circ C - 89}{TVD^* - 0}\right) = \left(\frac{105 - T}{TVD^* - TVD}\right)$$

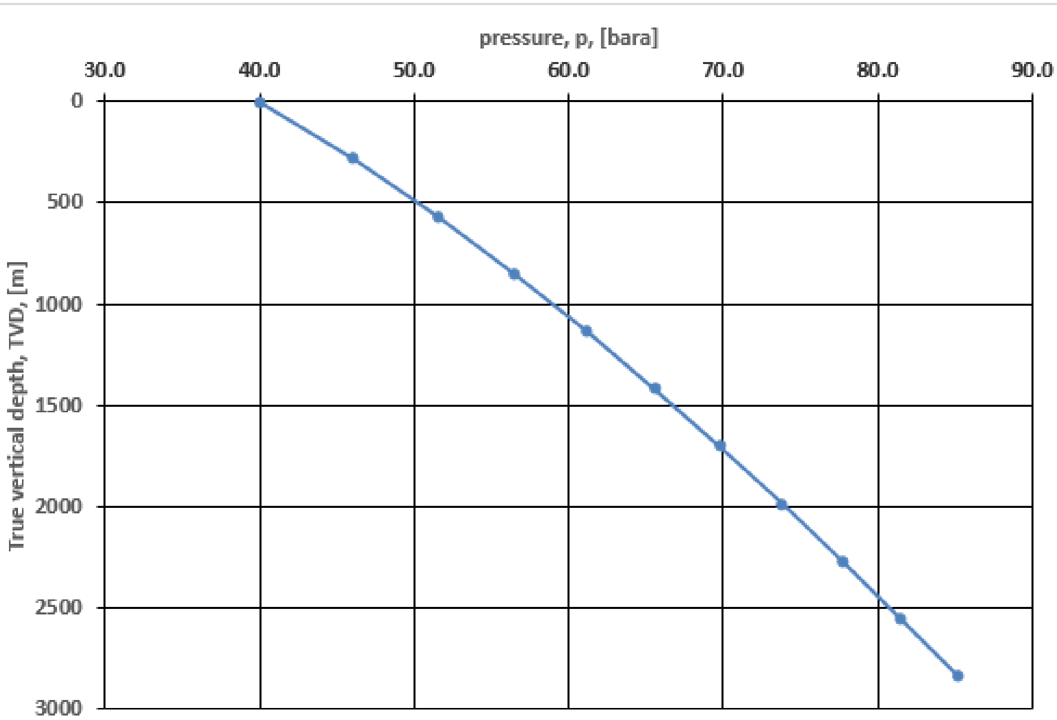
from equilibrium analysis $P_{wf\,eq} = 84.375$ bara

$P_{wh} = 40$ bar

$\boxed{\text{i assume}}$ $\Delta p = \text{const}$ for every section.

$$\Delta p = \frac{(P_{wf\,eq} - P_{wh})}{N_{section}} = \frac{84.378 - 40}{10}$$

Tubing MD [m]	2837							
Tubing TVD [m]	2837							
Tubing ID [m]	0.157							
Tubing Cross section A [m^2]	0.019							
Wellhead pressure [bara]	40							
Gas gravity	0.55							
Twf [K]	378	104.85						
Twh [K]	360	86.85						
pR [bara]	304			DP	4.4378			
friction factor [-]	0.012							
qg [Sm^3/d]	2.85E+06							
liquid density [kg/m^3]	8.97E+02							
TVD	T	Tav	passumed	Pav	Zav	S	Ct	p
[m]	[K]	[K]	[bara]	[bara]	[-]	[-]	[Sm^3/bar]	[bara]
0	360.0	360.9	40.0	42.2	0.967	0.015	1.3E+05	40.0
284	361.8	362.7	44.4	46.7	0.964	0.015	1.3E+05	46.0
567	363.6	364.5	48.9	51.1	0.962	0.015	1.3E+05	51.5
851	365.4	366.3	53.3	55.5	0.960	0.015	1.3E+05	56.5
1135	367.2	368.1	57.8	60.0	0.959	0.015	1.3E+05	61.1
1418	369.0	369.9	62.2	64.4	0.957	0.015	1.3E+05	65.6
1702	370.8	371.7	66.6	68.8	0.956	0.015	1.3E+05	69.8
1986	372.6	373.5	71.1	73.3	0.955	0.015	1.3E+05	73.8
2269	374.4	375.3	75.5	77.7	0.954	0.015	1.3E+05	77.7
2553	376.2	377.1	79.9	82.2	0.954	0.015	1.3E+05	81.4
2837	378.0		84.4					85.1



- Homework Solve this exercise by yourself at home
  find p vs TVD for the well studied in class !
  for $P_{wh} = 40$ bara and $q_g = 2.85\,E6\ Sm^3/d$

Note Title 12.01.2017

Day 5:

- Class exercise. Calculate u_g vs TVD for the example we made yesterday
  - gas velocity

TVD [m]	T [K]	p [bara]	z [-]	B_g	q_g (at p, T)	u_g
0	360	40	zfactStanding	–		
⋮	⋮	⋮		–		
				–		
				–		
				–		
2834	380	85 bara		–		

$q_{\bar{g}}$ (@ S.C) $\cdot B_g(p,T) = q_g$ ← volume rate at local conditions

$u_g = \frac{q_g}{A} = \frac{q_g}{\pi \phi^2} \cdot 4$ ← velocity of gas

z

$\frac{m}{d} \quad \frac{\cancel{d}}{24 \cdot 3600\, s} =$

Tubing MD [m]	2837					
Tubing TVD [m]	2837					
Tubing ID [m]	0.157					
Tubing Cross section A [m^2]	0.019					
Wellhead pressure [bara]	40					
Gas gravity	0.55					
Twf [K]	378	104.85				
Twh [K]	360	86.85				
qg [Sm^3/d]	2.85E+06					
liquid density [kg/m^3]	8.97E+02					
TVD	T	p	Z	Bg	qg_local	V_local
[m]	[K]	[bara]	[-]	[m^3/Sm^3]	[m^3/d]	[m/s]
0	360.0	40.0	0.9678	0.031	8.71E+04	52.1
284	361.8	46.0	0.9644	0.027	7.58E+04	45.3
567	363.6	51.5	0.9616	0.024	6.79E+04	40.6
851	365.4	56.5	0.9595	0.022	6.21E+04	37.1
1135	367.2	61.1	0.9577	0.020	5.75E+04	34.4
1418	369.0	65.6	0.9563	0.019	5.38E+04	32.2
1702	370.8	69.8	0.9552	0.018	5.08E+04	30.4
1986	372.6	73.8	0.9544	0.017	4.82E+04	28.8
2269	374.4	77.7	0.9537	0.016	4.60E+04	27.5
2553	376.2	81.4	0.9533	0.015	4.40E+04	26.3
2837	378.0	85.1	0.9531	0.015	4.23E+04	25.3

Z: VBA funct "zfactStanding"

Bg: VBA func "Bg"

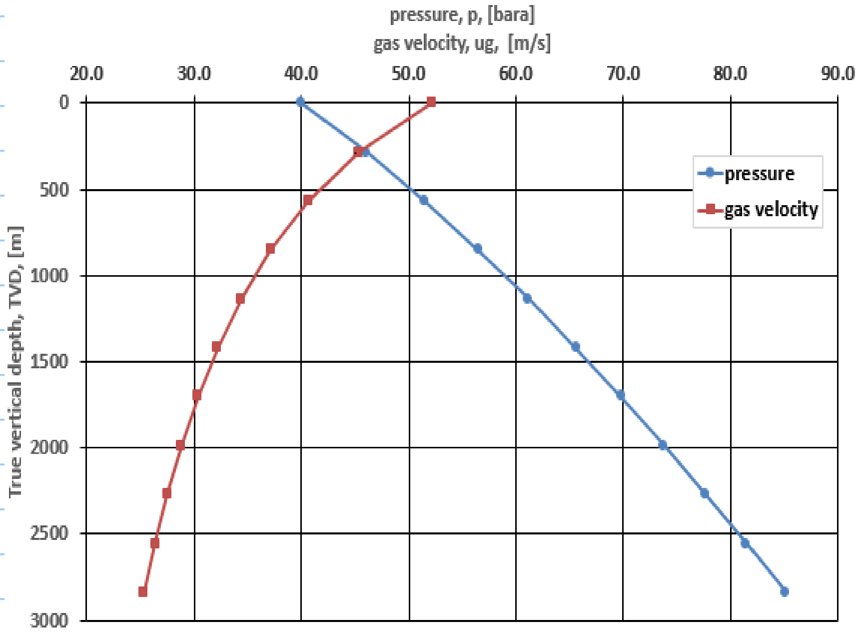
qg_local: $q_{\bar{g}} \cdot B_g$

V_local: $\frac{q_g}{A(24 \cdot 3600)}$

checking if there is erosion in the tubing:

$$u_g \le V_{erosional} = \frac{100}{\sqrt{\rho_g}}$$

API

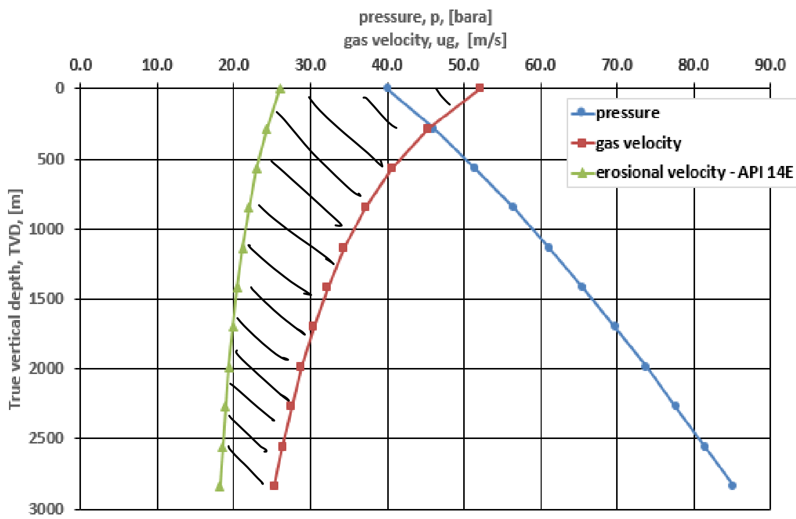


deng(p, T-273.15, Z, ρ_g)

VBA funct

VBA function "Verosional (ρ_g)"

Tubing MD [m]	2837								
Tubing TVD [m]	2837								
Tubing ID [m]	0.157								
Tubing Cross section A [m^2]	0.019								
Wellhead pressure [bara]	40								
Gas gravity	0.55								
Twf [K]	378	104.85							
Twh [K]	360	86.85							
qg [Sm^3/d]	2.85E+06								
liquid density [kg/m^3]	8.97E+02								
TVD	T	p	Z	Bg	qg_local	V_local	deng	Verosional	
[m]	[K]	[bara]	[-]	[m^3/Sm^3]	[m^3/d]	[m/s]	[kg/m^3]	[m/s]	
0	360.0	40.0	0.9678	0.031	8.71E+04	52.1	22.0	26.01	
284	361.8	46.0	0.9644	0.027	7.58E+04	45.3	25.3	24.26	
567	363.6	51.5	0.9616	0.024	6.79E+04	40.6	28.2	22.97	
851	365.4	56.5	0.9595	0.022	6.21E+04	37.1	30.9	21.96	
1135	367.2	61.1	0.9577	0.020	5.75E+04	34.4	33.3	21.13	
1418	369.0	65.6	0.9563	0.019	5.38E+04	32.2	35.6	20.45	
1702	370.8	69.8	0.9552	0.018	5.08E+04	30.4	37.7	19.86	
1986	372.6	73.8	0.9544	0.017	4.82E+04	28.8	39.8	19.35	
2269	374.4	77.7	0.9537	0.016	4.60E+04	27.5	41.7	18.89	
2553	376.2	81.4	0.9533	0.015	4.40E+04	26.3	43.5	18.49	
2837	378.0	85.1	0.9531	0.015	4.23E+04	25.3	45.3	18.13	



Checking Turner criteria. Minimum gas velocity required to lift liquid droplet.

~ constant

$$V = 5.46 \left[\frac{\sigma^{0.25} (\rho_L - \rho_g)^{0.25}}{\rho_g^{0.5}} \right]$$

if $V_g \geq V_{turner}$

from correlation

```
'   Oil-Gas interfacial tension in N/m
Function STog(DenO, deng)
'Density of the oil,kg/m^3
'Density of the gas,kg/m^3

    STog = (567 * (DenO - deng) * 0.001 / 213) ^ 4
    STog = 0.001 * STog
End Function
```

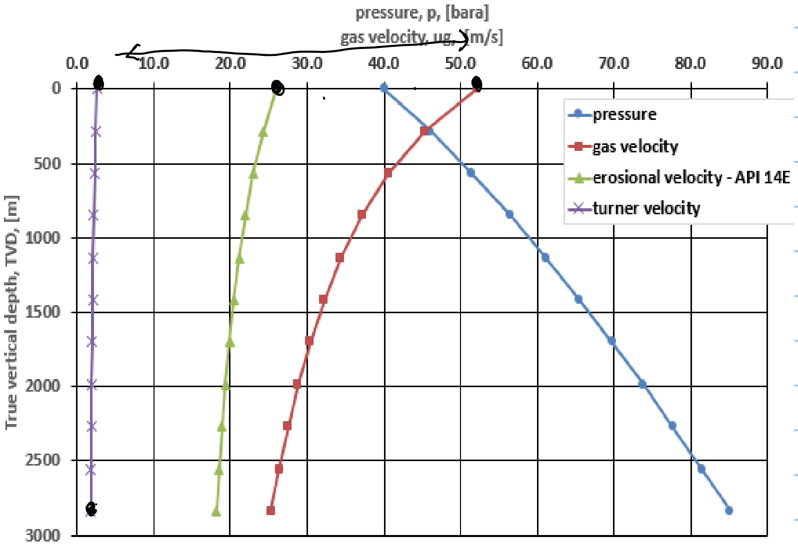
Tubing MD [m]	2837	
Tubing TVD [m]	2837	
Tubing ID [m]	0.157	
Tubing Cross section A [m^2]	0.019	
Wellhead pressure [bara]	40	
Gas gravity	0.55	
Twf [K]	378	104.85
Twh [K]	360	86.85
qg [Sm^3/d]	2.85E+06	
liquid density [kg/m^3]	8.97E+02	

6"

VBA function STog(denl, deng)

VBA function V_turner(ρ_L, ρ_g, σ_g

TVD	T	p	Z	Bg	qg_local	V_local	deng	Verosional	int_ten_o_g	Vturner
[m]	[K]	[bara]	[-]	[m^3/Sm^3]	[m^3/d]	[m/s]	[kg/m^3]	[m/s]	[N/m]	[m/s]
0	360.0	40.0	0.9678	0.031	8.71E+04	52.1	22.0	26.01	0.029	2.6
284	361.8	46.0	0.9644	0.027	7.58E+04	45.3	25.3	24.26	0.029	2.4
567	363.6	51.5	0.9616	0.024	6.79E+04	40.6	28.2	22.97	0.029	2.3
851	365.4	56.5	0.9595	0.022	6.21E+04	37.1	30.9	21.96	0.028	2.2
1135	367.2	61.1	0.9577	0.020	5.75E+04	34.4	33.3	21.13	0.028	2.1
1418	369.0	65.6	0.9563	0.019	5.38E+04	32.2	35.6	20.45	0.028	2.0
1702	370.8	69.8	0.9552	0.018	5.08E+04	30.4	37.7	19.86	0.027	2.0
1986	372.6	73.8	0.9544	0.017	4.82E+04	28.8	39.8	19.35	0.027	1.9
2269	374.4	77.7	0.9537	0.016	4.60E+04	27.5	41.7	18.89	0.027	1.9
2553	376.2	81.4	0.9533	0.015	4.40E+04	26.3	43.5	18.49	0.027	1.8
2837	378.0	85.1	0.9531	0.015	4.23E+04	25.3	45.3	18.13	0.026	1.8



offshore gas well

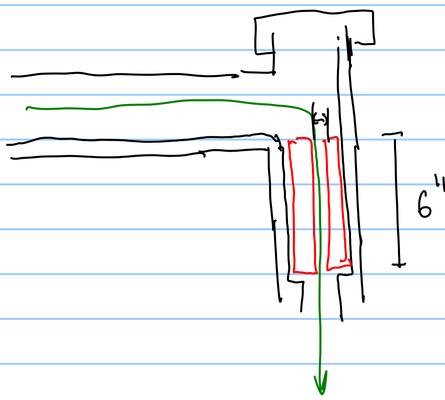
typical production

3 E6 Sm^3/d

30 MMscf/d

Production choke — types:
- Positive / bean choke
- Adjustable

Bean

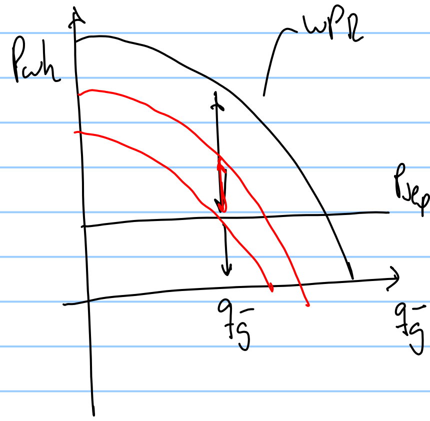


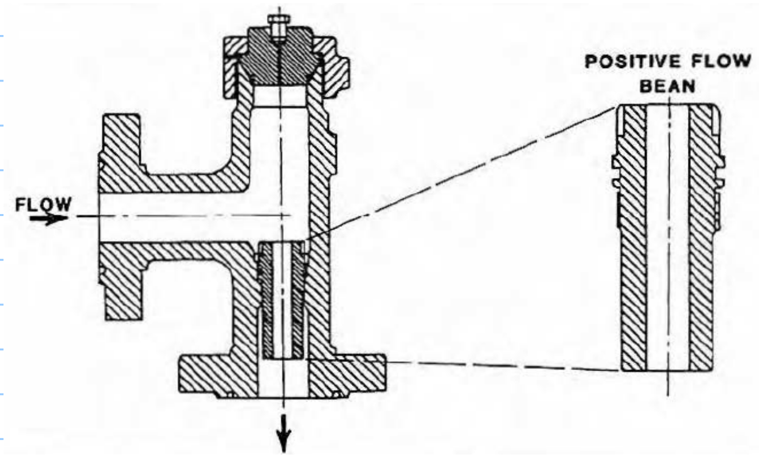
orifice size

1/8" → 2"

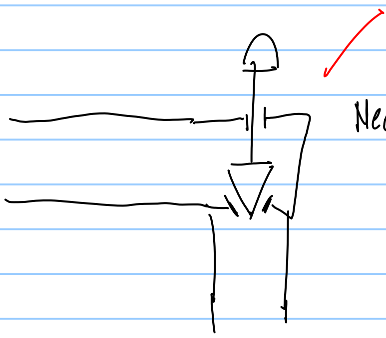
Steps 1/64"

$\frac{8}{64}$" → $\frac{256}{64}$"

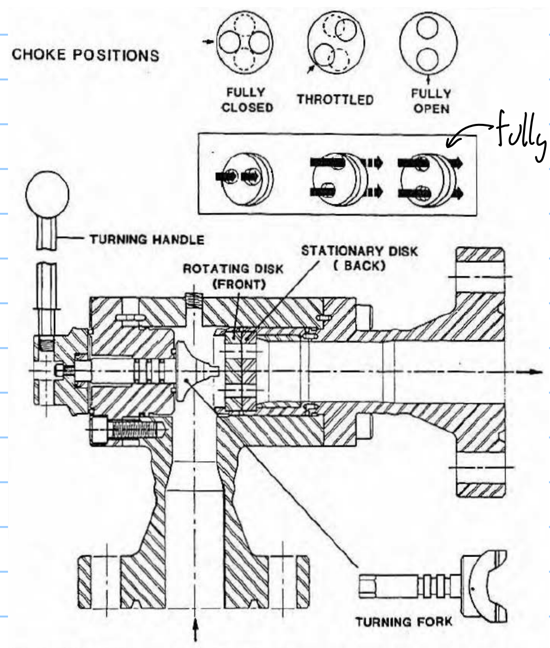




Adjustable



Needle choke , Rotary disk

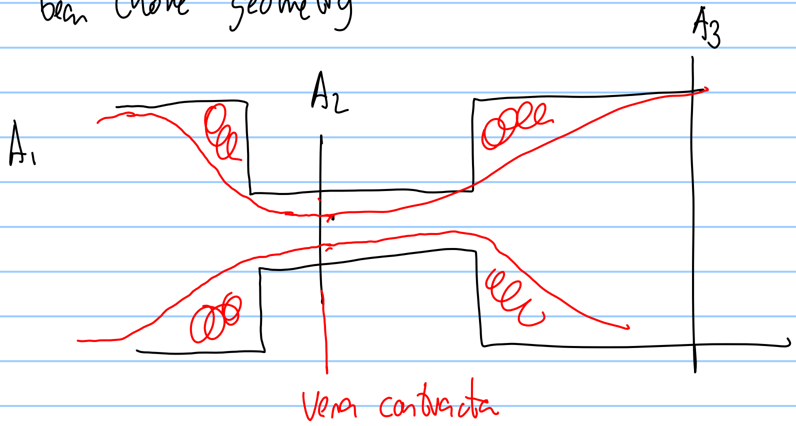


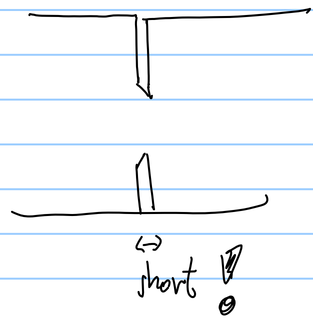
fully choked

Cage choke

focusing on bean choke geometry

Different than orifice for metering !





main function of choke : dissipate a lot of energy in a concentrated place ↓p

→ control production !

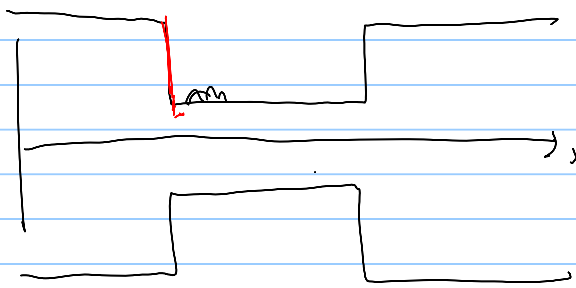
undesired consequences

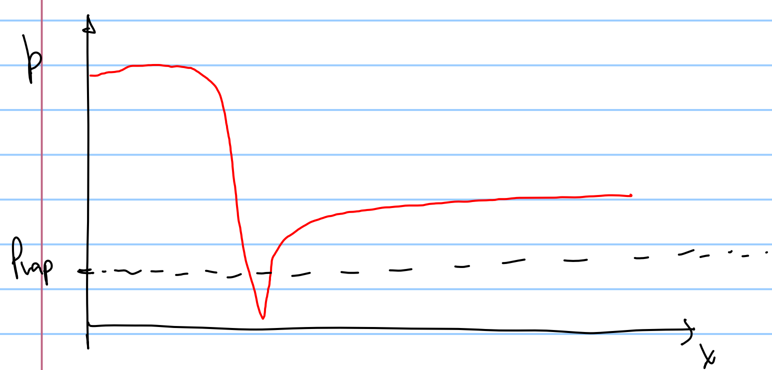
→ p drops ⇝ in oil you get gas vaporization
⇝ if gas you get liquid condensation

→ erosion ⇝ due to high velocities in chokes
sand - worsens the problem.

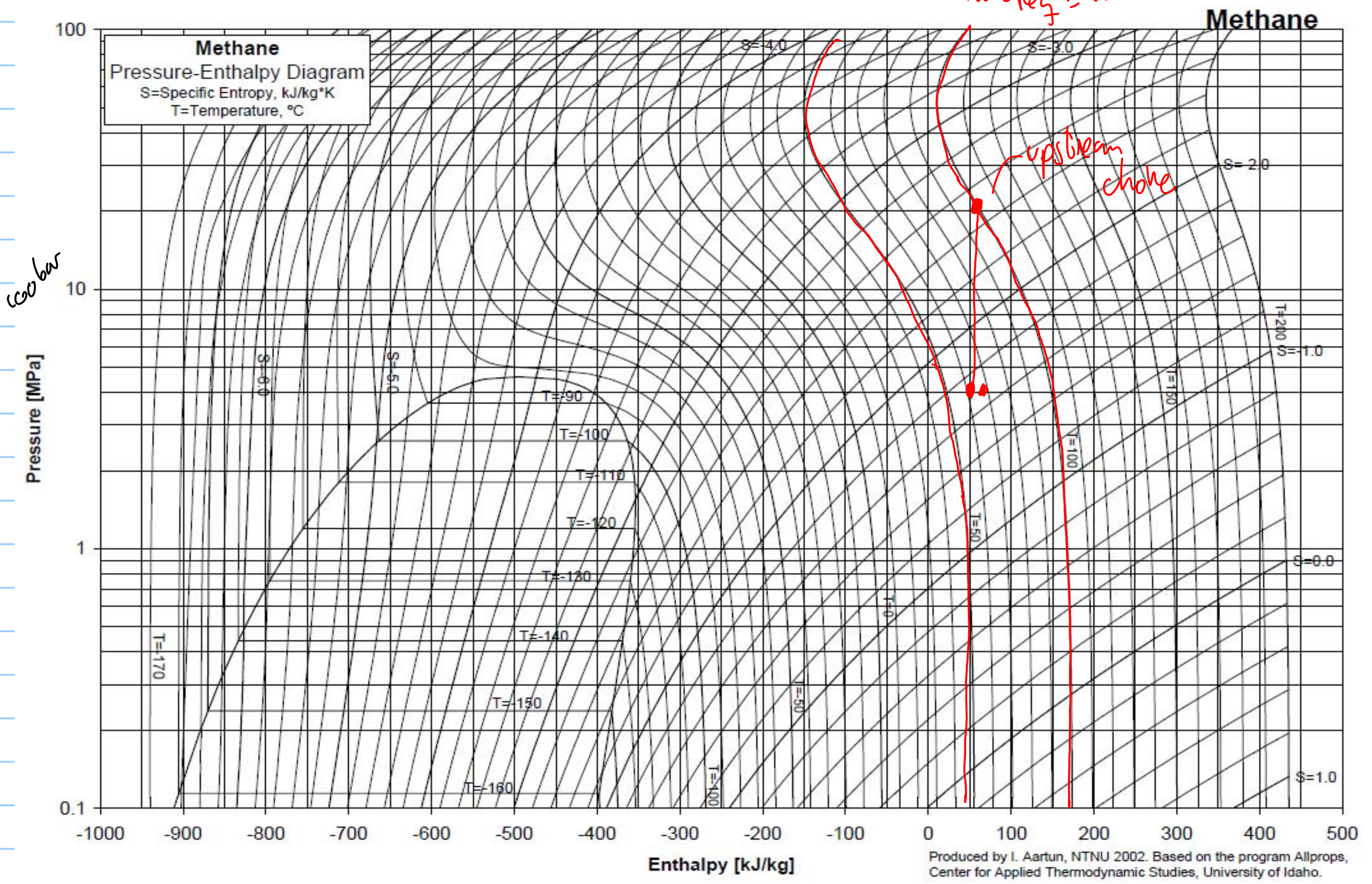
→ cooling ⇝ for gas Joule-Thomson effect
⇝ more liquid condensation
⇝ free water + low T ⇝ ice block !

→ cavitation.





p vs. h diagram

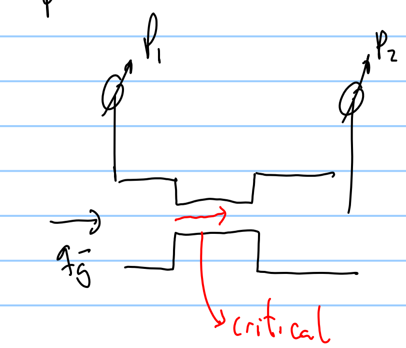


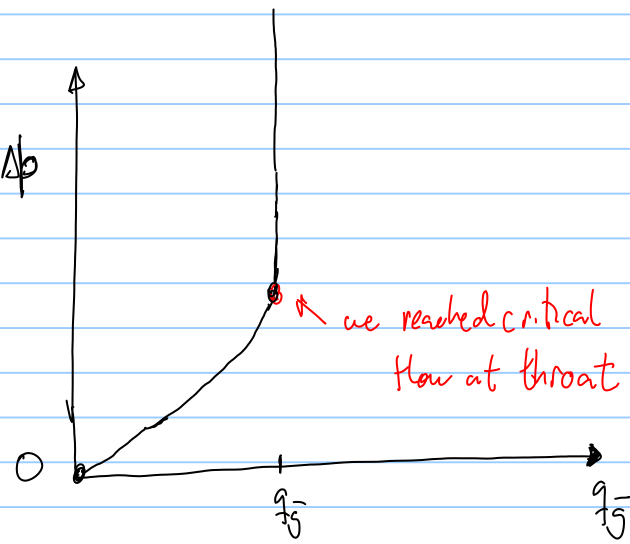
the process in the choke is isenthalpic !! (no $\dot{q}$ or $\dot{w}$ transferred out of the control volume)

1st law of thermodynamics for open systems $\dot{m}(h_2 - h_1) = \dot{q} - \dot{w}$, with $\dot{q} = 0$ and $\dot{w} = 0$, so $\boxed{h_2 = h_1}$!

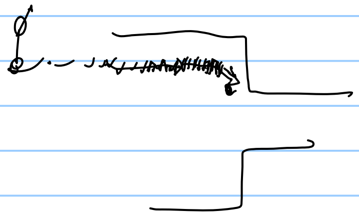
Experiment

p_1 is fixed





velocity of sound in a real gas $a = \sqrt{\frac{kRTZ}{Mw}}$



$k = \frac{C_p}{C_v}$

a $k = 1.6$

$R = 8314.3$

$T = 80 + 273.15$

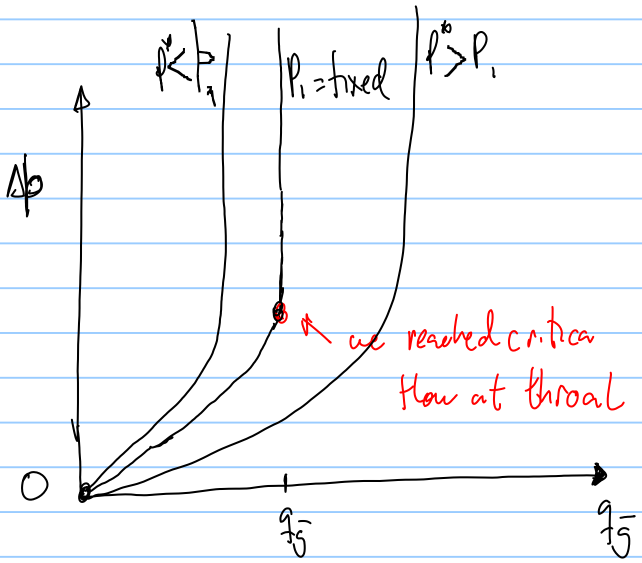
$M = 16$

as a rule of thumb critical pressure ratio is

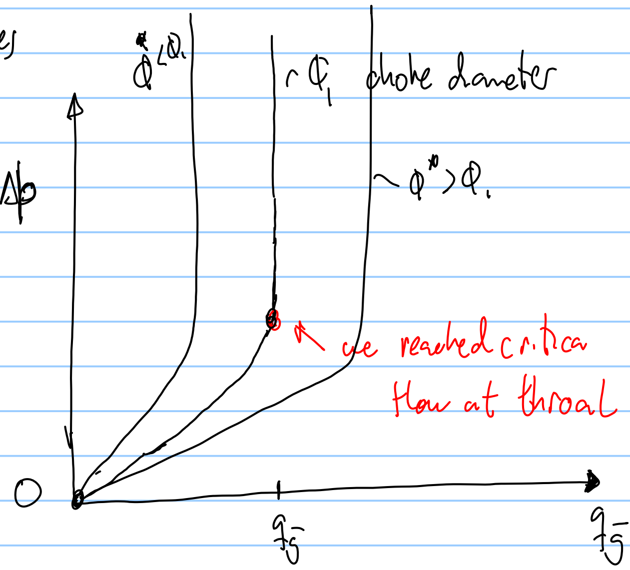
$a \approx 542$ m/s

$\frac{P_2}{P_1} \approx 0.5$ ✓

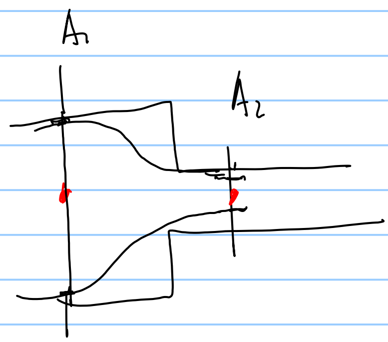
in gas $\left(\frac{P_2}{P_1}\right)_c = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$



if the orifice changes



Choke equation for liquid:



$dp + \rho \frac{2}{2} u\,du + \rho g \cancel{dz}^{\,0} = 0$

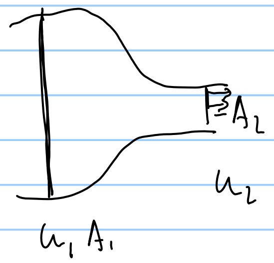
distance short   no frictional losses

$$\int_1^1 \frac{dp}{\rho} + \int_1^2 u\,du = 0$$

$$p_2 - p_1 = \rho_L \cdot 0.5 \cdot (u_1^2 - u_2^2)$$

$\underbrace{q_{sc} \text{ vs } \Delta p}$

mass balance



$$u_2 \cdot A_2 = u_1 A_1 \qquad A_1 = \frac{\pi \cdot d_1^2}{4}$$

$$(u_1)^2 = \left(\frac{d_2^2}{d_1^2}\right)^2 (u_2)^2 \qquad \beta = \frac{d_2}{d_1} \qquad A_2 = \frac{\pi\, d_2^2}{4}$$

$$u_1^2 = \beta^4 u_2^2$$

$$p_2 - p_1 = \rho_L\, 0.5 \left(\beta^4 u_2 - u_2^2\right)$$

$$\frac{\Delta p\; 2}{\rho_L (1-\beta^4)} = u_2^2 \qquad u_2 = \sqrt{\frac{\Delta p\, 2}{\rho_L (1-\beta^4)}}$$

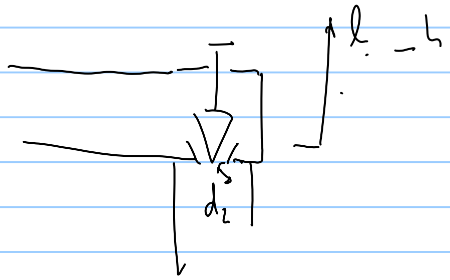
$$q_{sc} = \underbrace{u_2 \cdot A_2}\, C_d$$

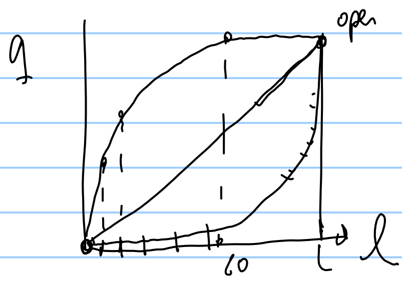
flow coefficient to account for vena contracta

$$\boxed{q = A_2\, C_d \sqrt{\frac{\Delta p\; 2}{\rho_L (1-\beta^4)}}}$$

in adjustable chokes d_2 is changing

$$q = f(\ell) \cdot C_d \sqrt{\frac{\Delta p \cdot 2}{\rho}}$$





if Δp is fixed

Derivation of choke equation for gas $\rightsquigarrow$ orifice

$$\int_1^2 \frac{dp}{\rho} + \int_1^2 u\,du \qquad \int_1^2 \frac{dp}{\rho} = 0.5\left(u_1^2 - u_2^2\right)$$

$$u_2 \gg u_1 \qquad u_2^2 \gg u_1^2$$

$$u_2^2 - u_1^2 \approx u_2^2$$

$$\rho = \frac{p\,M_w}{zRT}$$

$$pv^n = \text{constant}$$

$$n = k$$

adiabatic:

$$p\frac{1}{\rho^k} = \text{constant} = C \qquad \rho = \frac{p^{1/k}}{C^{1/k}}$$

$$C^{1/k}\int_1^2 \frac{dp}{p^{1/k}} = C^{1/k}\left(\frac{k}{k-1}\right)\left(p_2^{\frac{k-1}{k}} - p_1^{\frac{k-1}{k}}\right)$$

$$C^{1/k}\frac{k}{k-1}\,p_1^{\frac{k-1}{k}}\left(\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right) \qquad y = \frac{p_2}{p_1}$$

$$C^{1/k} = \frac{p_1^{1/k}}{\rho_1}$$

$$-u_2^2 = 2\frac{p_1}{\rho_1}\frac{k}{k-1}\left(y^{\frac{k-1}{k}} - 1\right) \qquad \rho_1 = \frac{p_1 M_w}{RZ_1T_1}$$

$$u_2 = \sqrt{2\frac{\cancel{p_1}\,RZ_1T_1}{\cancel{p_1}\,M_w}\left(\frac{k}{k-1}\right)\left(y^{\frac{k-1}{k}} - 1\right)}$$

$$\rho_1 = \frac{p_1 M_w}{RZ_1T_1}$$

$$u_2 = \frac{\dot{m}}{\rho_2 \cdot C_d A_2} \qquad p\rho^k = \text{Constant}$$

$$p_1\rho_1^k = p_2\rho_2^k \qquad \rho_2 = \left(\frac{p_1}{p_2}\right)^{1/k}\rho_1$$

$$\dot{m} = q_{sc} \cdot \rho_{sc} \qquad \rho_{sc} = \frac{p_{sc} M}{T_{sc}\, \cancel{Z}\, R}, \quad Z = 1$$

$$q_{sc} = c_d A_2 p_1 \left(\frac{T_{sc}}{p_{sc}}\right) \sqrt{2 \frac{R}{M_g Z_1 T_1}} \sqrt{\left(\frac{k}{k-1}\right)\left[(y)^{\frac{2}{k}} - (y)^{\frac{k+1}{k}}\right]}$$

$$A_2 = \frac{\pi d_2^2}{4}$$

if $y \geq y_c$ (≈ 0.5)

then use this equation

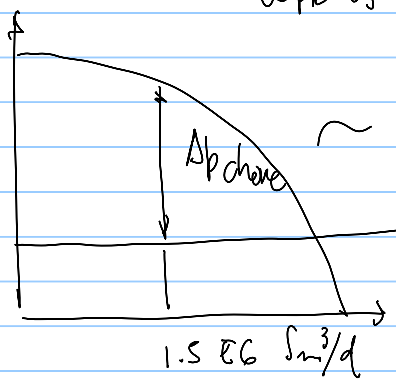
if $y \leq y_c$

then use this equation with

$y = y_c$

Exercise I performed

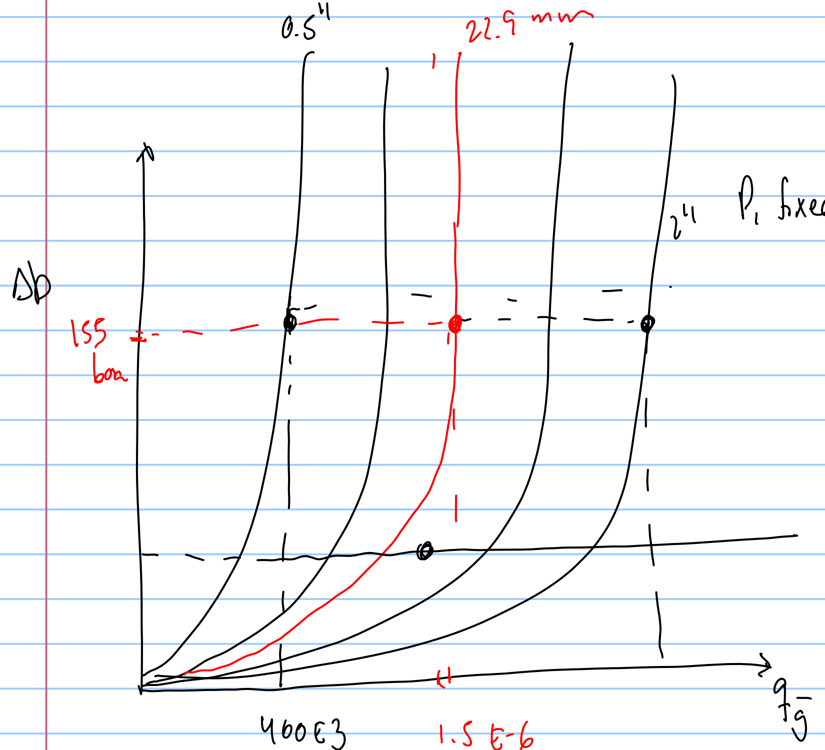
WPR vs P_{sep}

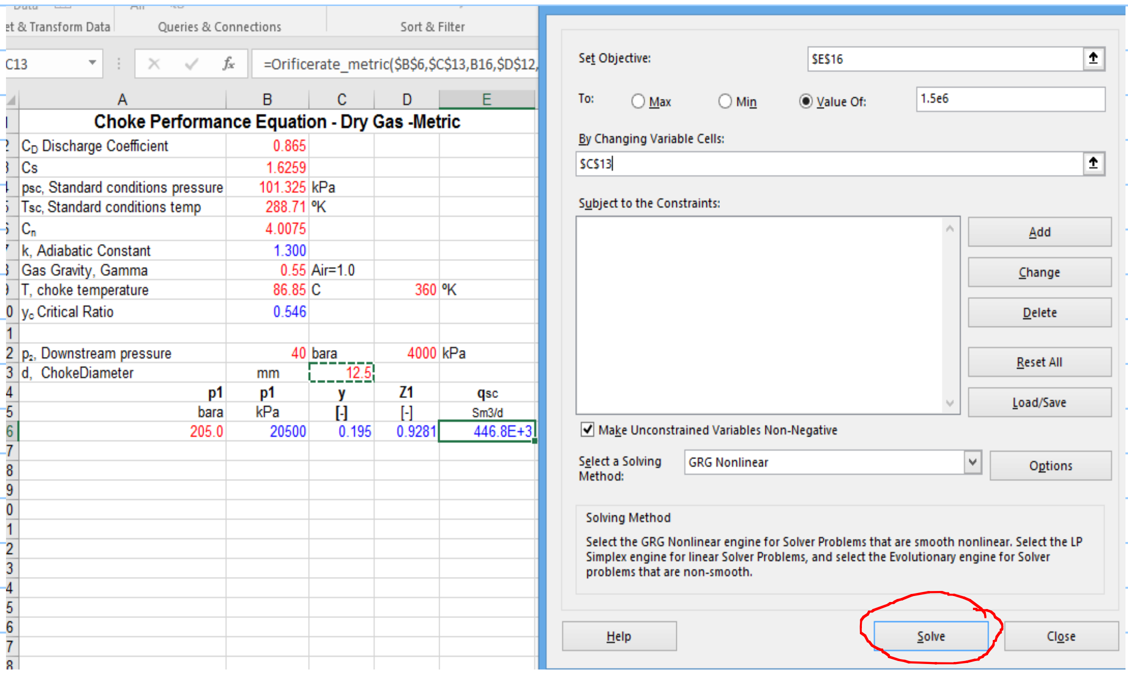


$p_{wh\,avail} = 205$ bara

$p_{wh\,req} = 40$ bara

$\Delta p = 155$ bara





Choke Performance Equation - Dry Gas -Metric

C_D Discharge Coefficient	0.865			
Cs	1.6259			
psc, Standard conditions pressure	101.325	kPa		
Tsc, Standard conditions temp	288.71	ºK		
C_n	4.0075			
k, Adiabatic Constant	1.300			
Gas Gravity, Gamma	0.55	Air=1.0		
T, choke temperature	86.85	C	360	ºK
y_c Critical Ratio	0.546			
p_2, Downstream pressure	40	bara	4000	kPa
d, ChokeDiameter	mm	22.90383		
p1	p1	y	Z1	qsc
bara	kPa	[-]	[-]	Sm3/d
205.0	20500	0.195	0.9281	1.5E+6

Home exercise

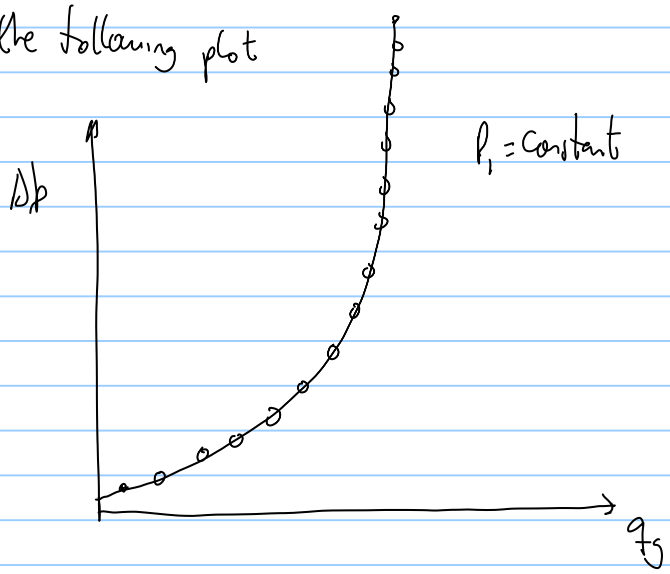
Using the same data shown before

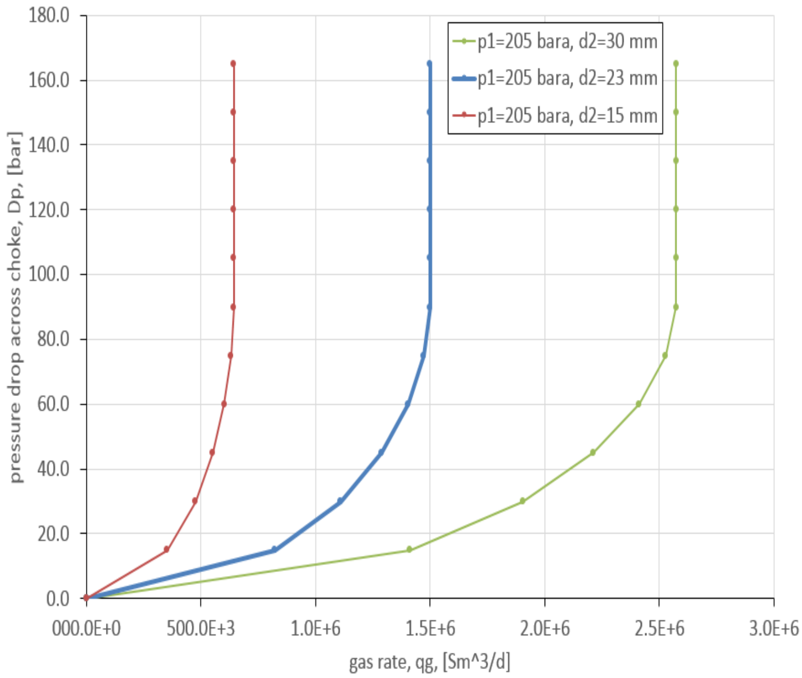
$P_1 = 205$ bara

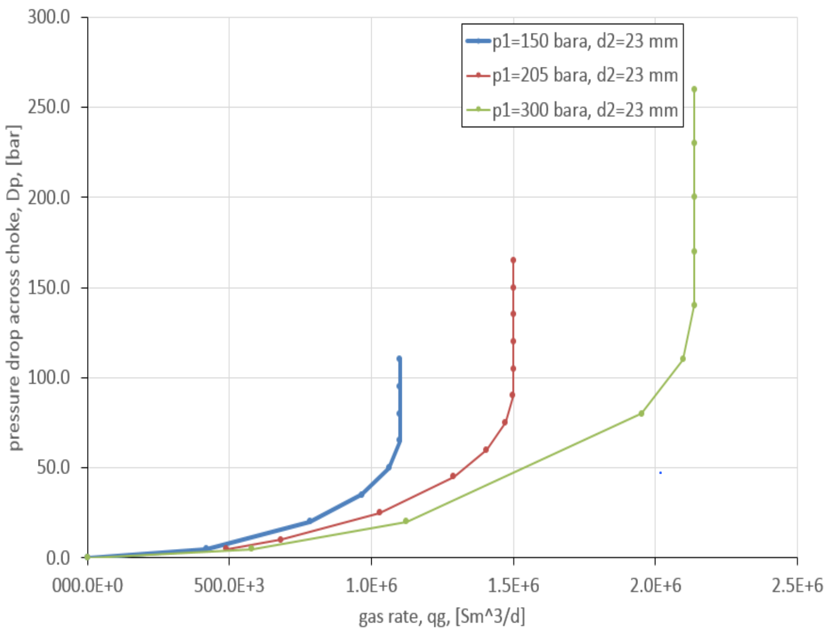
$P_2 = 40$ bara

$d_2 = 22.9$ mm

make the following plot



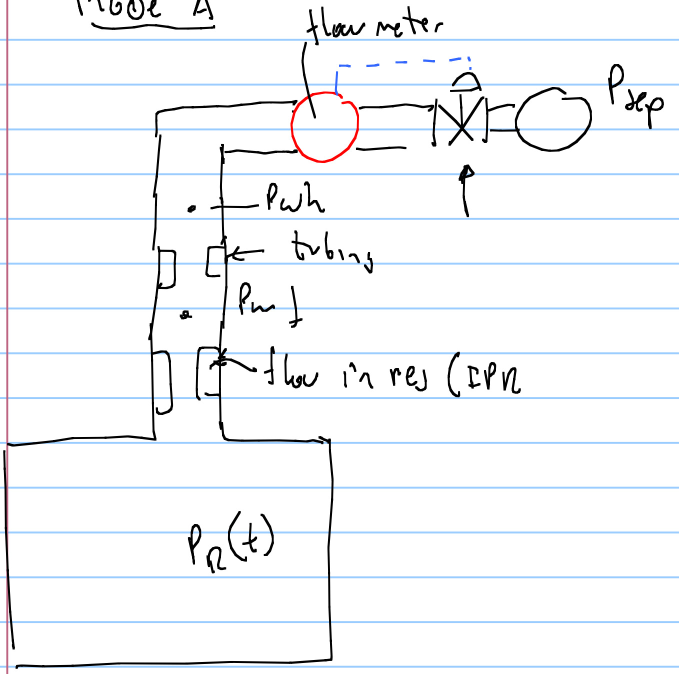

p1=205 bara, d2=30 mm
p1=205 bara, d2=23 mm
p1=205 bara, d2=15 mm
pressure drop across choke, Dp, [bar]
gas rate, qg, [Sm^3/d]
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
000.0E+0
500.0E+3
1.0E+6
1.5E+6
2.0E+6
2.5E+6
3.0E+6


p1=150 bara, d2=23 mm
p1=205 bara, d2=23 mm
p1=300 bara, d2=23 mm
pressure drop across choke, Dp, [bar]
gas rate, qg, [Sm^3/d]
300.0
250.0
200.0
150.0
100.0
50.0
0.0
000.0E+0
500.0E+3
1.0E+6
1.5E+6
2.0E+6
2.5E+6

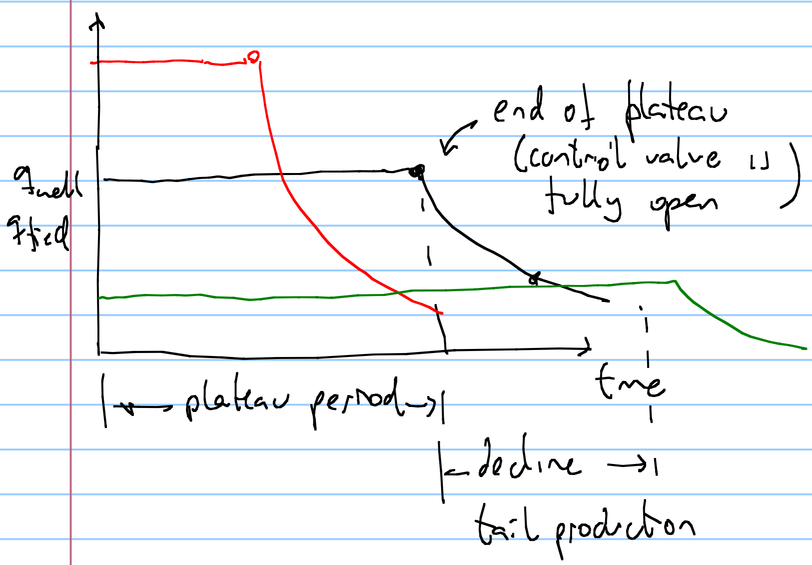
Week 2 _ Day 6:

Production modes of wells and field

MODE A

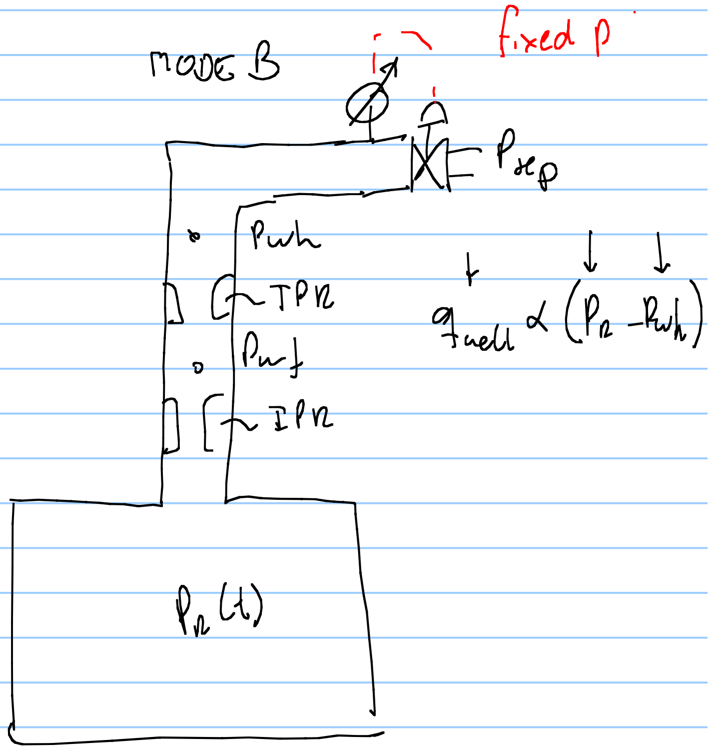


Constant production mode

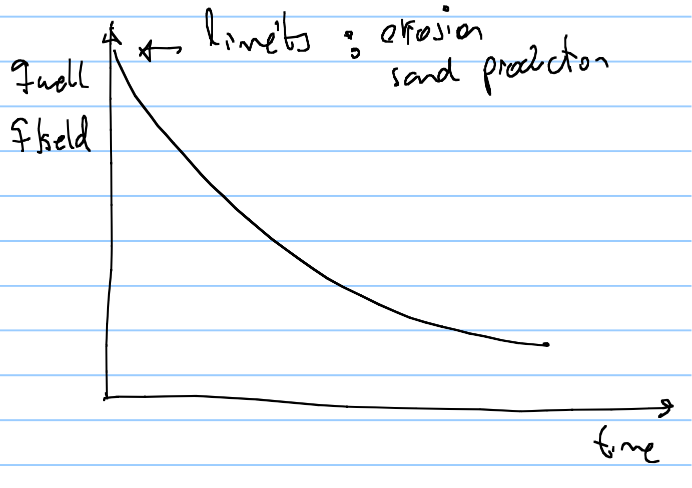


- New development with standalone processing facilities
- Big size
- typically for gas (offshore), LNG
  predefined delivery contract
  long term

MODE B



constant pressure mode



- Produce as much as possible as early as possible
- Satellite fields (medium to small size)

the production is routed to existing processing facilities with spare capacity

Rule of thumb for defining plateau for oil reservoirs:

yearly outtake = 0.1 . TRR (total recoverable reserve)

$TRR = R.F. \cdot G$ (initial gas in place)

$R.F. \cdot N$ (initial oil in place)

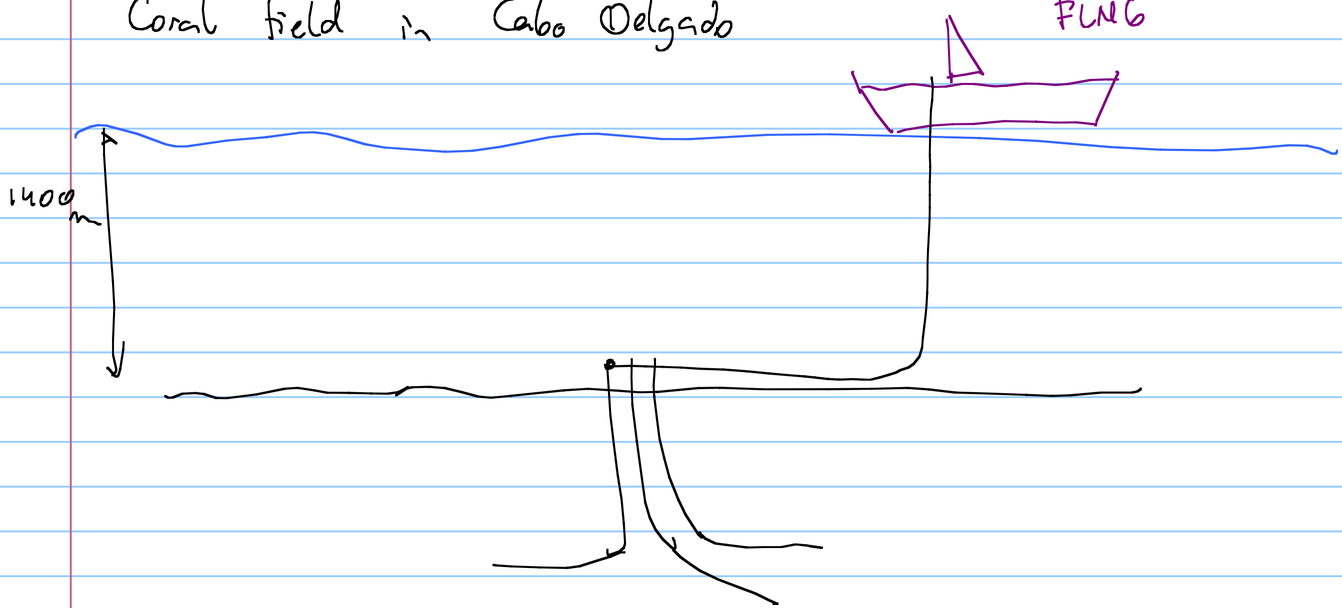
R.F.: recovery factor

$$q_{plateau} = \frac{0.1\ TRR}{N_{operational\ days\ per\ year}}$$

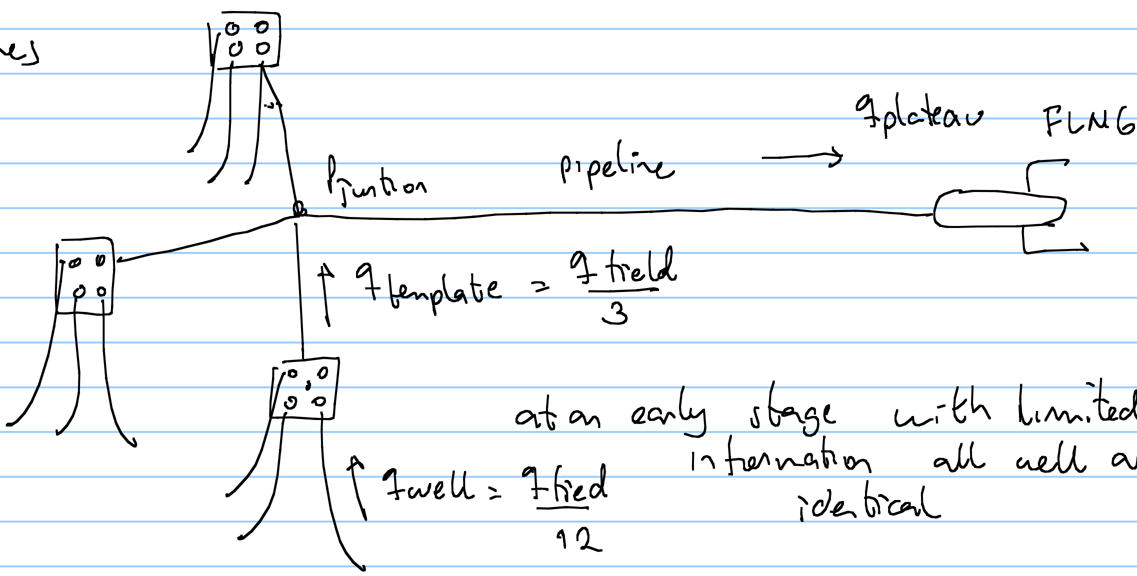
for gas

yearly outtake = (0.03-0.05) TRR

Coral field in Cabo Delgado

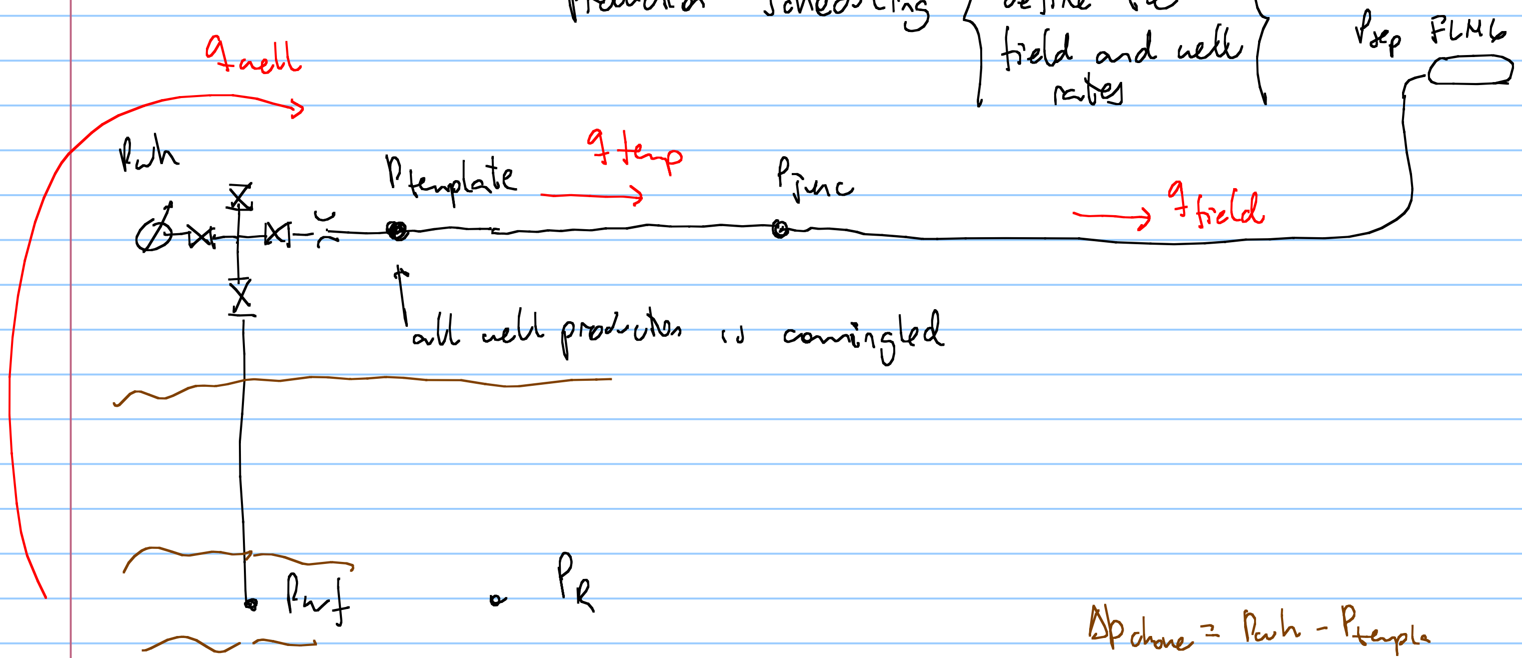


identical flowlines

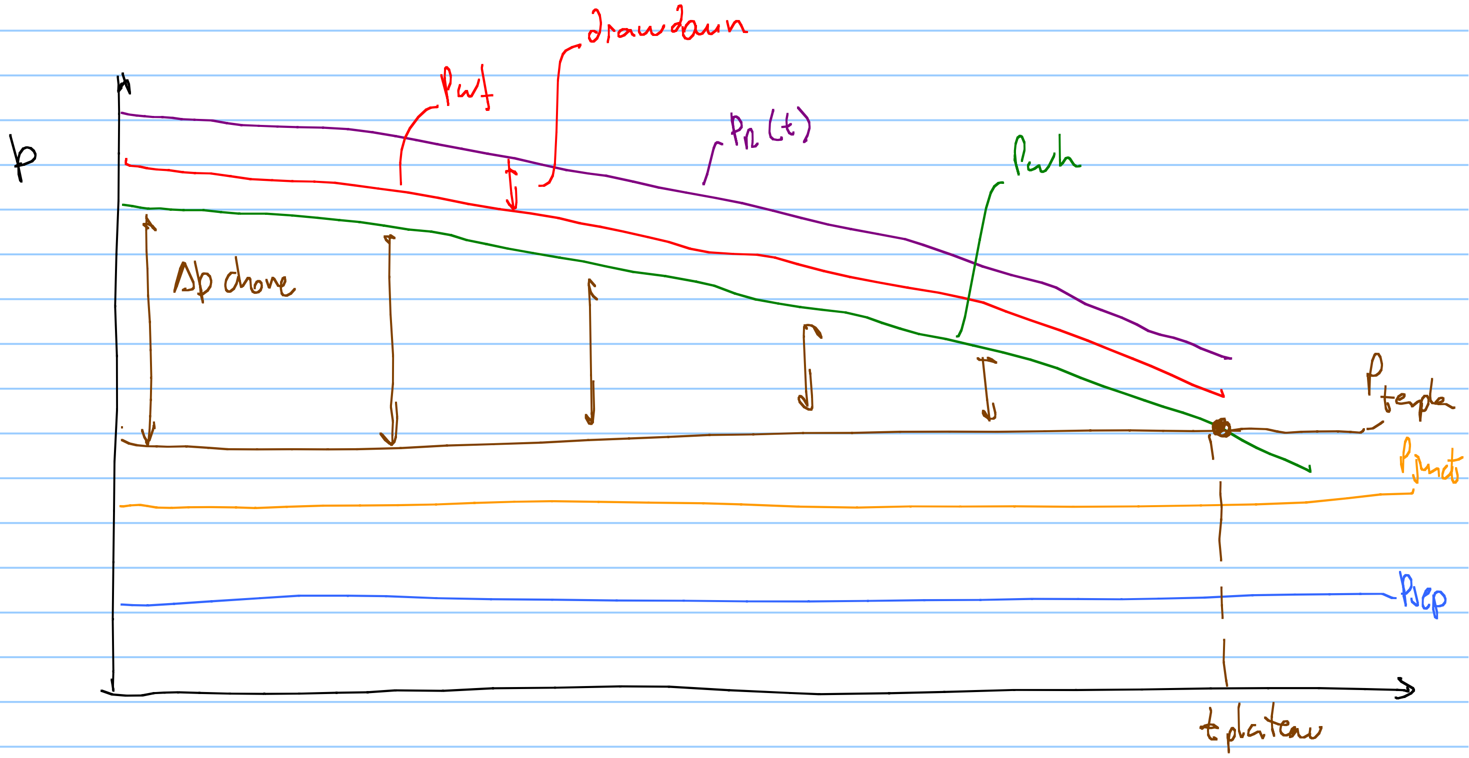


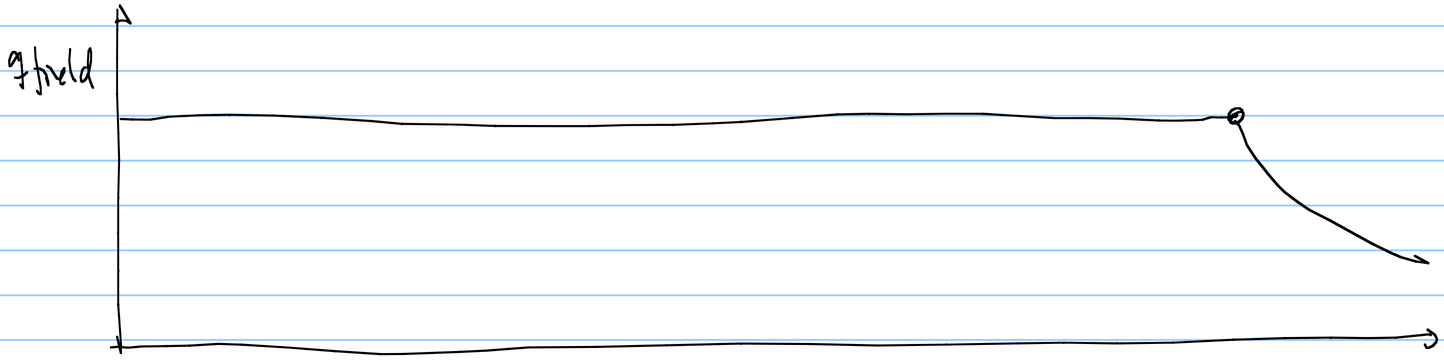
at an early stage with limited information all well are identical

Production scheduling {define the field and well rates}

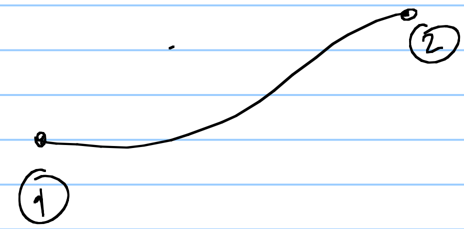


$\Delta p_{choke} = P_{wh} - P_{template}$





- **Pressure drop for liquids**: undersaturated oil + water



$$\underbrace{z_1 + \cancel{\frac{1}{2}\frac{v_1^2}{g}} + \frac{P_1}{\rho g}} = \frac{P_2}{\rho g} + z_2 + \cancel{\frac{1}{2}\frac{v_2^2}{g}} + f\frac{L}{\phi}\frac{v^2}{2g}$$

tubing $P_1 = f(P_2, q)$

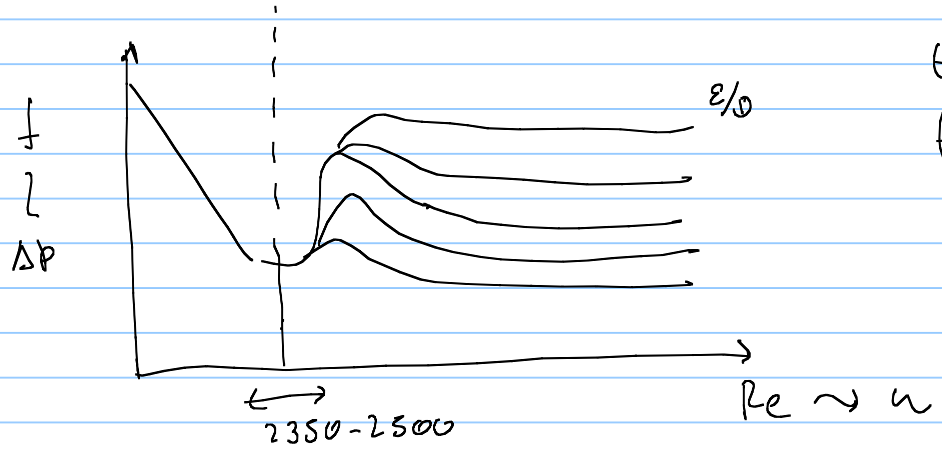
tubing $P_2 = f(P_1, q)$

tubing $q = f(P_1, P_2)$

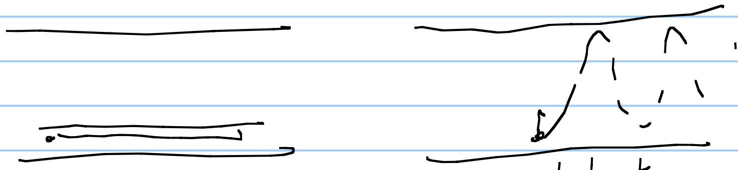
$$q = v \cdot A = \frac{\pi\phi^2}{4} \cdot v$$

$$v = \left(\frac{q}{\pi\phi^2} \cdot 4\right)$$

$$v^2 = \frac{q^2 \, 16}{\pi\phi^2}$$



laminar



laminar turbulent

$$f_{laminar} = \frac{64}{Re} \qquad f_{turbulent} =$$

Colebrook-White equation

implicit $\rightarrow$ $$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7\,\phi} + \frac{2.51}{Re\sqrt{f}}\right)$$

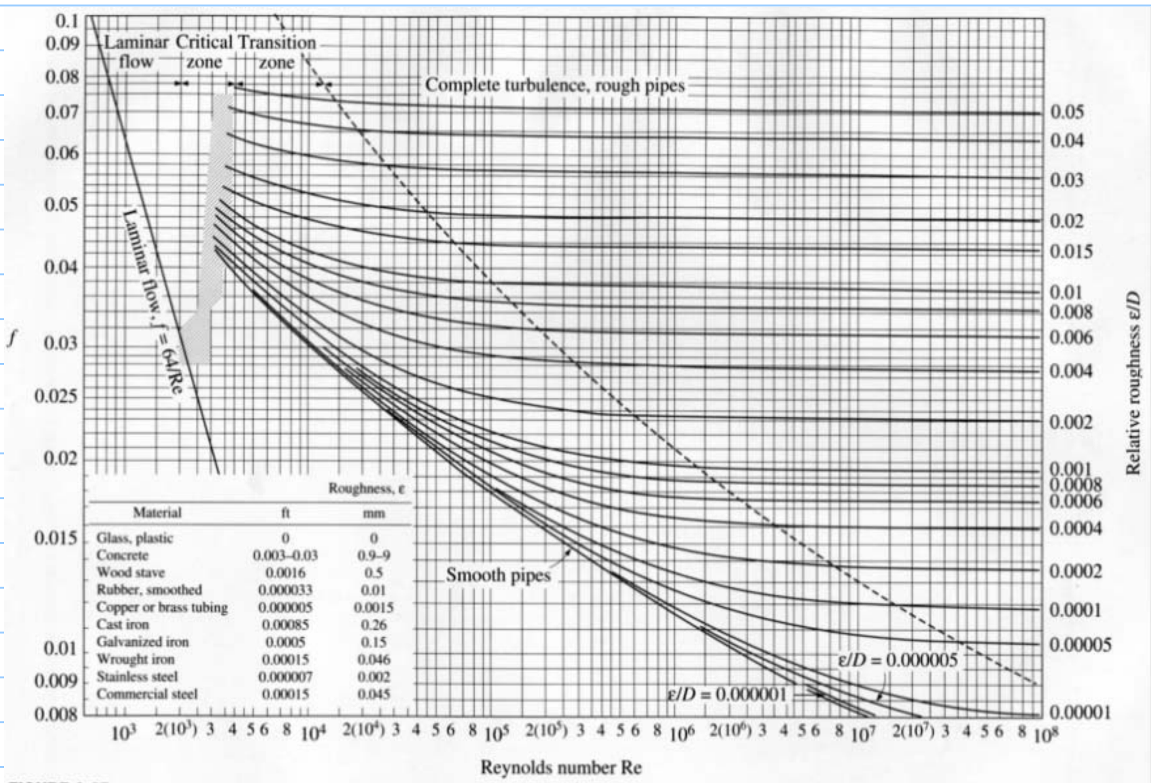


FIGURE A-27
The Moody chart for the friction factor for fully developed flow in circular tubes.

https://en.wikipedia.org/wiki/Darcy_friction_factor_formulae all expressions for friction factor

Table of Colebrook equation approximations

Equation	Author	Year	Range	Ref
$f = .0055\left[1+\left(2\times10^4\cdot\frac{\varepsilon}{D}+\frac{10^6}{\mathrm{Re}}\right)^{\frac{1}{3}}\right]$	Moody	1947	$Re = 4000 - 5.10^8$ $\varepsilon/D = 0 - 0.01$	
$f = .094\left(\frac{\varepsilon}{D}\right)^{0.225} + 0.53\left(\frac{\varepsilon}{D}\right) + 88\left(\frac{\varepsilon}{D}\right)^{0.44}\cdot \mathrm{Re}^{-\Psi}$ where $\Psi = 1.62\left(\frac{\varepsilon}{D}\right)^{0.134}$	Wood	1966	$Re = 4000 - 5.10^7$ $\varepsilon/D = 0.00001 - 0.04$	
$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.715}+\frac{15}{\mathrm{Re}}\right)$	Eck	1973		
$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{5.74}{\mathrm{Re}^{0.9}}\right)$	Swamee and Jain	1976	$Re = 5000 - 10^8$ $\varepsilon/D = 0.000001 - 0.05$	
$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.71}+\left(\frac{7}{\mathrm{Re}}\right)^{0.9}\right)$	Churchill	1973	Not specified	
$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.715}+\left(\frac{6.943}{\mathrm{Re}}\right)^{0.9}\right)$	Jain	1976		
$f = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12}+\frac{1}{(\Theta_1+\Theta_2)^{1.5}}\right]^{\frac{1}{12}}$ where $\Theta_1 = \left[-2.457\ln\left(\left(\frac{7}{\mathrm{Re}}\right)^{0.9}+0.27\frac{\varepsilon}{D}\right)\right]^{16}$ $\Theta_2 = \left(\frac{37530}{\mathrm{Re}}\right)^{16}$	Churchill	1977		
$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7065}-\frac{5.0452}{\mathrm{Re}}\log\left(\frac{1}{2.8257}\left(\frac{\varepsilon}{D}\right)^{1.1098}+\frac{5.8506}{\mathrm{Re}^{0.8981}}\right)\right]$	Chen	1979	$Re = 4000 - 4.10^8$	
$\frac{1}{\sqrt{f}} = 1.8\log\left[\frac{\mathrm{Re}}{0.135\mathrm{Re}(\varepsilon/D)+6.5}\right]$	Round	1980		
$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{4.518\log\left(\frac{\mathrm{Re}}{7}\right)}{\mathrm{Re}\left(1+\frac{\mathrm{Re}^{0.52}}{29}(\varepsilon/D)^{0.7}\right)}\right)$	Barr	1981		
$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7}-\frac{5.02}{\mathrm{Re}}\log\left(\frac{\varepsilon/D}{3.7}-\frac{5.02}{\mathrm{Re}}\log\left(\frac{\varepsilon/D}{3.7}+\frac{13}{\mathrm{Re}}\right)\right)\right]$ or $\frac{1}{\sqrt{f}} = -2\log\left[\frac{\varepsilon/D}{3.7}-\frac{5.02}{\mathrm{Re}}\log\left(\frac{\varepsilon/D}{3.7}+\frac{13}{\mathrm{Re}}\right)\right]$	Zigrang and Sylvester	1982		
$\frac{1}{\sqrt{f}} = -1.8\log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11}+\frac{6.9}{\mathrm{Re}}\right]$	Haaland[9]	1983		
$\frac{1}{\sqrt{f}} = \Psi_1 - \frac{(\Psi_2-\Psi_1)^2}{\Psi_3-2\Psi_2+\Psi_1}$ or $\frac{1}{\sqrt{f}} = 4.781 - \frac{(\Psi_1-4.781)^2}{\Psi_2-2\Psi_1+4.781}$ where $\Psi_1 = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{12}{\mathrm{Re}}\right)$	Serghides	1984		

$\Psi_2 = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{2.51\Psi_1}{Re}\right)$ $\Psi_3 = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{2.51\Psi_2}{Re}\right)$				
$A = 0.11\left(\frac{68}{Re}+\varepsilon\right)^{0.25}$ if $A \geq 0.018$ then $f = A$ and if $A < 0.018$ then $f = 0.0028 + 0.85A$	Tsal	1989		
$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7}+\frac{95}{Re^{0.983}}-\frac{96.82}{Re}\right)$	Manadilli	1997	$Re = 4000-10^8$ $\varepsilon/D = 0-0.05$	
$\frac{1}{\sqrt{f}} = -2\log\left\{\frac{\varepsilon/D}{3.7065}-\frac{5.0272}{Re}\log\left[\frac{\varepsilon/D}{3.827}-\frac{4.657}{Re}\log\left(\left(\frac{\varepsilon/D}{7.7918}\right)^{0.9924}+\left(\frac{5.3326}{208.815+Re}\right)^{0.9345}\right)\right]\right\}$	Monzon, Romeo, Royo	2002		
$\frac{1}{\sqrt{f}} = 0.8686\ln\left[\frac{0.4587Re}{(S-0.31)^{\frac{S}{(S+1)}}}\right]$ where: $S = 0.124Re\frac{\varepsilon}{D}+\ln(0.4587Re)$	Goudar, Sonnad	2006		
$\frac{1}{\sqrt{f}} = 0.8686\ln\left[\frac{0.4587Re}{(S-0.31)^{\frac{S}{(S+0.9633)}}}\right]$ where: $S = 0.124Re\frac{\varepsilon}{D}+\ln(0.4587Re)$	Vatankhah, Kouchakzadeh	2008		
$\frac{1}{\sqrt{f}} = \alpha - \frac{\alpha+2\log\left(\frac{B}{Re}\right)}{1+\frac{2.18}{B}}$ where $\alpha = \frac{0.744\ln(Re)-1.41}{1+1.32\sqrt{\varepsilon/D}}$ $B = \frac{\varepsilon/D}{3.7}Re+2.51\alpha$	Buzzelli	2008		
$f = \frac{6.4}{(\ln(Re)-\ln(1+.01Re\frac{\varepsilon}{D}(1+10\sqrt{\frac{\varepsilon}{D}})))^{2.4}}$	Avci, Kargoz	2009		
$f = \frac{0.2479-0.0000947(7-\log Re)^4}{(\log\left(\frac{\varepsilon/D}{3.615}+\frac{7.366}{Re^{0.9142}}\right))^2}$	Evangelides, Papaevangelou, Tzimopoulos	2010		
$f = 1.613\left[\ln\left(0.234\varepsilon^{1.1007}-\frac{60.525}{Re^{1.1105}}+\frac{56.291}{Re^{1.0712}}\right)\right]^{-2}$	Fang	2011		
$f = \left[-2\log\left(\frac{2.18\beta}{Re}+\frac{\varepsilon}{3.71}\right)\right]^{-2}, \beta = \ln\frac{Re}{1.816\ln\left(\frac{1.1Re}{\ln(1+1.1Re)}\right)}$	Brkić	2011		
$f = 1.325474505\log_e\left(A-0.8686068432B\log_e\left(A-0.8784893582B\log_e\left(A+(1.665368035B)^{0.8378492157}\right)\right)\right)^{-2}$ where $A = \frac{\varepsilon/D}{3.7065}$ $B = \frac{2.5226}{Re}$	Alashkar	2012		

explicit

Haaland

Prof @ NTNU

~ 1983

$$\frac{1}{\sqrt{f}} = -1.8\log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11}+\left(\frac{6.9}{Re}\right)\right]$$

$$f = \underbrace{\left[-1.8\log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11}+\left(\frac{6.9}{Re}\right)\right]\right]^{-2}}$$

friction factor

Beware !

Darcy - Weisbach $\quad f = 4 \cdot f_{FANNING}$

Fanning (american) $\quad f_{FANNING} = \frac{\tau}{\frac{1}{2}\rho v^2}$

$$f_{DARCY} = \frac{\tau}{\frac{1}{8}\rho v^2}$$

Class exercise IPR-TPR equilibrium for undersaturated oil well

(peregrino field, offshore Brazil).

			IPR		TPR
p_R	bara	231			
J, for oil flow	Sm^3/d/bar	70			
L, tubing length	m	2340	pwf	qo	pwf
d, tubing diameter	m	0.14	[bara]	[Sm^3/d]	[bara]
e, tubing roughness	m	0.00010	231		
teta, tubing angle	[deg]	90	208		
muo, oil viscosity	[Pa s]	0.1	185		
rhoo, oil density	[kg/m^3]	897	162		
pwh, wellhead pressure	[bara]	7	139		
			116		
			92		
			69		
			46		
			23		
			0		

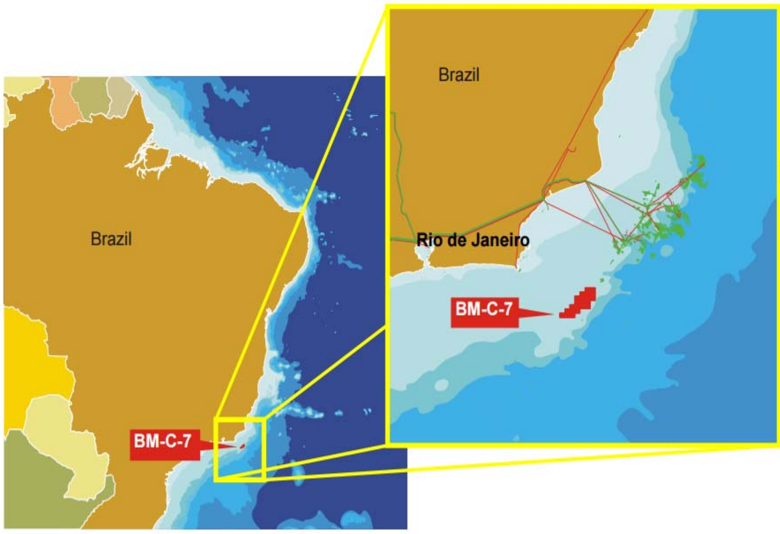
$$q_o = J\,(P_R - P_{wf})$$

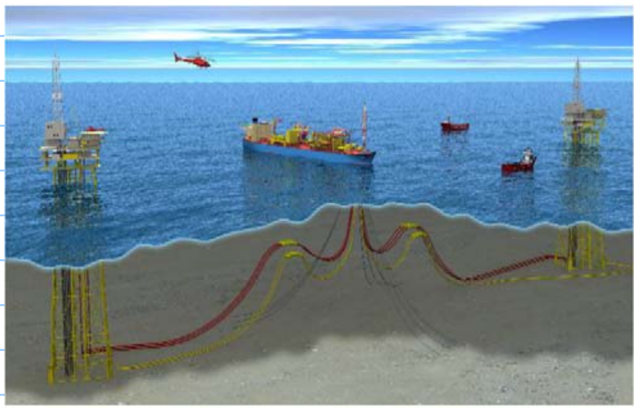
pressure required at well bottom to flow against 7 bara

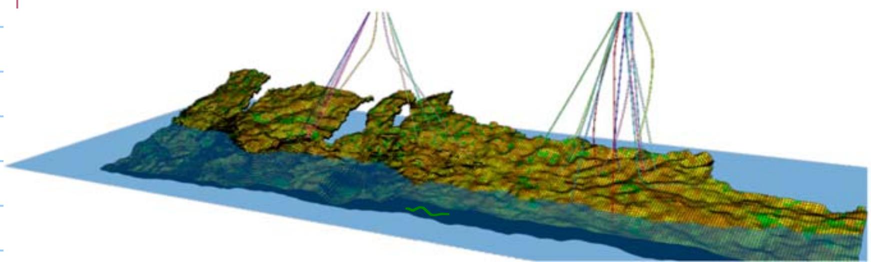
ϕ $P_{wh} = 7$ bara

tubing P_1 ?

tubing P_2 ?







- LQ
- Drilling module
- Movable drill rig
- Electrical plant
- Wellheads
- Booster pumps
- Water Injection
- Uptime 99% bracket

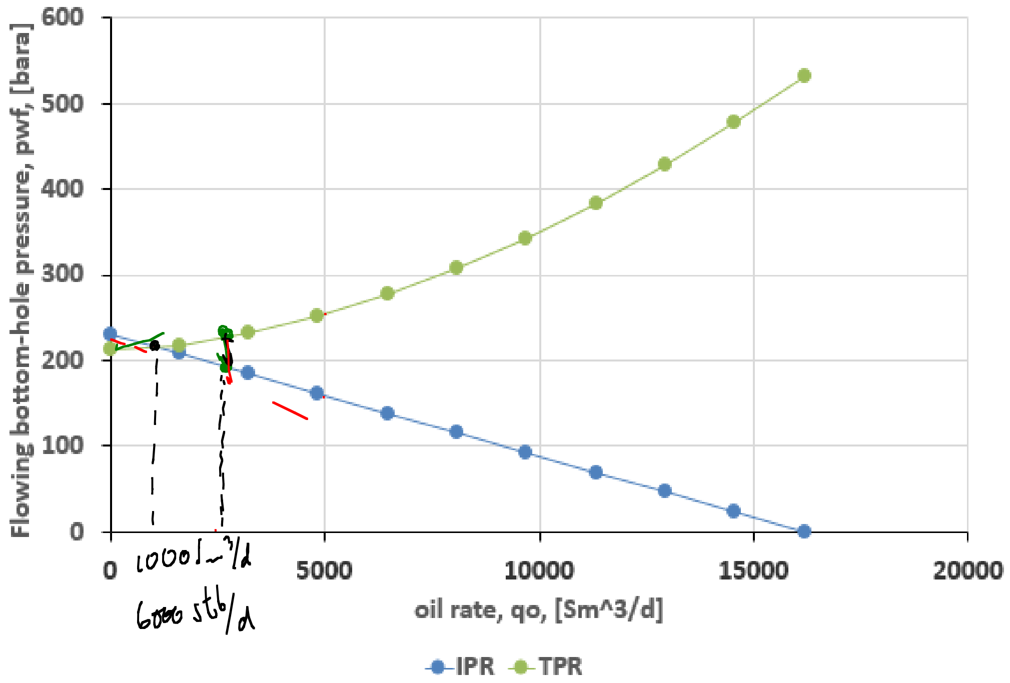
p_R	bara	231
J, for oil flow	Sm^3/d/bar	70
L, tubing length	m	2340
d, tubing diameter	m	0.14
e, tubing roughness	m	0.00010
teta, tubing angle	[deg]	90
muo, oil viscosity	[Pa s]	0.1
rhoo, oil density	[kg/m^3]	897
pwh, wellhead pressure	[bara]	7

IPR		TPR
pwf [bara]	qo [Sm^3/d]	pwf [bara]
231	0	213
208	1618	218
185	3236	233
162	4853	252
139	6471	277
116	8089	307
92	9707	343
69	11325	383
46	12942	428
23	14560	477
0	16178	531

3236 Sm^3/d

$\Delta p_{pump} = 233 - 185$

$\Delta p_{pump} = 48$ bar



Electric submersible pump (ESP) → as close as possible to formation

↳ installed as vertical as possible

↳ takes liquid ONLY !

↳ typical lifetime 2 years

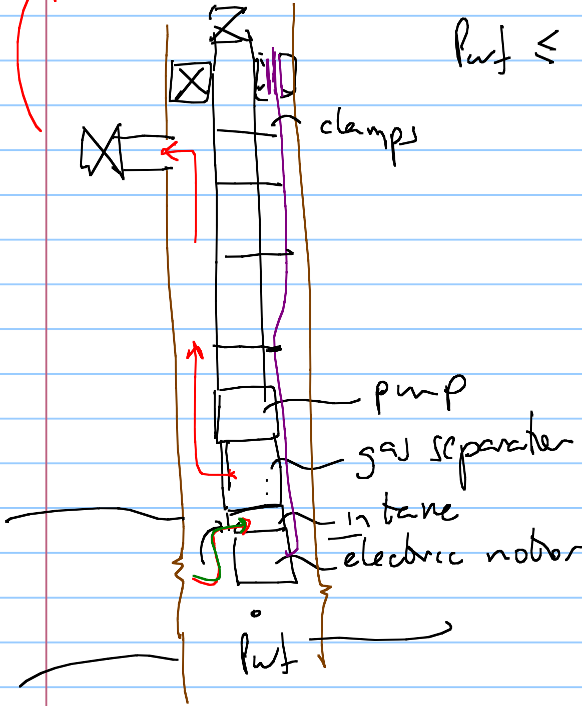
10% GVF high tolerance

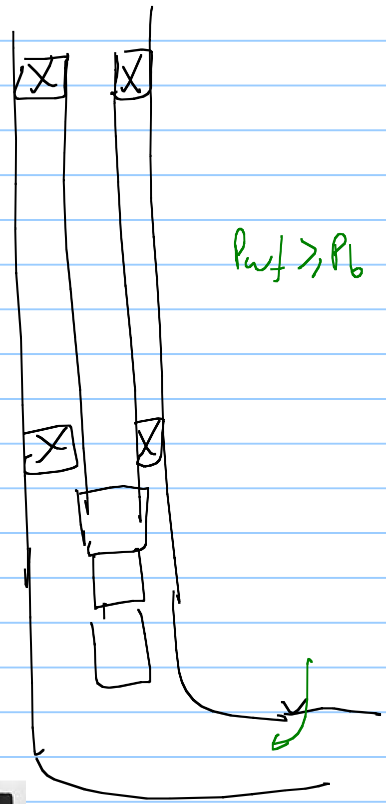
↳ gas volume fraction

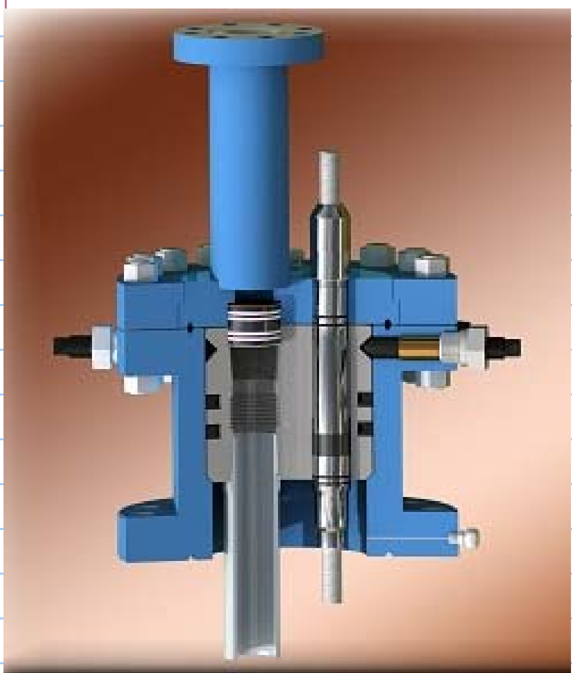
producing gas through the annulus

$P_{wf} \leq P_b\,(T_R)$

bubble point pressure







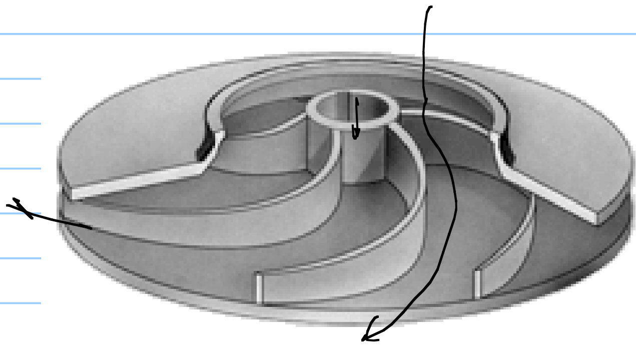
Armais

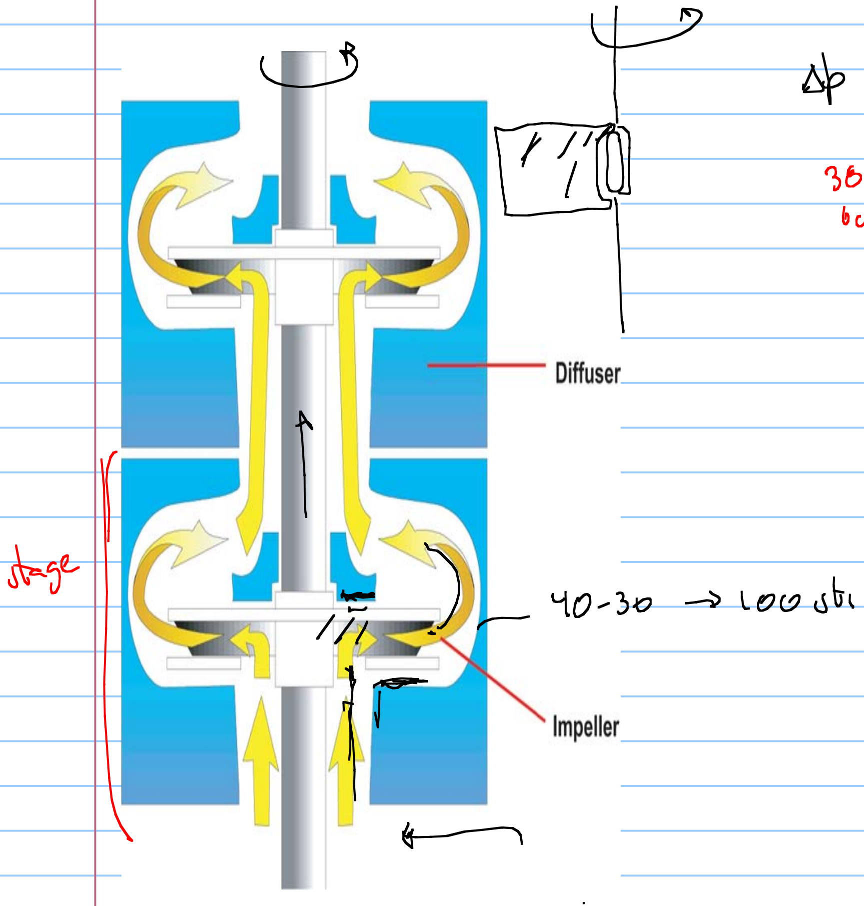
Arutunoff ≃1930

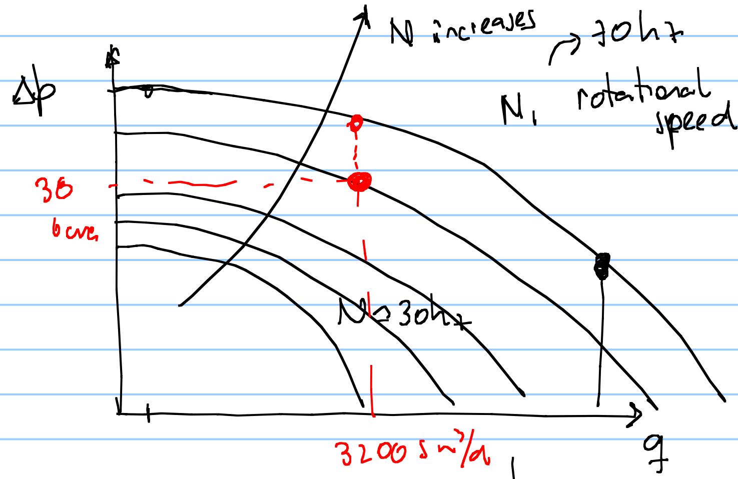
Oklahoma

Reda pump

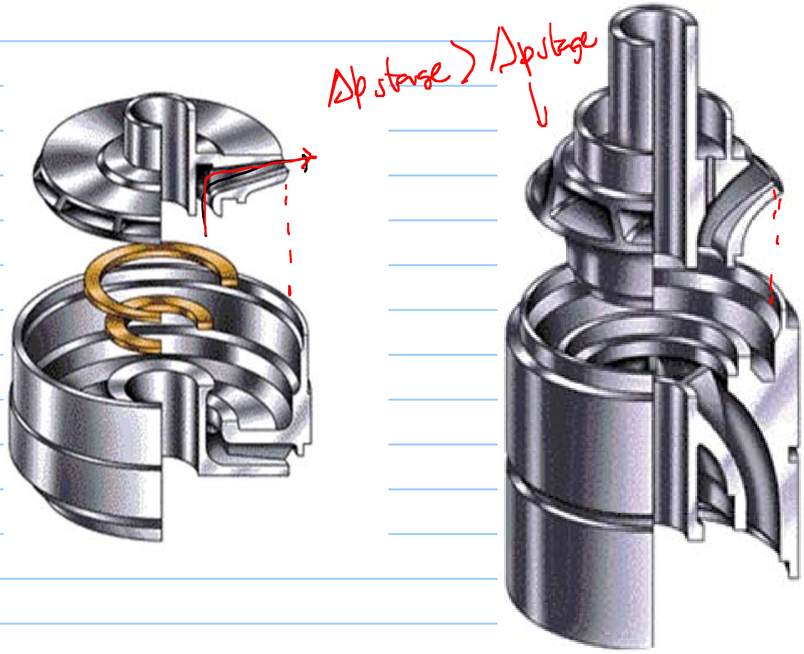
Schlumberger



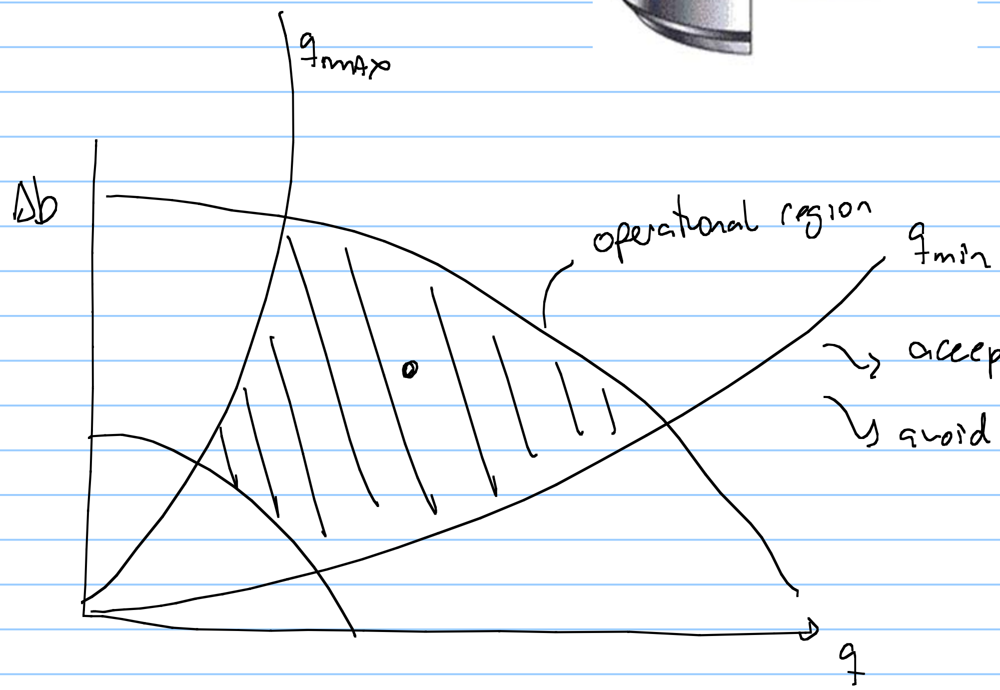




$Power = q\,\Delta p$

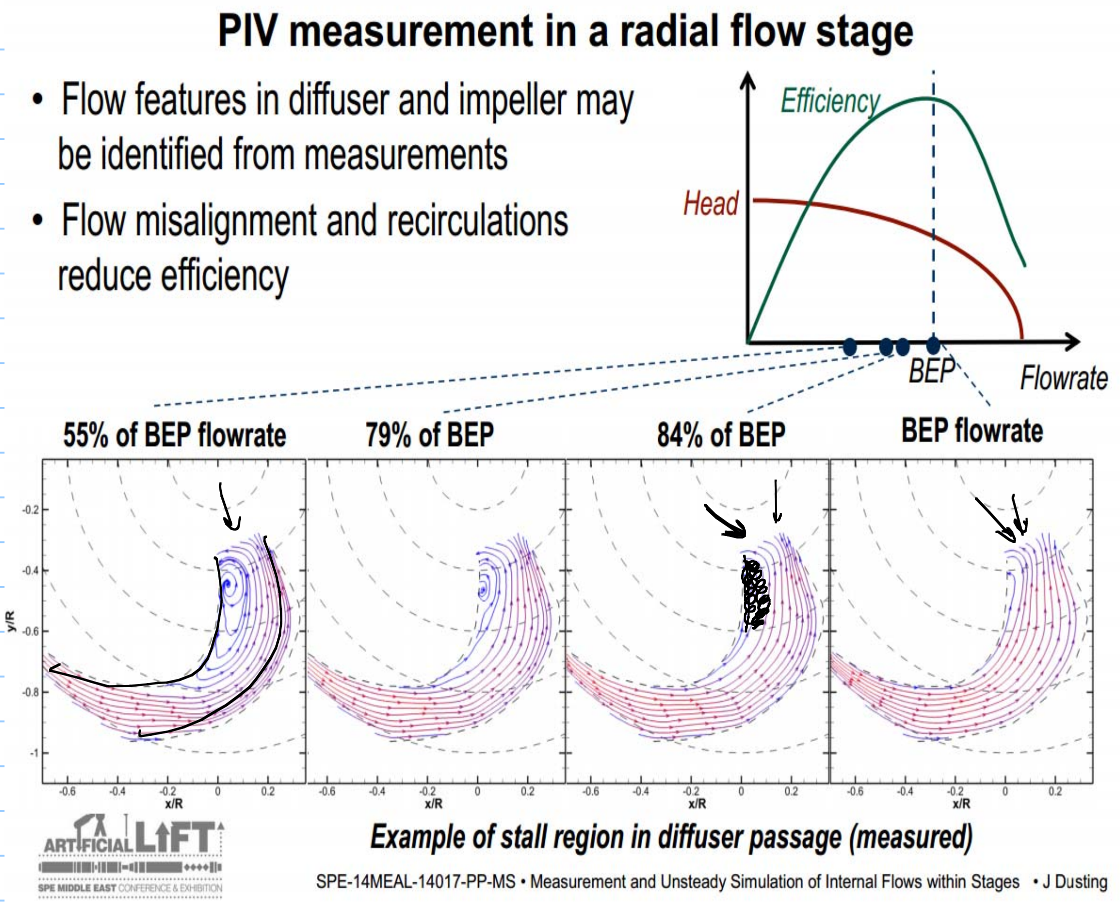


gas friendly

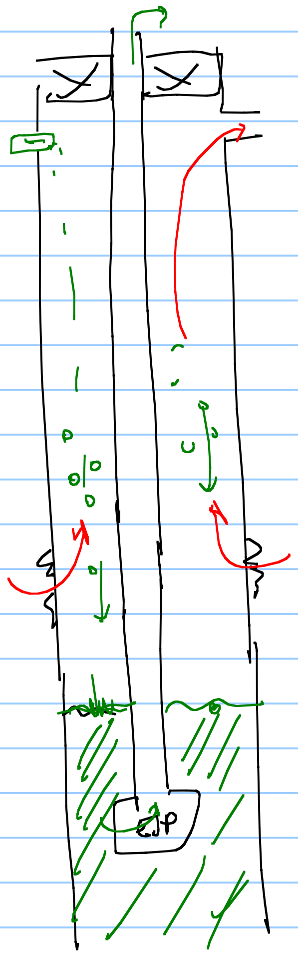


→ acceptable efficiency

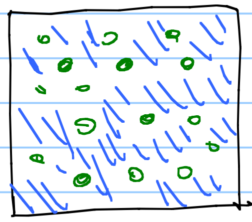
→ avoid upthrust rotor
downthrust rotor



ESP are also used to drain liquid accumulated in gas wellbores



Pressure drop expressions for liquid are also useful to deal with oil + water emulsions ⇝ stable dispersion ⇝ oil in water
water in oil

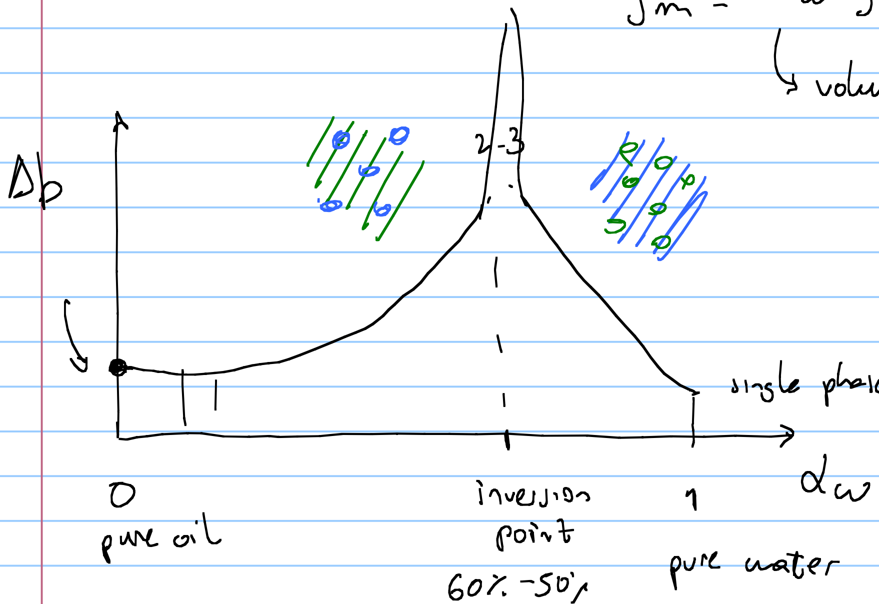


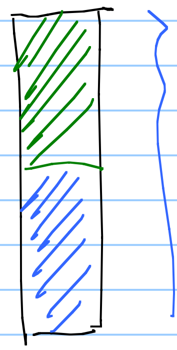
$$\frac{p_1}{\rho g} + z_1 + \; = \frac{p_2}{\rho g} + z_2 + f \frac{L}{D} \frac{v^2}{2g}$$

$\mu_{mixture}$

$$\rho_m = \alpha_w \rho_w + (1-\alpha_w)\rho_o$$

↳ volume fraction of water $\frac{q_w}{q_o + q_w}$ $\frac{10}{40} =$



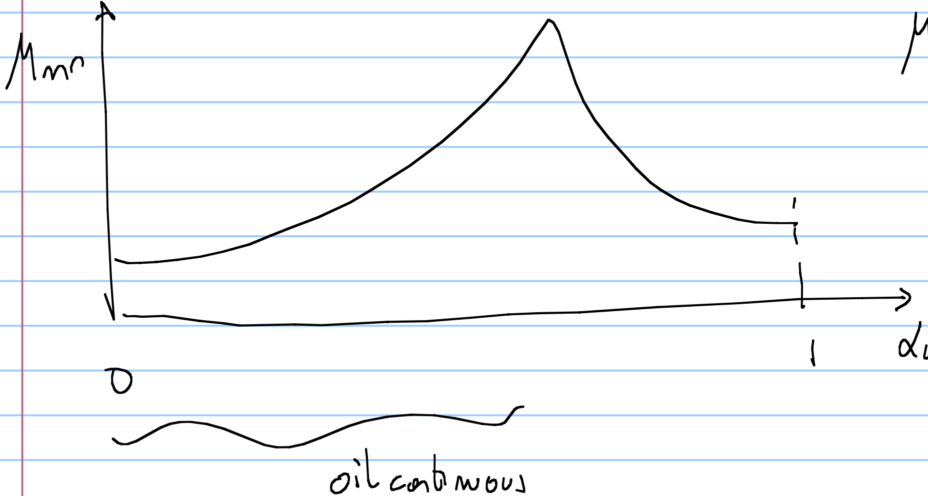


oil continuous

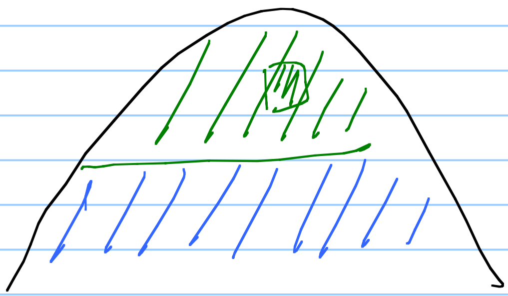
$$\mu_m = \mu_o e^{\alpha_w}$$

water continuous

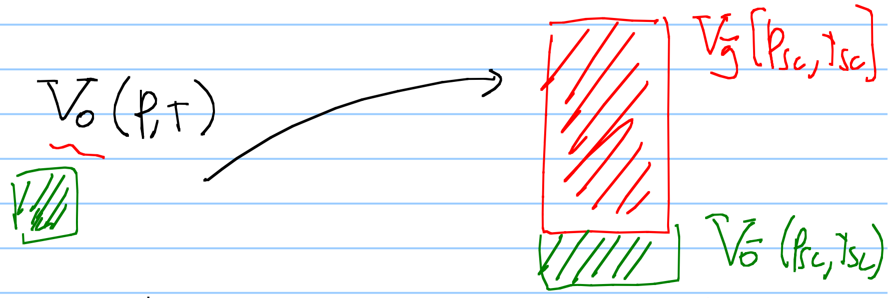
$$\mu_m = \mu_w e^{\alpha_o}$$



$$u_{fluid} = \frac{q}{\frac{\pi \phi^2}{4}} \leftarrow m^3/d \qquad q_{\bar{o}} \quad Sm^3/d$$



$V_o(P,T)$



$$B_g = \frac{q_g(P,T)}{q_{\bar{g}}(P_{sc}, T_{sc})} \ll 1$$

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

$$B_o = \frac{q_o(P,T)}{q_{\bar{o}}(P_{sc}, T_{sc})}$$

oil volume factor

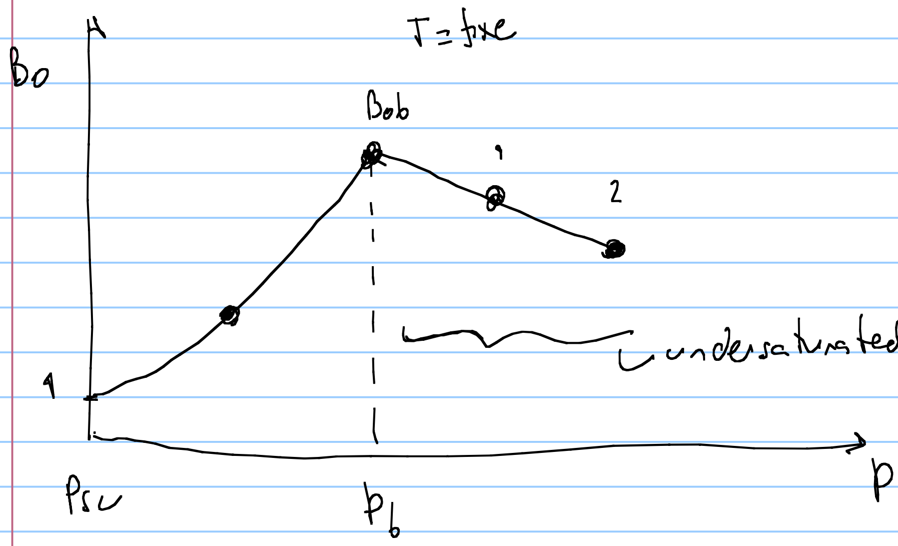
formation volume factor

oil

1.3-1.5 "Normal" → 600-900 scf/stb

1. → 1.05 "Low" → 5-150 scf/stb

1.7 → 2 "high" → 2500 →



undersaturated B_o

oil compressibility

$$C_o = -\frac{1}{V_o}\frac{\partial V_o}{\partial p} \quad \text{thermodynamic definition}$$

$$V_o = B_o \cdot V_{sc}$$

$$C_o = -\frac{1}{\cancel{V_{sc}} B_o}\frac{\partial (B_o \cancel{V_{sc}})}{\partial p}$$

$$c_o = -\frac{1}{B_o}\frac{\partial B_o}{\partial p}$$

$$\int_{p_b}^{p>p_b} c_o\,\partial p = \int_{B_{ob}}^{B_o} -\frac{\partial B_o}{B_o}$$

Vazquez Beggs

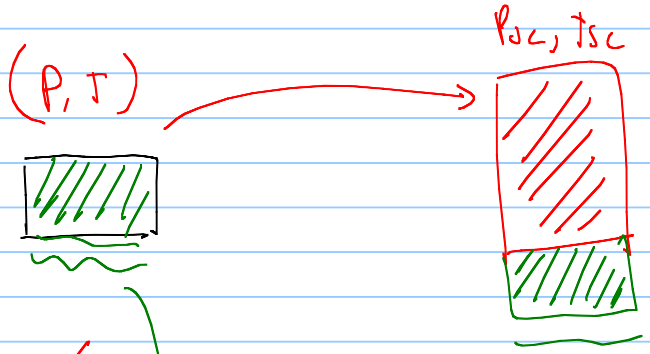
check

$$B_o = B_{ob}\, e^{c_o(p_b-p)}$$

standing Standing

$$f(SG_g, SG_o, GOR, p, T)$$

Black oil correlations



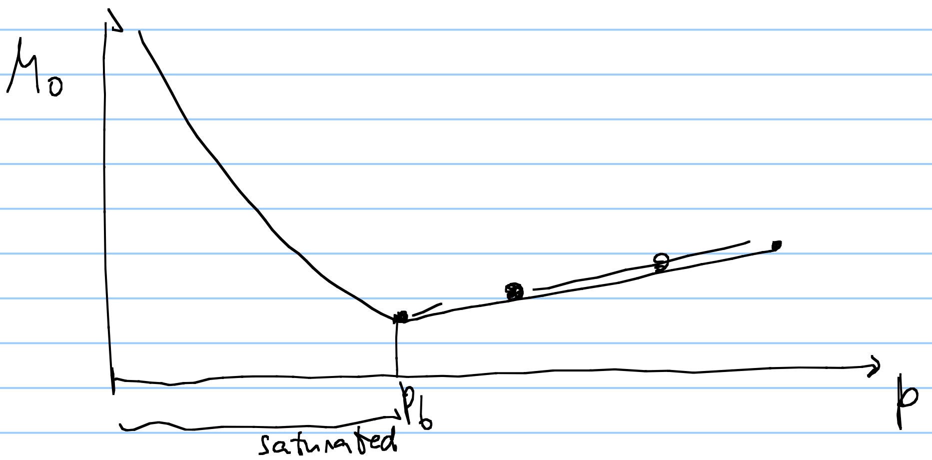
$$\frac{q}{A} \quad B_o$$

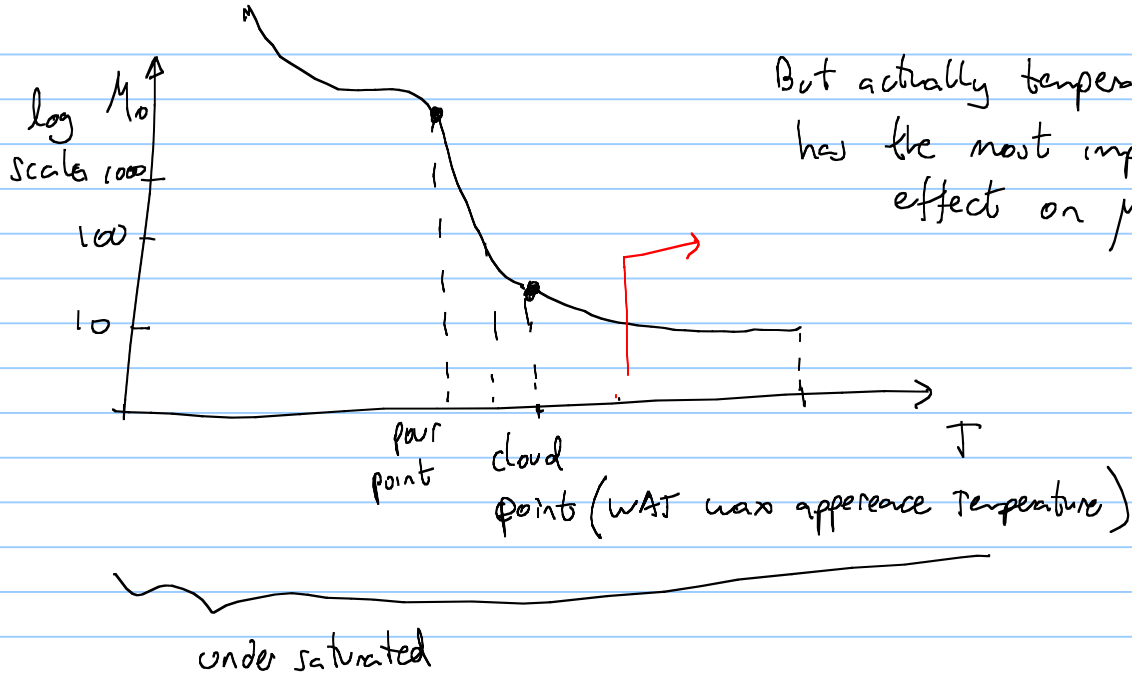
$$\rho_o = \frac{M_o}{V_o} = \frac{V_g \cdot \rho_g + V_o \cdot \rho_o}{V_o} \qquad V_g = GOR \cdot V_o$$

$$Re = \frac{v \cdot \Phi \cdot \rho}{\mu}$$

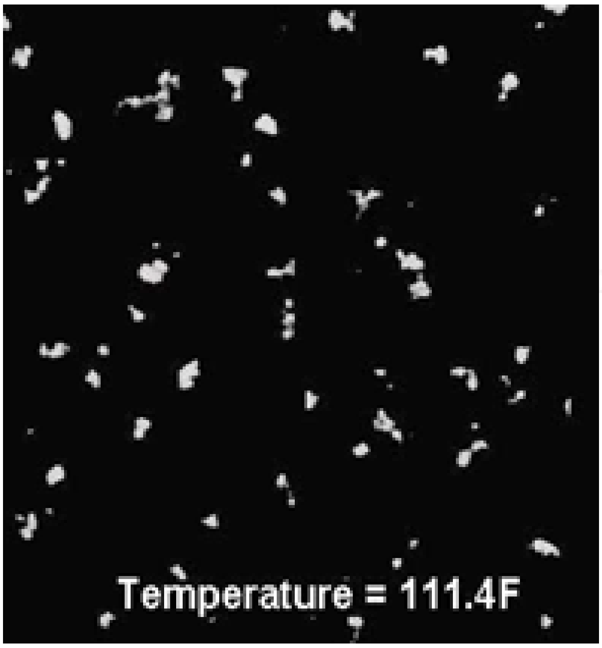
$$\rho_o = \frac{SG_g \cdot 1.224\ GOR \cdot V_o + V_o\ SG_o \cdot 1000}{V_o}$$

$$\rho_o(P,T) = \frac{SG_g \cdot 1.224\ GOR + SG_o \cdot 1000}{B_o}$$





But actually temperature has the most important effect on μ_o !



cloud point

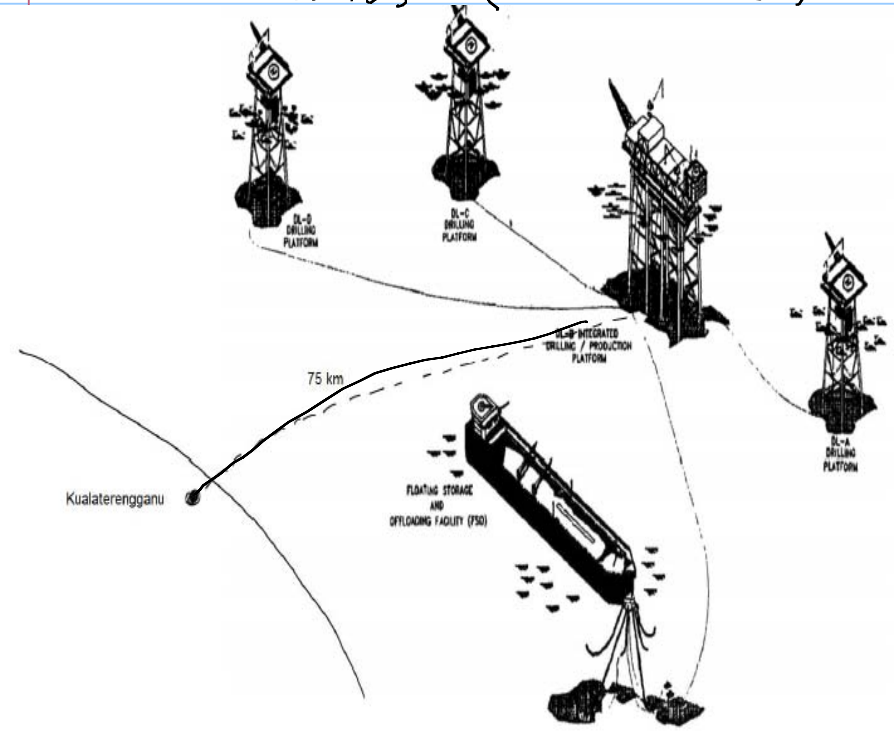
pour point (no flow)

Note Title 12.01.2017

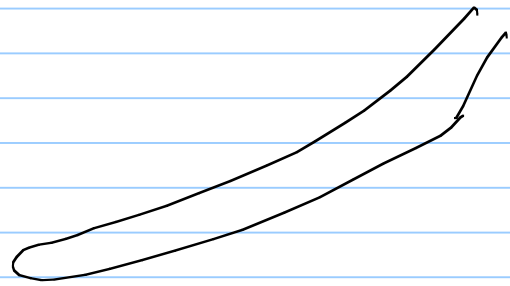
Day 7:

- exercise P and T drop in pipeline (75 km) → oil with low GOR (Sm^3/Sm^3)
- Introduction to multiphase flow in wells (tubing)

Class exercise (home exercise)



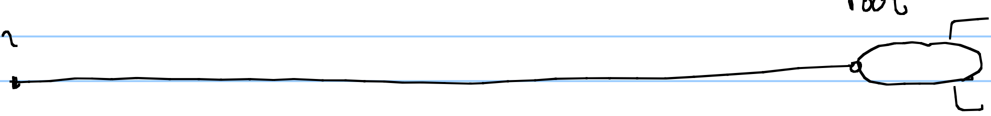
Dulang Malaysia



Kualaterengganu

75 km

P_{in} P_{out} $P_{sep} = 50$ bara



16" ID

100 000 stb/d

GOR = 0.5 Sm^3/Sm^3

60°C

$\Delta x = 10000$ m

home exercise

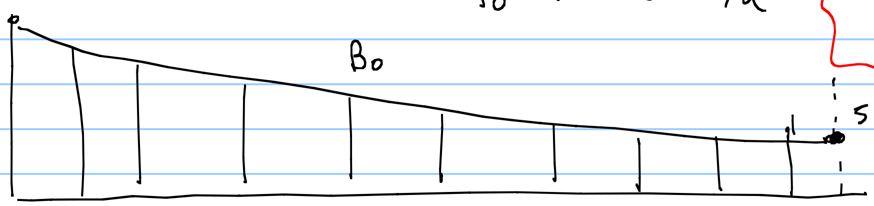
$\Delta x = 1000$ m

q_o = 100000 stb/d

p

B_o

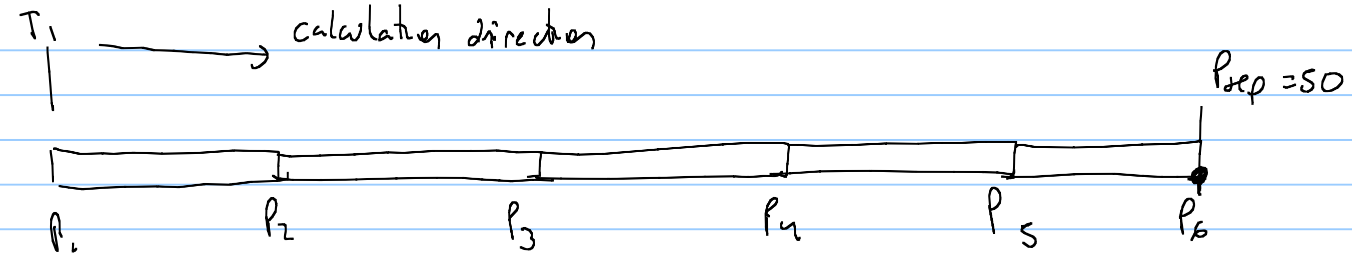
50 bara



q_o

x

B_o, ρ_o, μ_o.



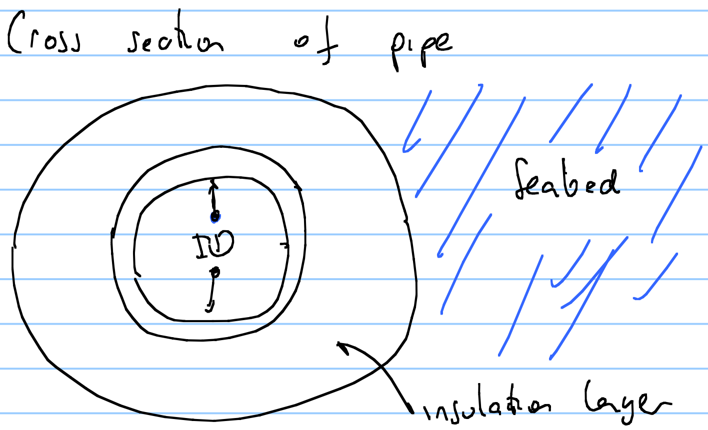
p calculation direction

$$P_5 = P_{sep} + \left.\frac{\partial p}{\partial x}\right| \cdot \Delta x$$

$f(\mu_{o6}, \rho_{o6}, B_{o6})$

$f(T)$ $f(B_o)$

$f(p, T)$



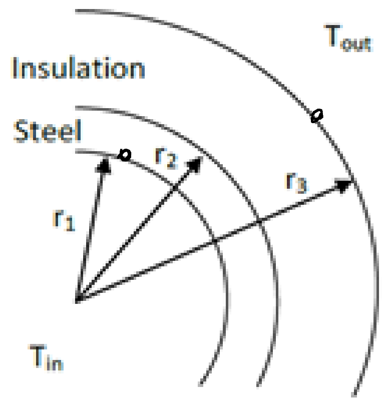
$T = 14°C$

@ $T = 20°C$ $\mu_o \approx 2000$ cp

too high!

The overall heat transfer coefficient based on the pipe outer area is defined as:

$$\frac{1}{U} = \left(\frac{r_{pipe\_inner}}{h_{out} \cdot r_{insulation\_outer}} + \frac{\ln\left(\frac{r_{insulation\_outer}}{r_{pipe\_outer}}\right) \cdot r_{pipe\_inner}}{k_{insulation}} + \frac{\ln\left(\frac{r_{pipe\_outer}}{r_{pipe\_inner}}\right) \cdot r_{pipe\_inner}}{k_{pipe}} + \frac{1}{h_{inner}} \right)$$



$T_{fluid} - \cancel{T_1} = \dot{q}$

$(\cancel{T_1} - \cancel{T_2}) = \vec{q}$

$(\cancel{T_2} - \cancel{T_3}) = q$

$(\cancel{T_3} - T_{out}) = q$

$$\dot{q} = 2\pi r_3 \cdot L \, U \, (T_{fluid} - T_{amb})$$

Short derivation of Temperature equation for liquid flow in pipe

$$\frac{d\dot{q}}{dl} = \left[\frac{dh}{dl} + \left(\cancel{\frac{v\,dv}{dl}}\right)^{0} + \cancel{\frac{dz}{dl}}^{0} \cdot g\right]\dot{m}$$

$$\frac{d\dot{q}}{dl} = \frac{dh}{dl}\dot{m}$$

for liquid $dh = C\,dT$

$T_{fluid} = T$

$$d\dot{q} = dl \cdot 2\pi r_3 \cdot U \cdot (T - T_{amb})$$

$$(T_{amb} - T)\,2\pi r_3 U = \frac{dT}{dl} \cdot C\dot{m}$$

$$A = \frac{C\dot{m}}{2\pi r_3 U}$$

$$T_{amb} - T = \frac{dT}{dl}\,\frac{C \cdot \dot{m}}{2\pi r_3 U}$$

$$\frac{dT}{dl} + \frac{T}{A} - \frac{T_{amb}}{A} = 0$$

multiply by $e^{+l/A}$

$$\frac{dT}{dl}e^{l/A} + T e^{l/A}\frac{1}{A} = \frac{T_{amb}}{A}e^{l/A}$$

$$\frac{d}{dl}\left(e^{l/A} \cdot T\right) = \frac{T_{amb}}{A}e^{l.A}$$

$$\int_0^l d\left(e^{l/A} \cdot T\right) = \int_0^l \frac{T_{amb}}{A}e^{l/A}\,dx$$

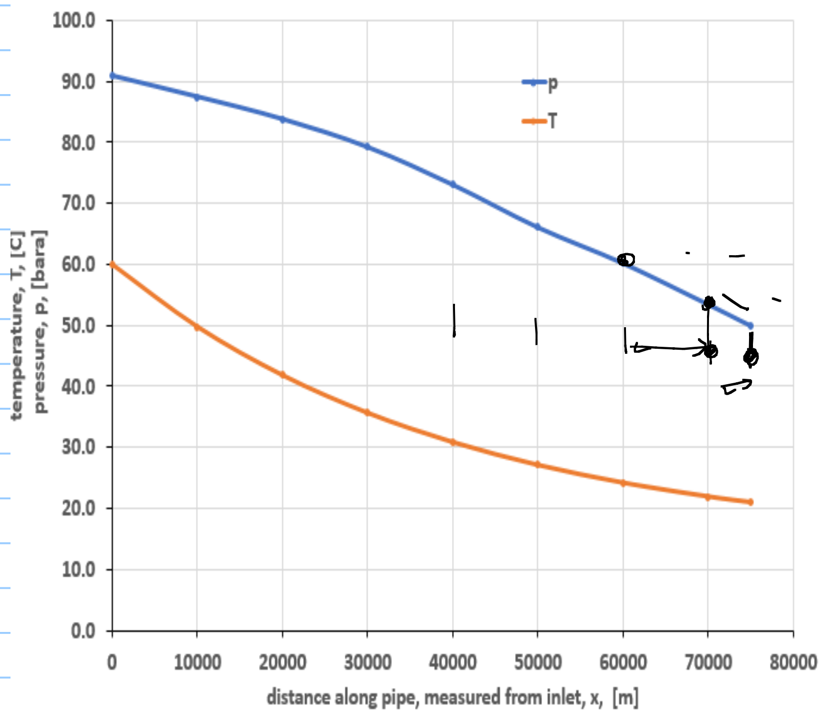
$$e^{l/A}\,T(l) - T(l=0) = \left(e^{l/A}\,T_{amb} - T_{amb}\right)$$

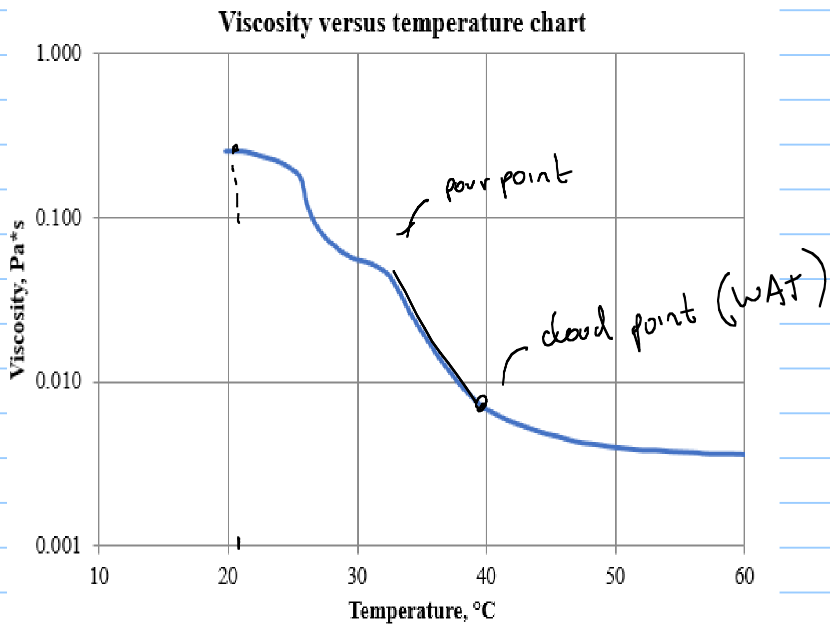
$$\boxed{T(l) = \left(T(l=0) - T_{amb}\right)e^{-l/A} + T_{amb}}$$

```
Function unburied_pipeline_TiL(Te, Ti0, L, A)
unburied_pipeline_TiL = Te + (Ti0 - Te) * Exp(-L / A)
End Function
```

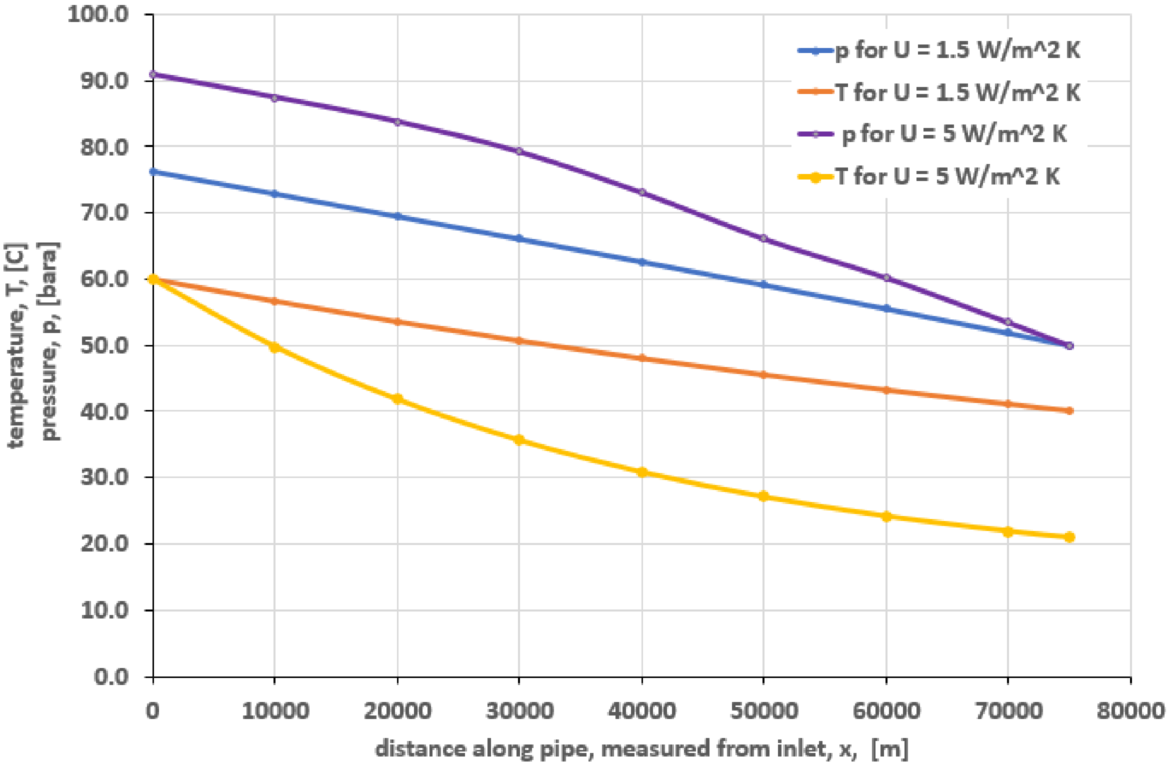
$$B_o = \frac{V_o}{V_{\bar{o}}} \qquad q_o = B_o \cdot q_{\bar{o}}$$

Distance from pipe inlet	T	Bo	deno	visco	qo	p
[m]	[C]	[m^3/Sm^3]	[kg/m^3]	[Pa s]	[m^3/d]	[bara]
0	60.0	1.028	730.2	0.004	16338.4	90.9
10000	49.8	1.021	734.9	0.004	16235.9	87.5
20000	41.8	1.016	738.4	0.006	16158.4	83.8
30000	35.6	1.013	741.1	0.017	16099.6	79.2
40000	30.8	1.010	743.1	0.053	16054.9	73.1
50000	27.1	1.008	744.7	0.083	16020.7	66.1
60000	24.2	1.006	745.9	0.212	15994.6	60.2
70000	21.9	1.005	746.9	0.244	15974.4	53.5
75000	21.0	1.004	747.3	0.252	15966.2	50





Comparing pipelines with different heat transfer coefficients (insulation)



saving in pump power by insulating better the pipe !

$$P = q\,\Delta p = (15\ 10^5\ Pa) \cdot \frac{15966.2\ sm^3/s}{3600 \cdot 24}$$

$$P_{hyd} = 0.28\ MW$$

$$P_{actual} = \frac{P_{hydra}}{\eta} = \frac{0.28}{0.7} =$$

$$P_{actual} = 0.4\ MW$$

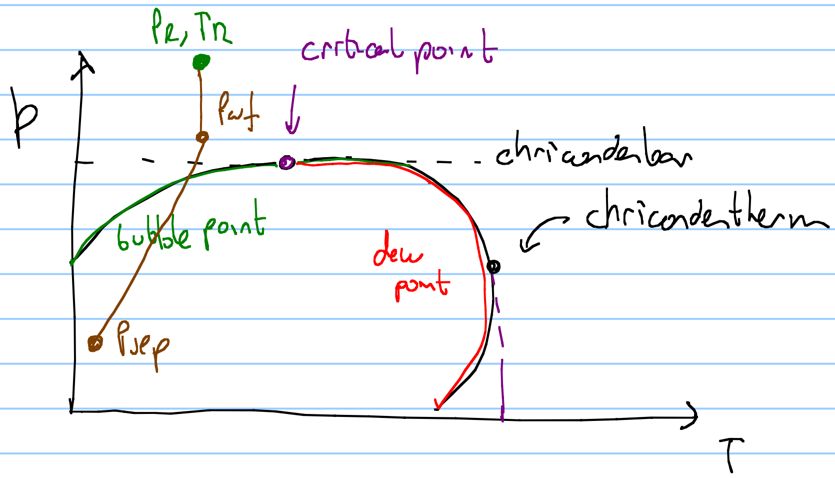
- Non-newtonian fluids { Some Oil + water emulsions, drilling muds

Not covered in this course!!

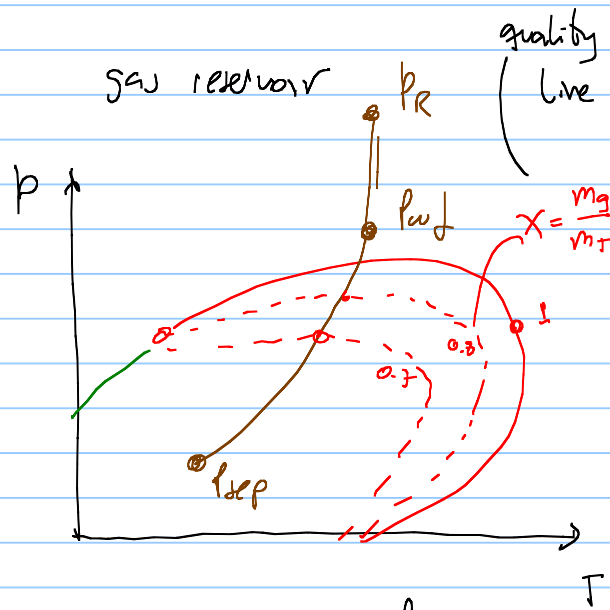
Multiphase flow in wellbores:

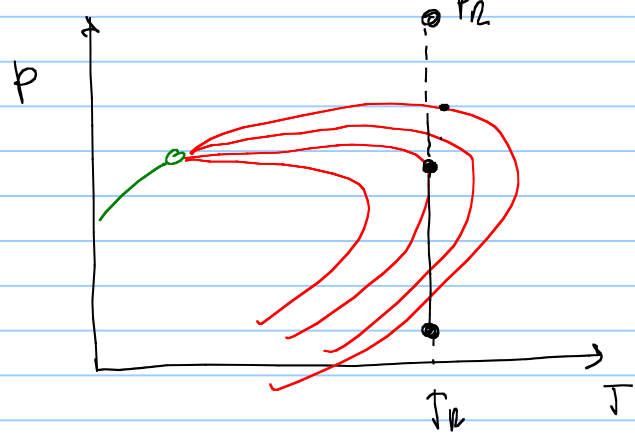
Phase diagram of reservoir fluids

oil reservoir   composition z_i



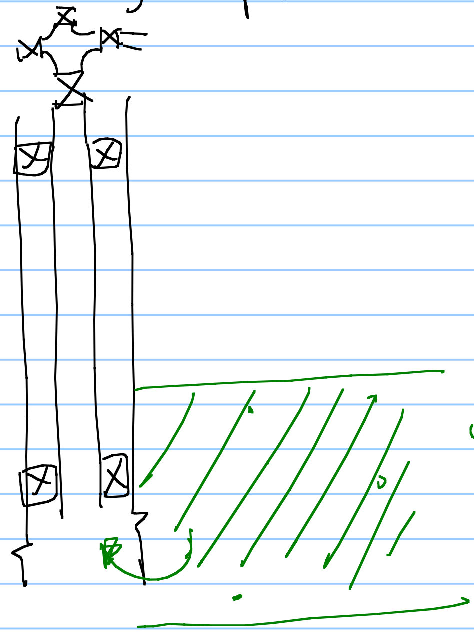
gas reservoir





retrograde condensation

well flowing composition with time

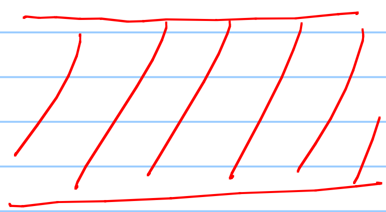


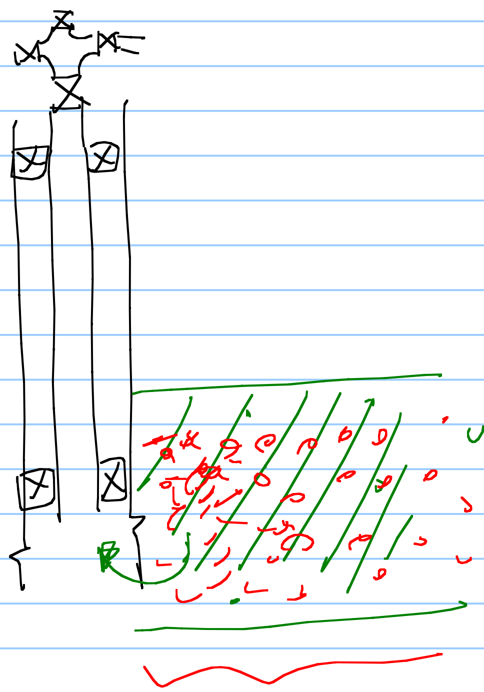
undersaturated oil $z_i = f(t)$?

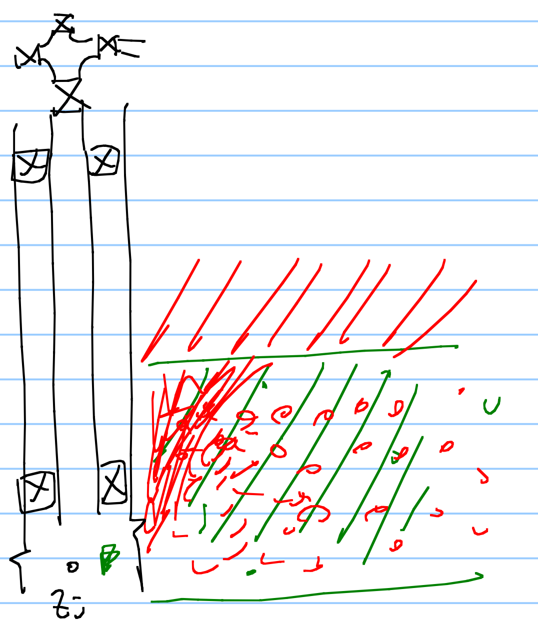
$p_{wf} > p_b(T_R)$

undersaturated gas z_i is constant

$p_{wf} > p_d(T_R)$





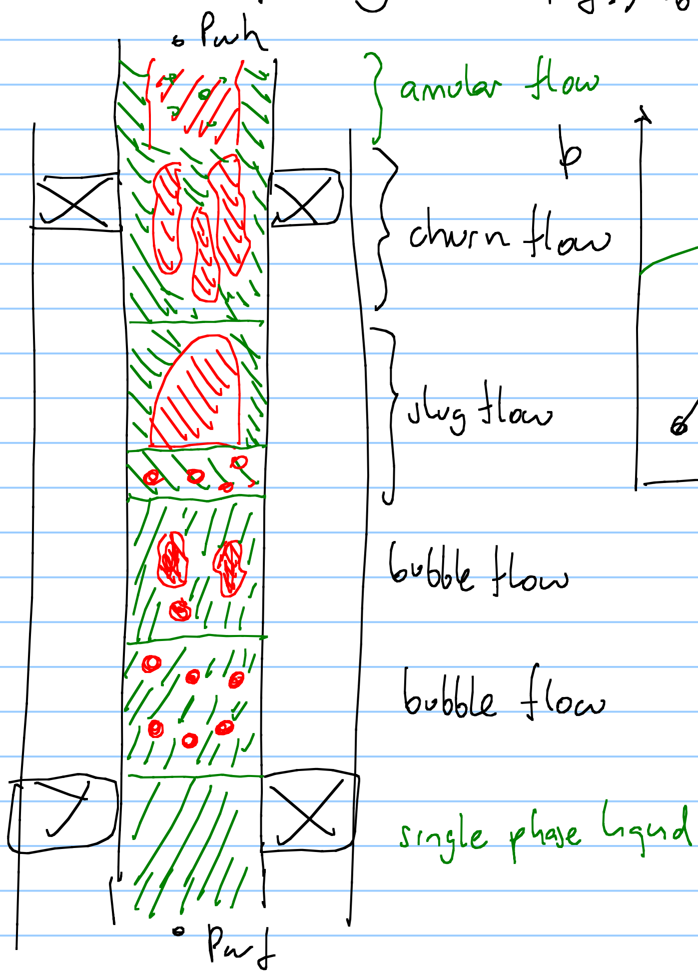


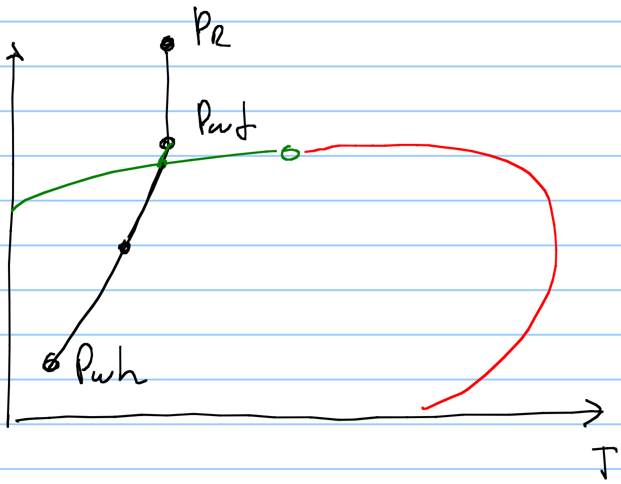
S_g ↑ with time

gas coning $z_i = f(t)$

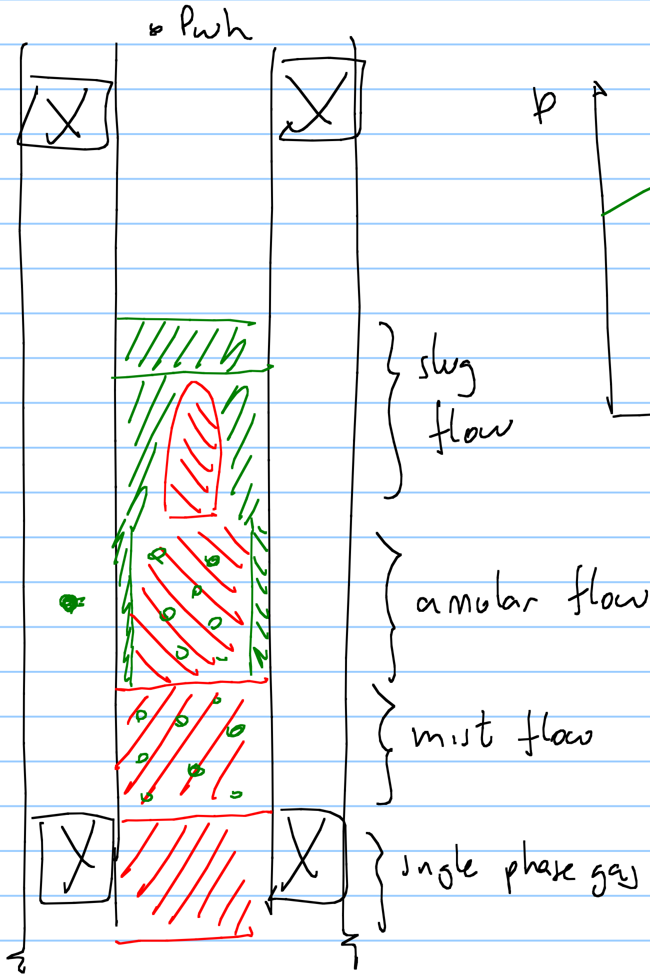
GOR also increases, z_i is $f(t)$

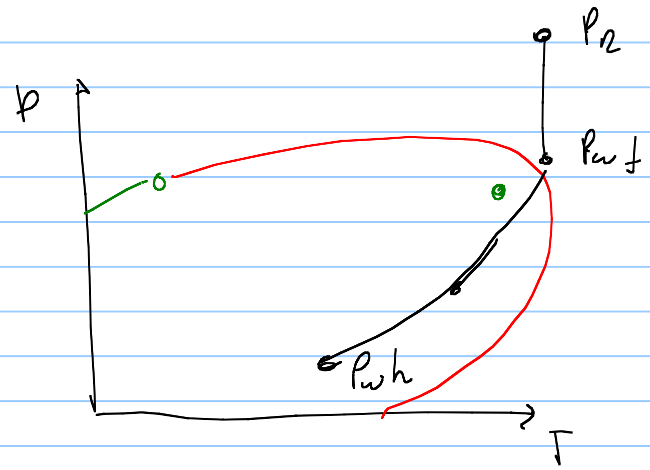
For wellbore producing with $P_{wf} \geq P_b(T_R)$



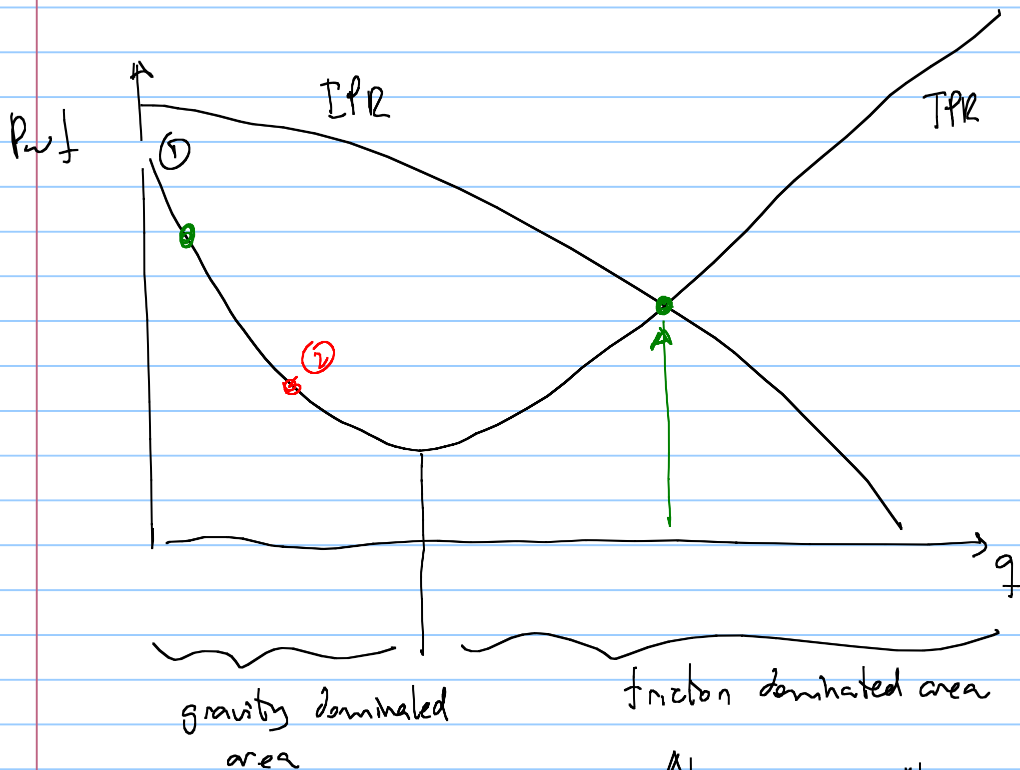


for gas well

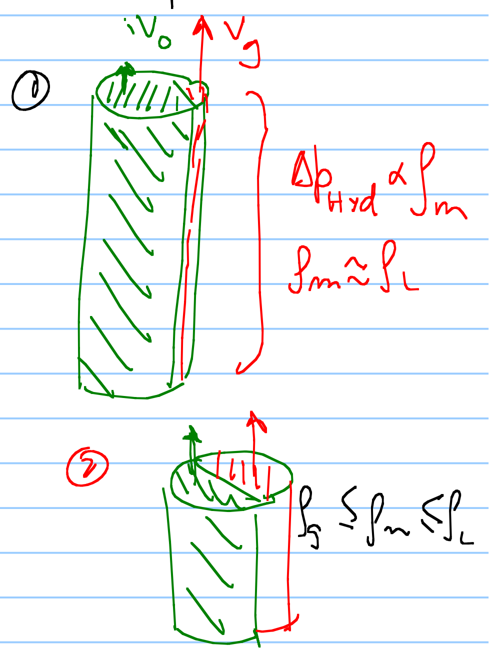




flow pattern ~> flow regime



for multiphase



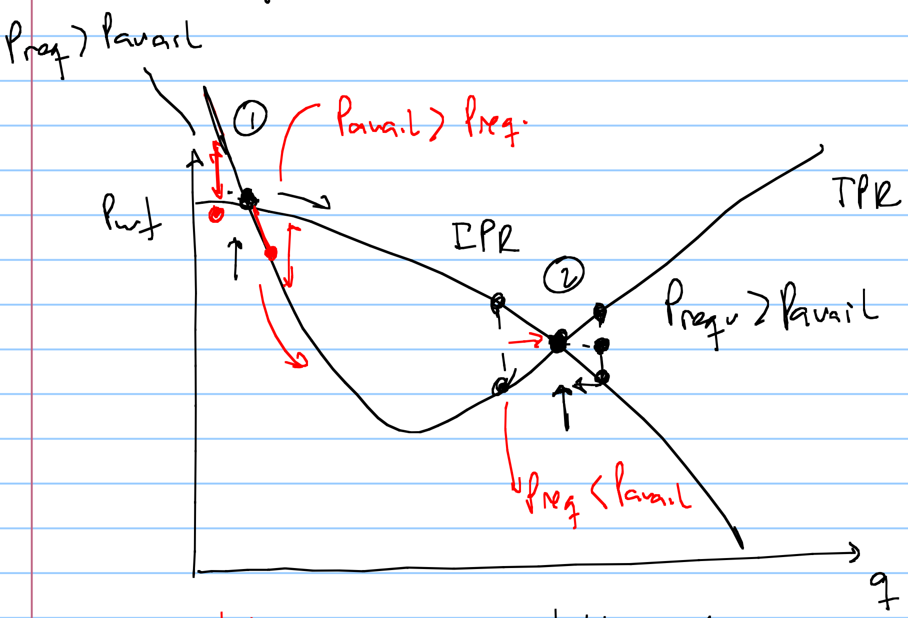
$\Delta p_{friction} \gg \Delta p_{Hydrostatic}$

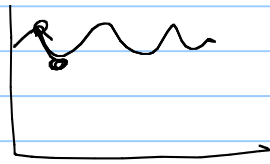
$\Delta p_{Hydros} > \Delta p_{friction}$

$$\Delta p_{TOTAL} = \cancel{\Delta p_{acc}} + \Delta p_{Hydrostatic} + \Delta p_{friction}$$

0 ↓ ↓ (q)

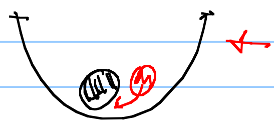
It is possible to have 2 intersections between TPR-IPR in two phase





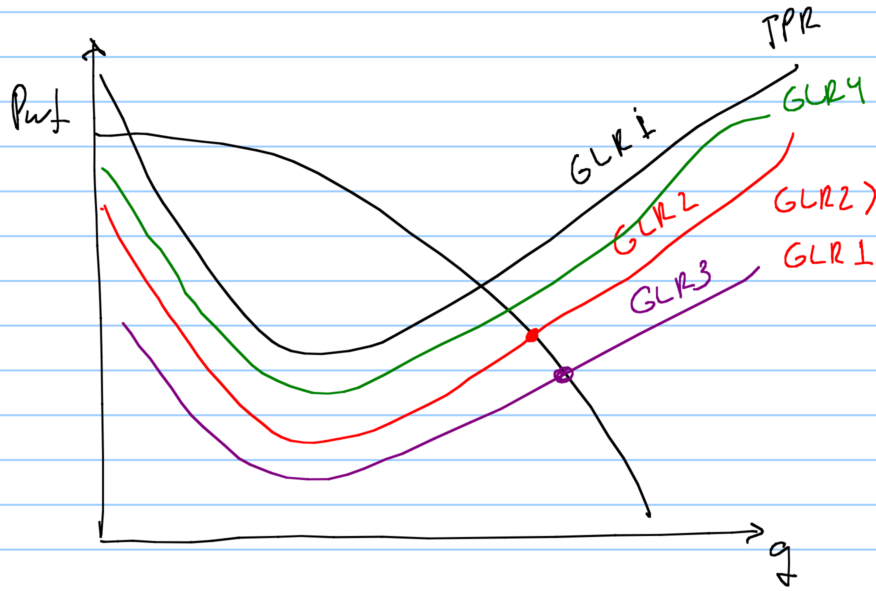
unstable equilibrium

stable equilibrium



to move from unstable equilibrium to stable equilibrium we need sometimes flow induction methods.

Gilbert 1954 { IPR, TPR, Choke



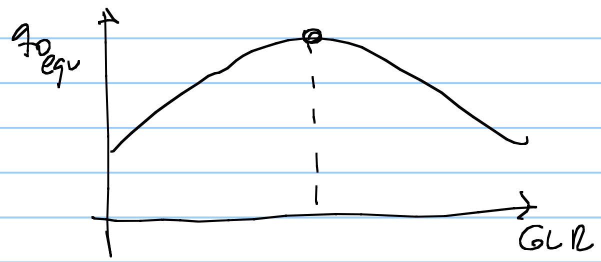
GLR -- gas liquid ratio

↑ GLR $\rho_{mixture}$ ↓

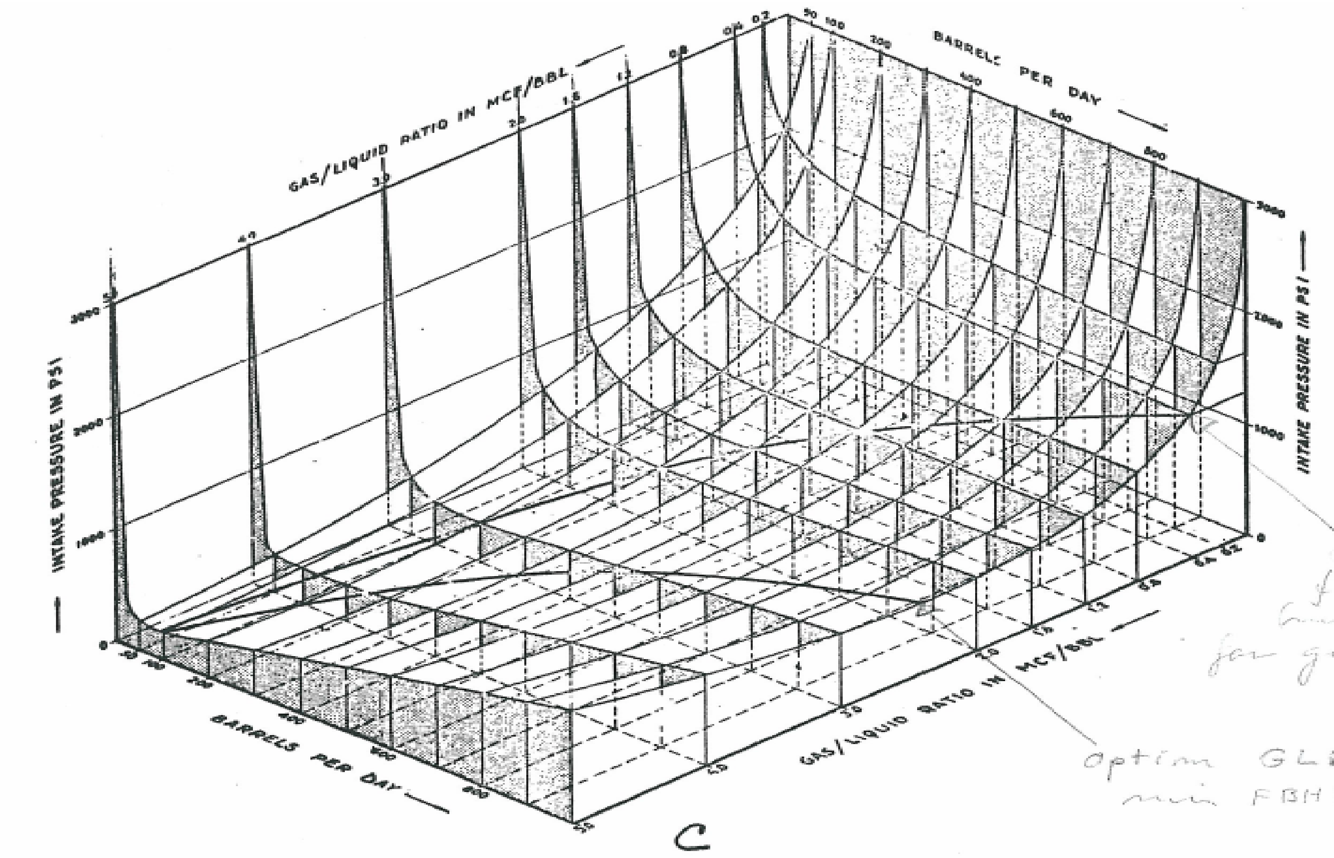
GLR 4 > GLR 3 > GLR 2 > GLR 1

$\Delta p_{hydrostatic} < \Delta p_{friction}$

change of trend in the equilibrium rate



Gilbet 1954

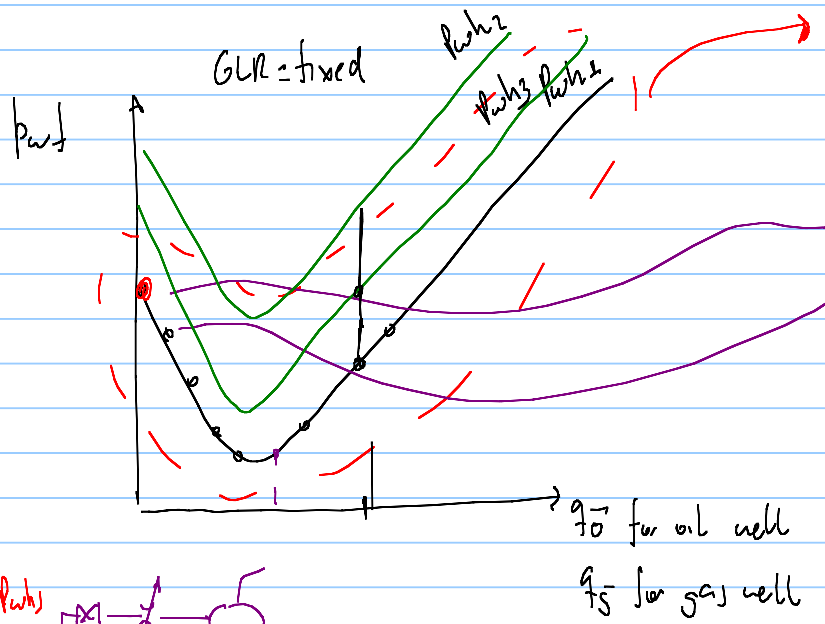


THE TWO-PHASE VERTICAL-LIFT FUNCTION
FOR 2.875 –INCH TUBING SET AT 8000 FEET
(TUBING PRESSURE = ZERO PSI GAUGE)

FIGURE 6

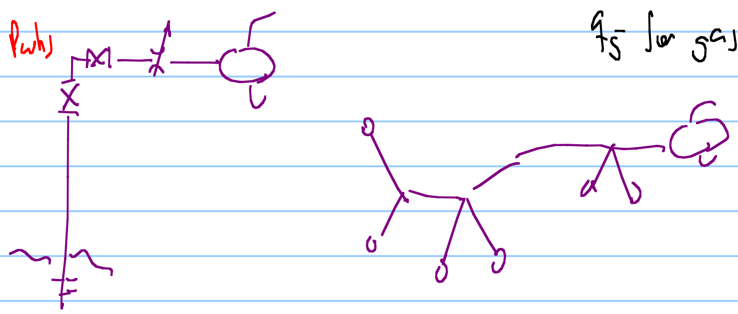
Day 8

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 conditions using BO properties.



Pwh = Pwh1

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



Pwh = Pwh1

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

Pwh = Pwh2

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

Pwh = Pwh3

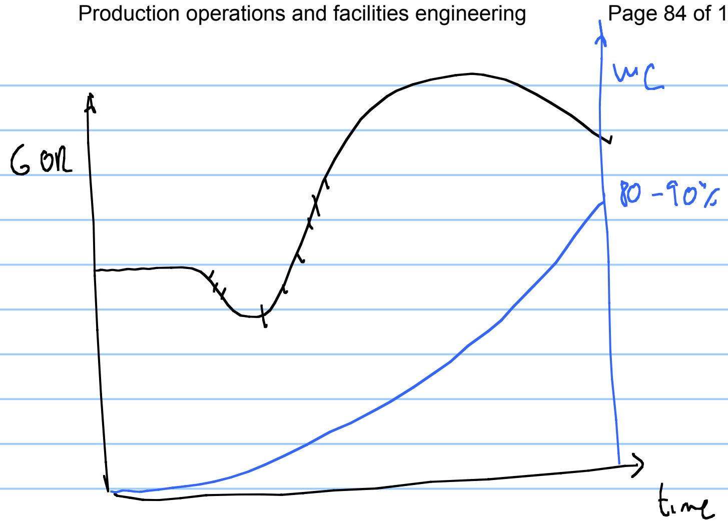
$q_{\bar{o}}$	$q_{\bar{g}}$	$q_{\bar{w}}$	Pwf	Twh
0				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

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_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

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

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

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

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

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

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

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

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

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

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

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

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

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

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

$P_{wh} = P_{wh3}$ GO_3 WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
0				
-	-	-	-	-
-	-		-	-
-	-		-	

$wh = P_{wh1}$ GOR_1 WC_2

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

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

$q_{f\bar{o}}$	$q_{f\bar{g}}$	q_{fw}	P_{wf}	J_{wh}
0				

$P_{wh} = P_{wh1}$ 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				
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-

$P_{wh} = P_{wh3}$ $GO3$ WC_3

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

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

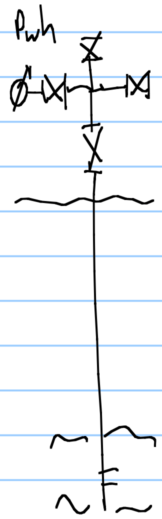
$N_{simulations\ per\ tables} = 10$ (rates $q_{\bar{o}}$)

= 270 ! calculations of Δp in tubing

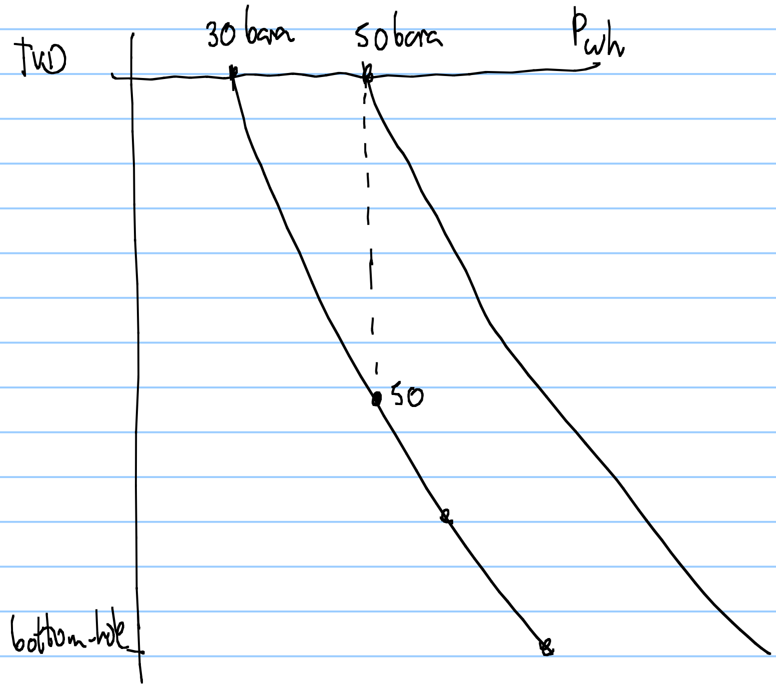
- Reservoir simulator uses tables
- GAP uses tables for wells
  ↳ commercial production simulator by PETEX

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

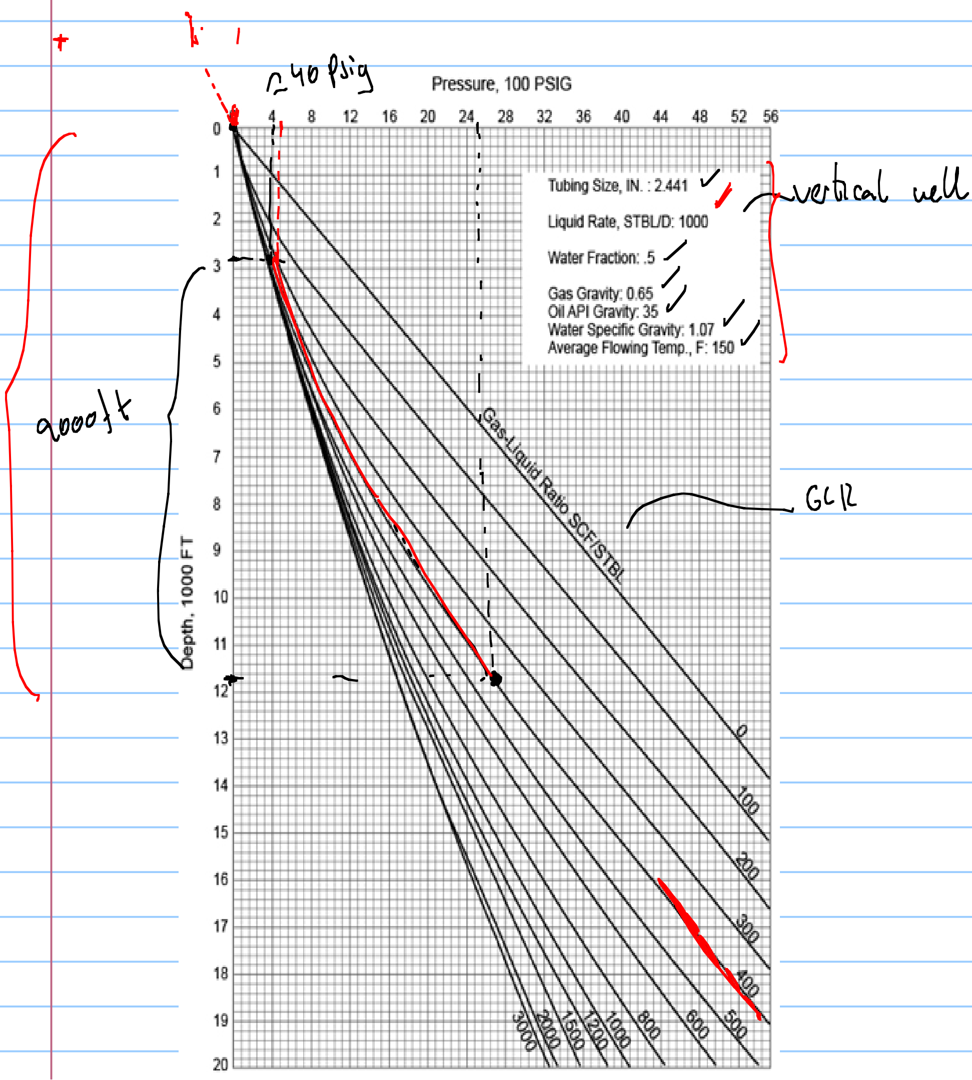
- Pressure traverse curves: graphical method to solve pressure drop calculation in vertical oil wells



q_o = constant
θ = constant
GLR = constant
γ_o = constant
γ_g = constant

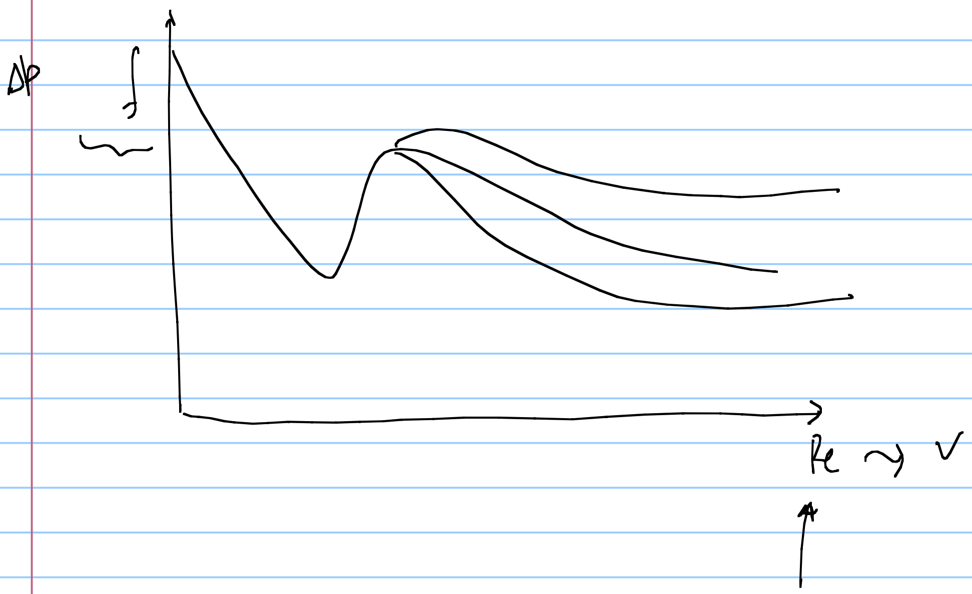


$$\frac{dp}{dz} = f(p)$$



- 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

$$GLR = \frac{q_g}{q_o + q_w}$$



superficial velocity: $u_{sL} = \frac{q_L}{A}$ ↪ local volume rate @ p, T m/s

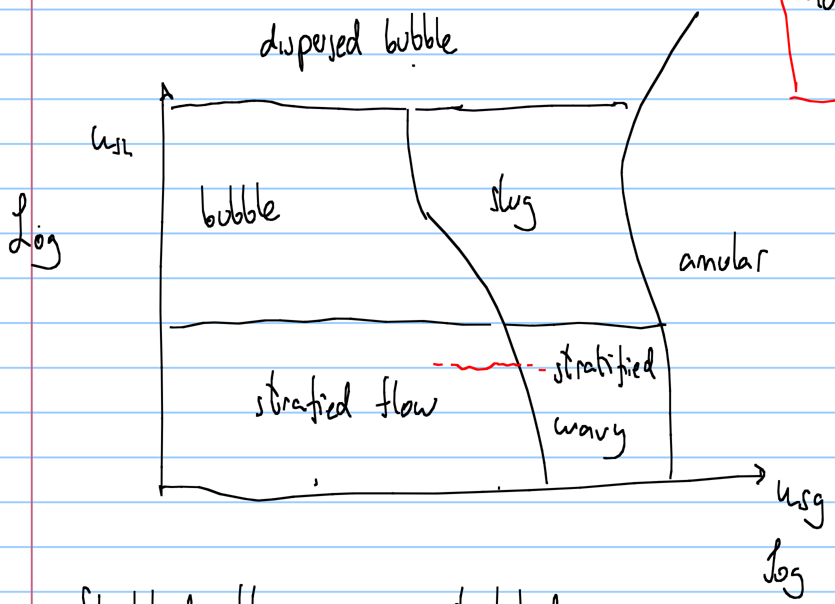
↪ cross section area of pipe

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

flow pattern map:

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

horizontal line



bubble

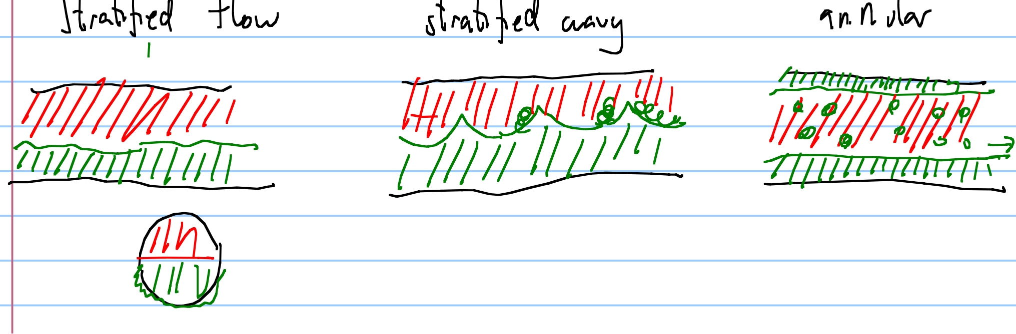
dispersed bubble

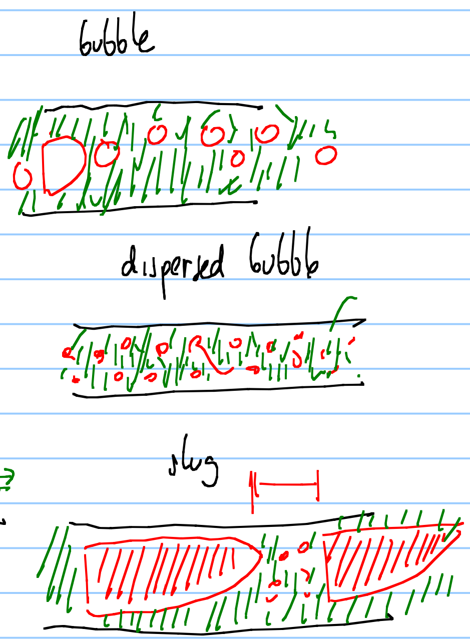
Stratified flow

stratified wavy

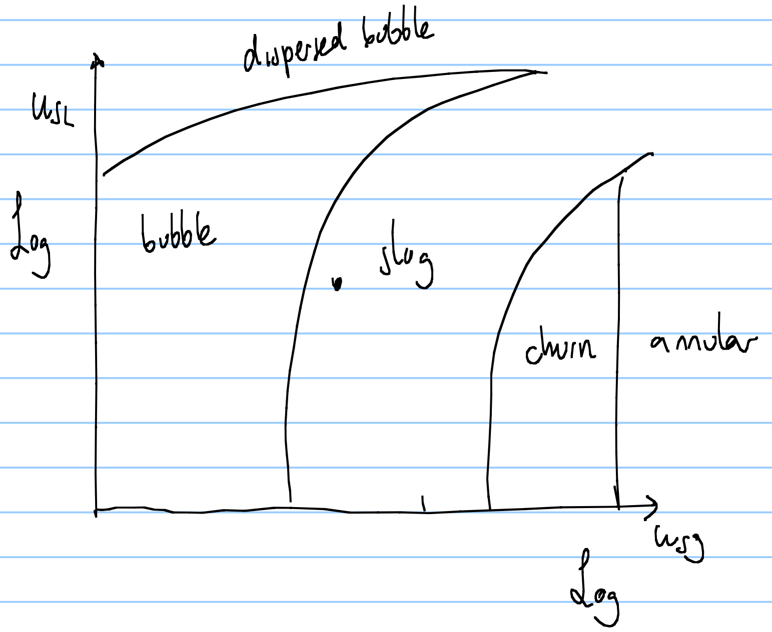
annular

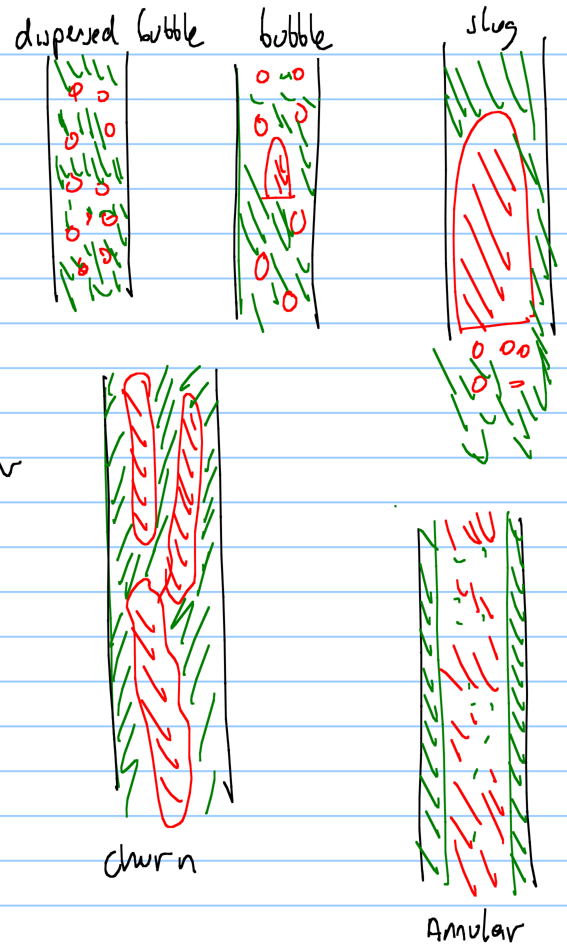
slug





for vertical pipe

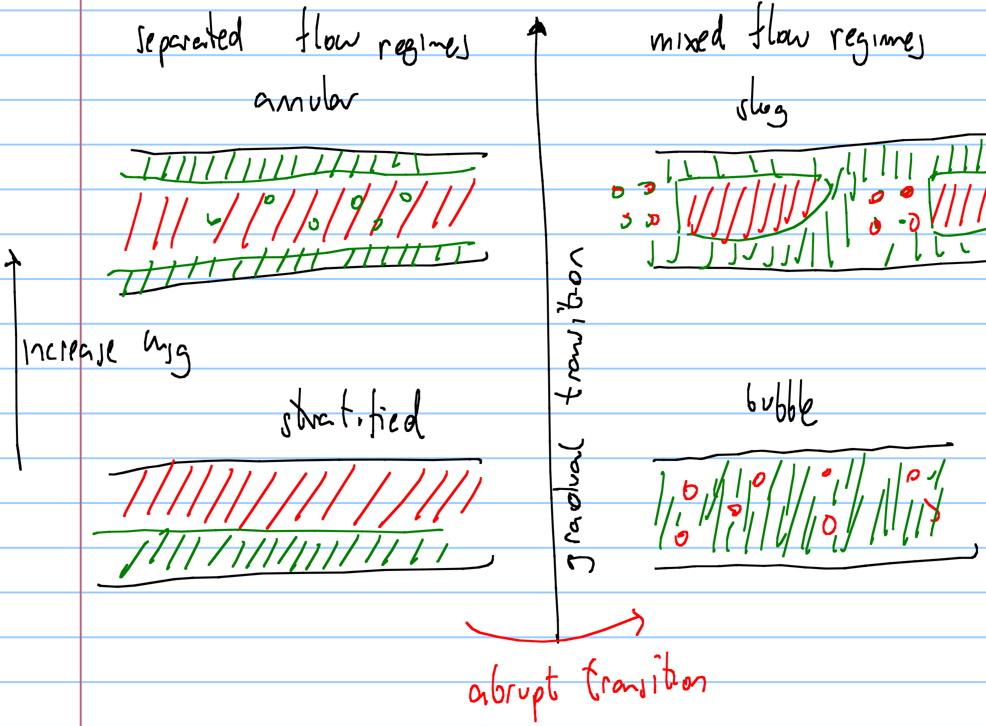




Re_l We weber number $= \frac{\rho \cdot v^2 \cdot D}{\sigma} \sim$ inertia

Re_g

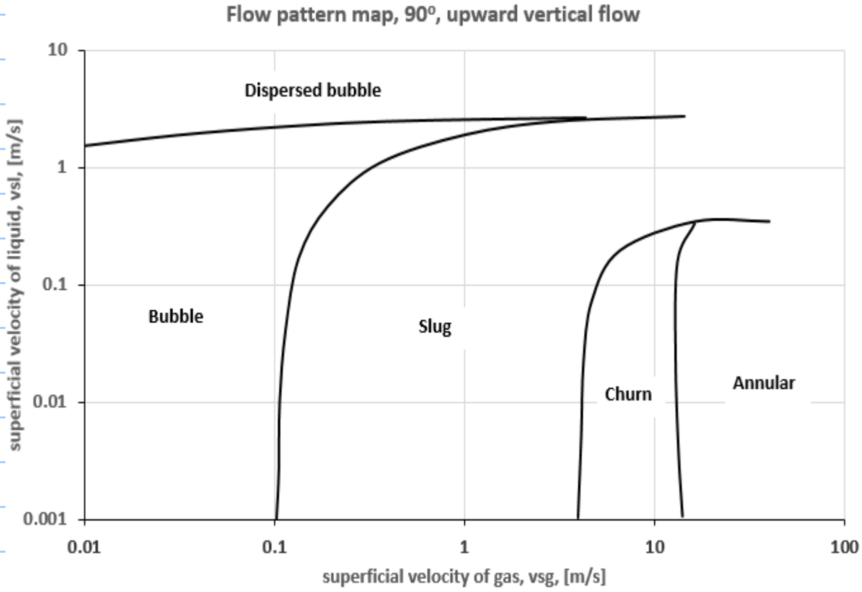
$$\text{Froude} = \frac{v^2}{gD}$$



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

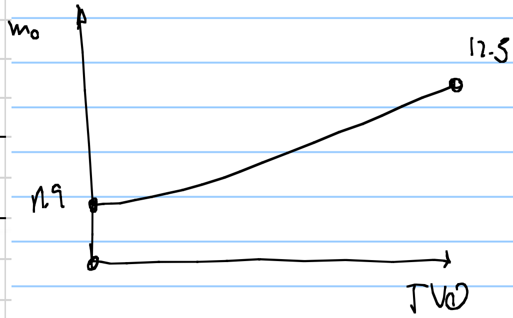
segregating forces	mixing forces
gravitational acceleration	inertia v^2
surface forces	viscosity
viscosity	

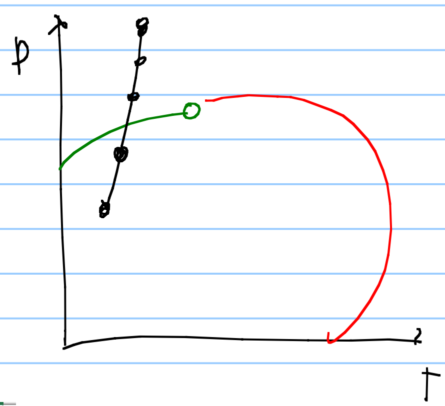
class exercise to define flow pattern along tubing



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	-				





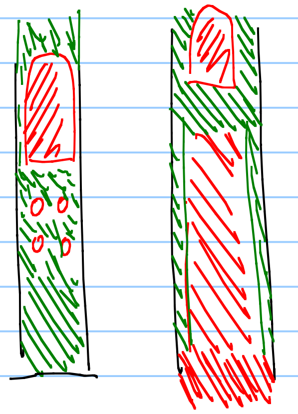
oil well

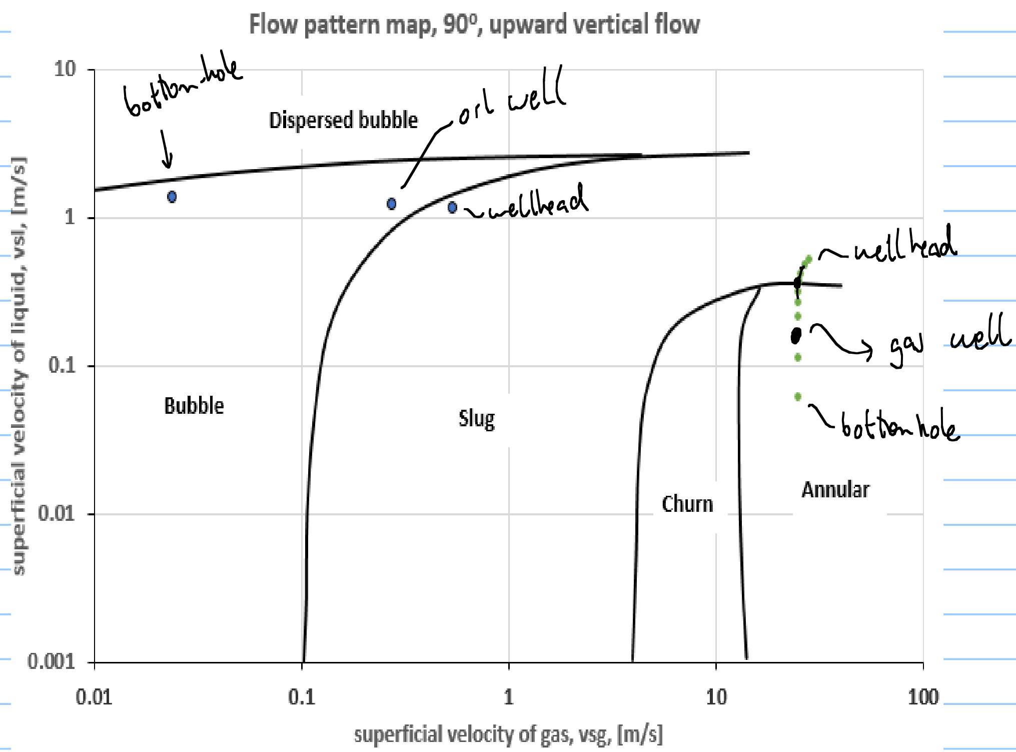
Vertical oil well								
Tubing ID [m]	0.14							
Cross section area [m^2]	0.015							
TVD [m]	mo [kg/s]	mg [kg/s]	ρoil [kg/m3]	ρgas [kg/m3]	qo [m3/s]	qg [m3/s]	vso [m/s]	vsg [m/s]
0	11.9	0.58	659.7	69.9	0.018	0.008	1.17	0.54
610	12.1	0.37	630.0	89.3	0.019	0.004	1.25	0.27
1219	12.5	0.04	591.8	114.3	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

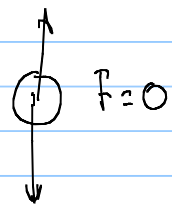
gas well

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





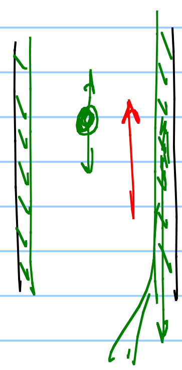


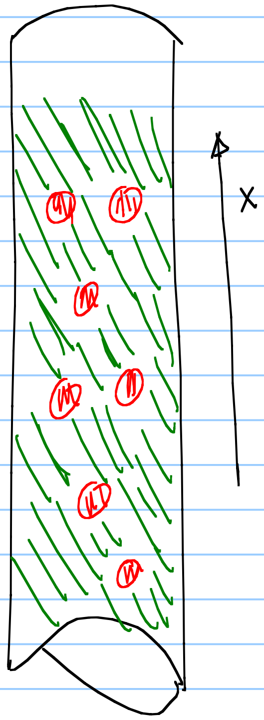
Short comment on liquid loading

alternative explanation

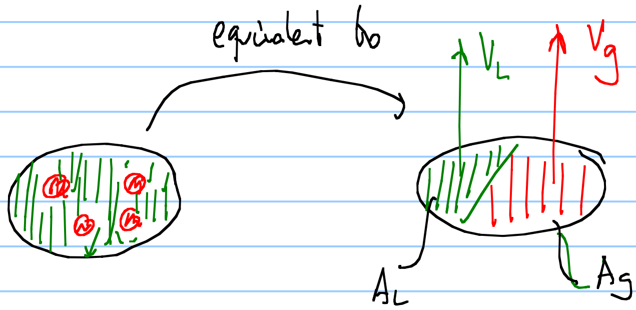
wall slippage

transition from annular flow to slug flow



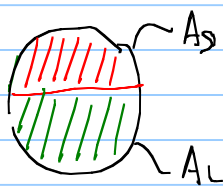


1-D



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

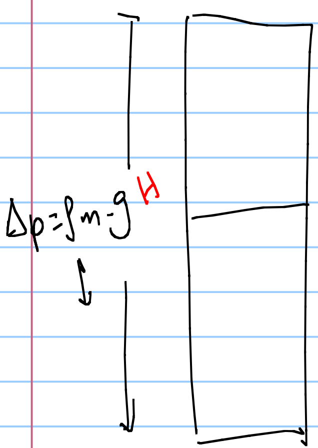
$$V_g = V_L = V_m$$

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

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

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

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



λ_g, λ_L ? for $V_L = V_g = V_m$

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

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

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

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

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

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

$u_d = V_g - u_m$

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

$H_L = (1 - \varepsilon)$

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

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

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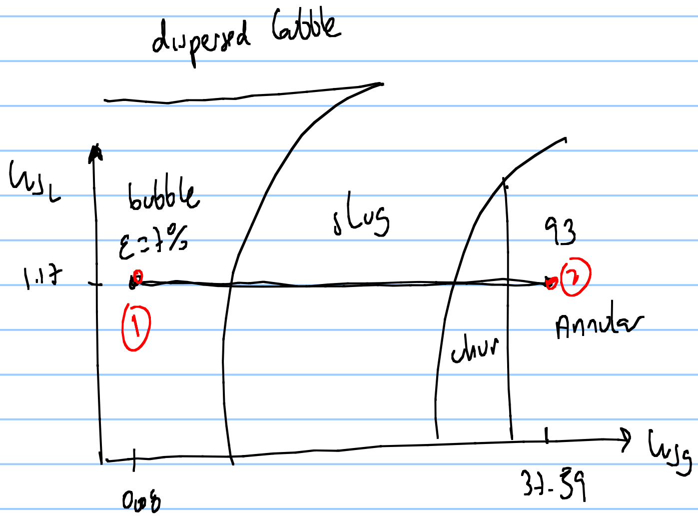
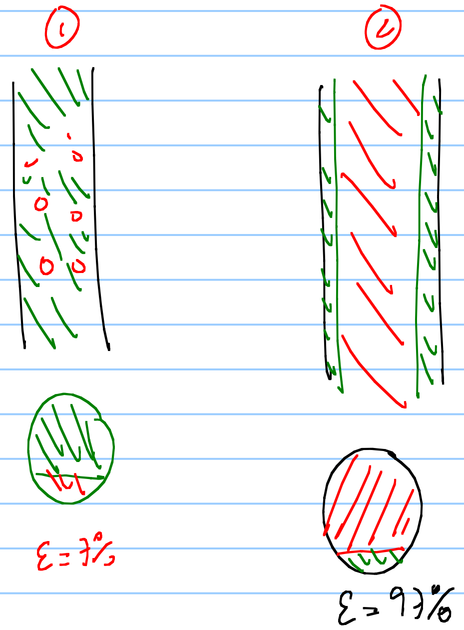
8 parameters.

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

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 u_{sg}

S vs H_L $(1-\varepsilon)$

Day 9:

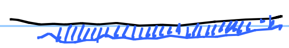
- methods to compute multiphase flow ~> $\frac{dp}{dx}$
- the drift flux model ~>
- Conversion from local to standard conditions using BO properties
- Exercise
- Pressure integration in multiphase flow
- Exercise
- final comments - end

two approaches to study multiphase flow

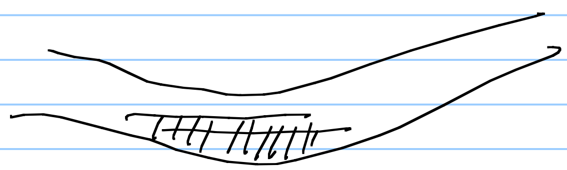
empirical
- based on adimensional numbers
- experiments

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

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

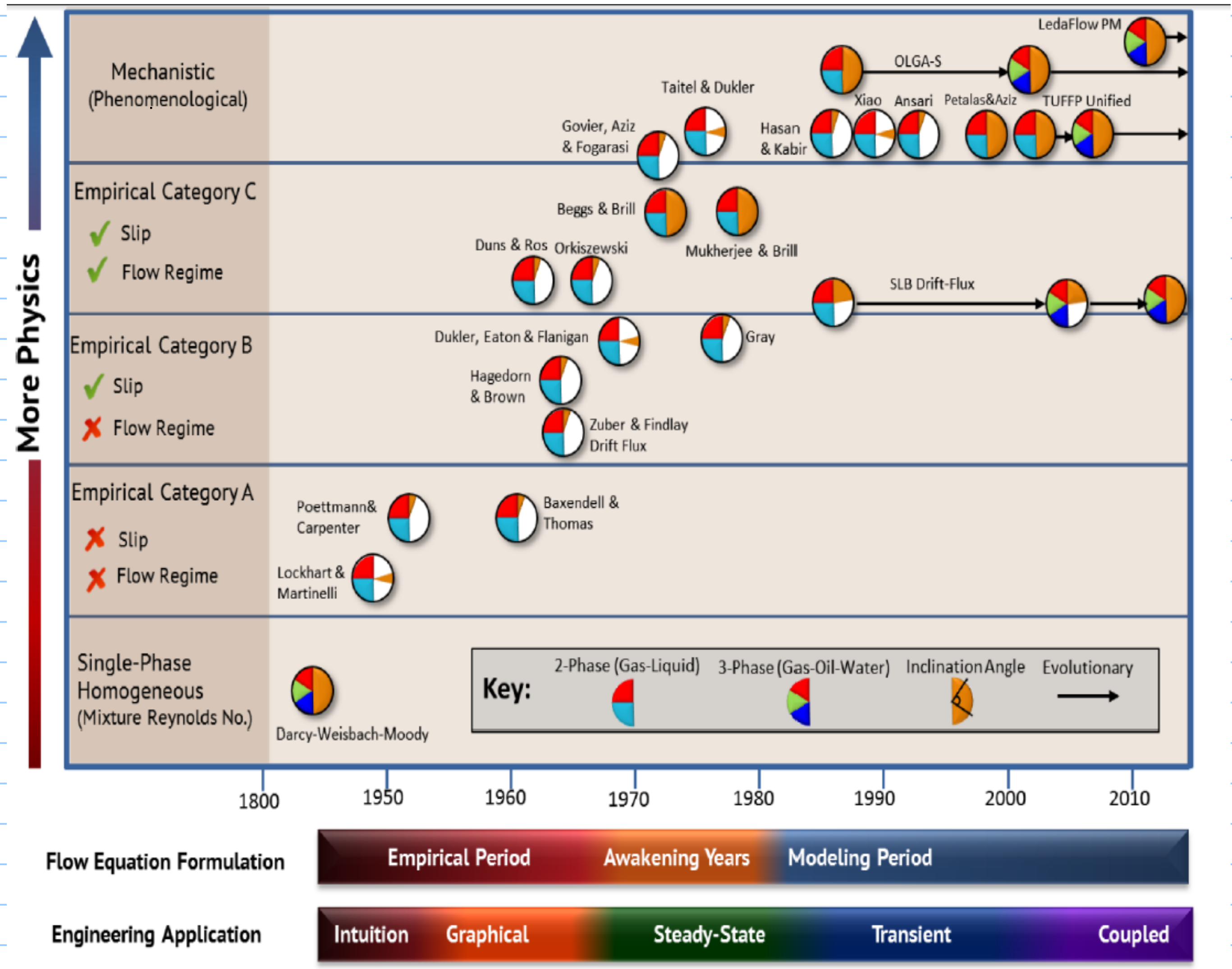

Top of line corrosion

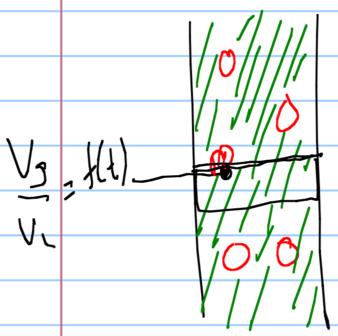
- O+W emulsion
- liquid accumulation and slugging



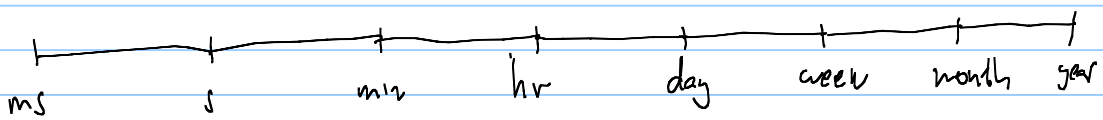
- sand erosion
- hydrate and wax --
- etc

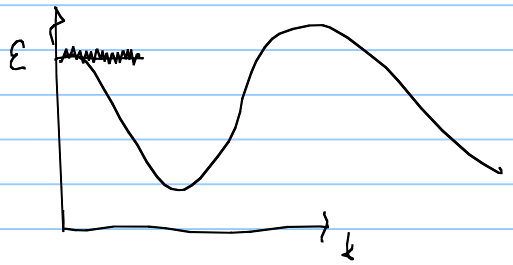
Shippen and Bailey (2012)





$\boxed{\text{steady state}}$ $\boxed{\text{transient}}$ slugging !





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

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

$\boxed{\text{if } \lambda_g \text{ is used then homogeneous model}}$

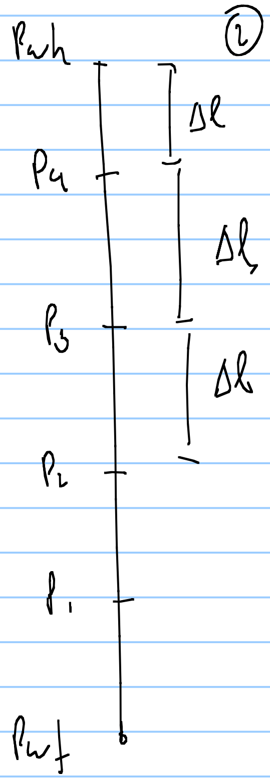
$$\rho_{TP} = \overset{\text{slip}}{\varepsilon}\rho_g + (1-\varepsilon)\rho_L$$

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

$\frac{dV_m}{dl} \simeq 0$ ~ 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. $P_4 = P_{wh} - \left.\frac{dp}{dl}\right|_{TVD=0} \cdot \Delta l$

- 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

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

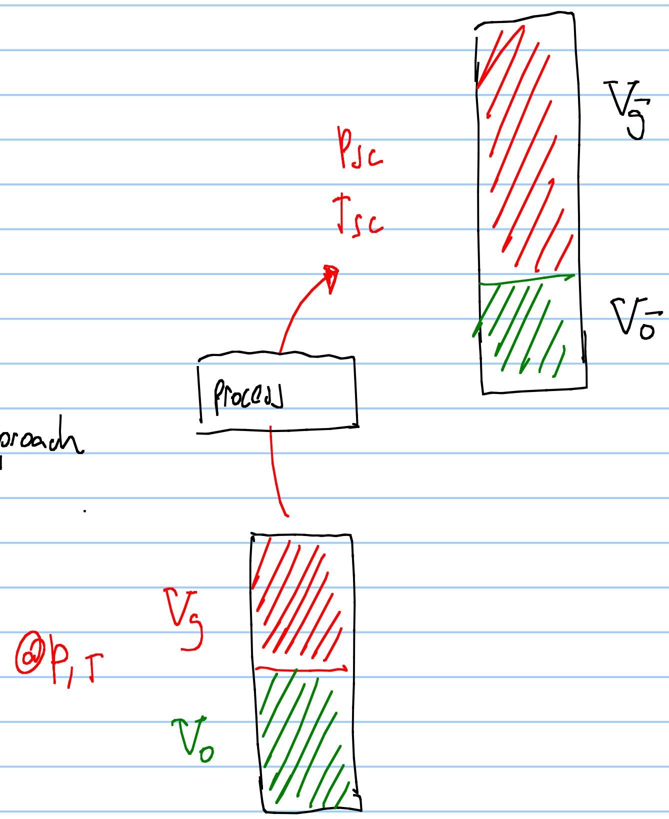
undersaturated oil

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

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

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

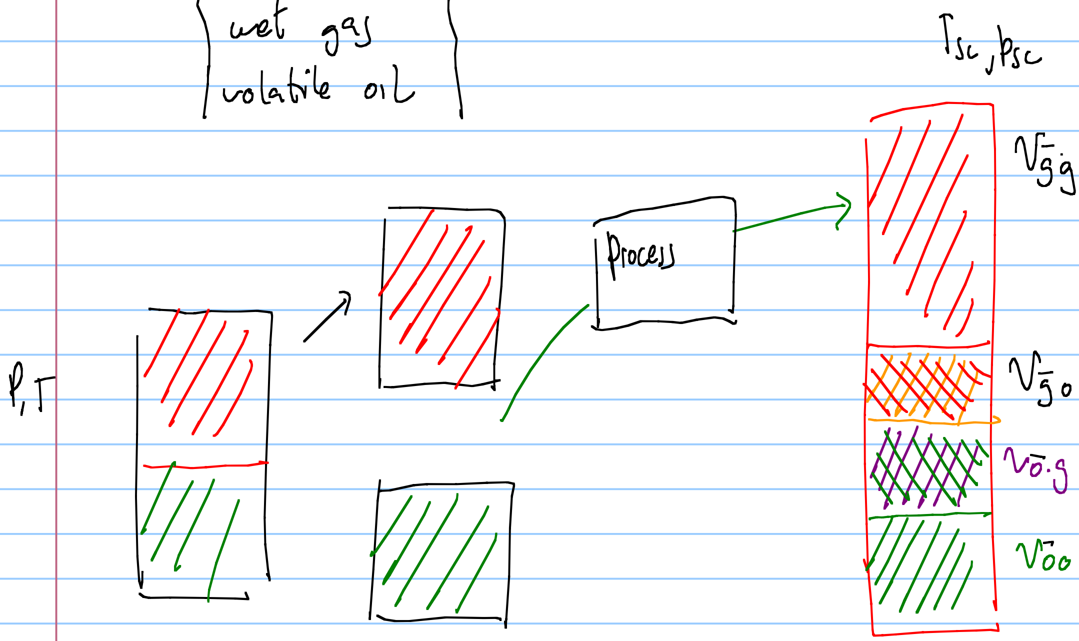
$$B_g(P,T) = \frac{V_g(P,T)}{V_{\bar{g}}}$$

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

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

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

- gas condensate
- wet gas
- volatile oil



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

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

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	$r_s(p,T) = \dfrac{V_{\bar{o}g}}{V_{\bar{g}g}}$

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

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			

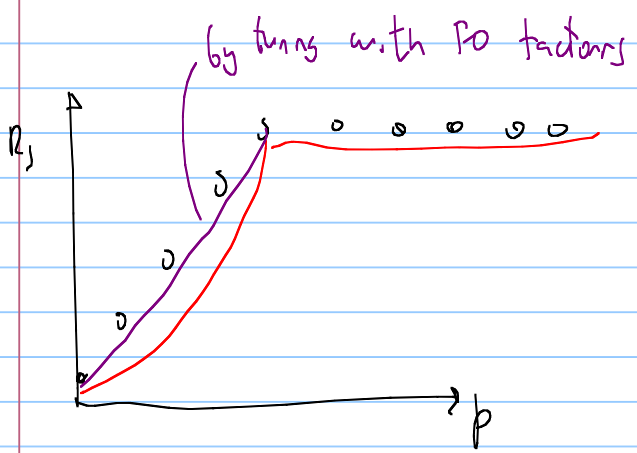
assuming $r_s = 0$

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

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

tuning BO correlations: FO1, FO2, FO3, FO4, FO5, FO6

in field units

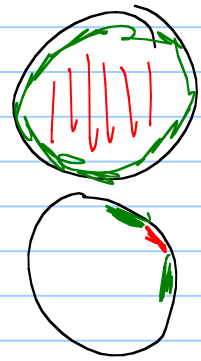


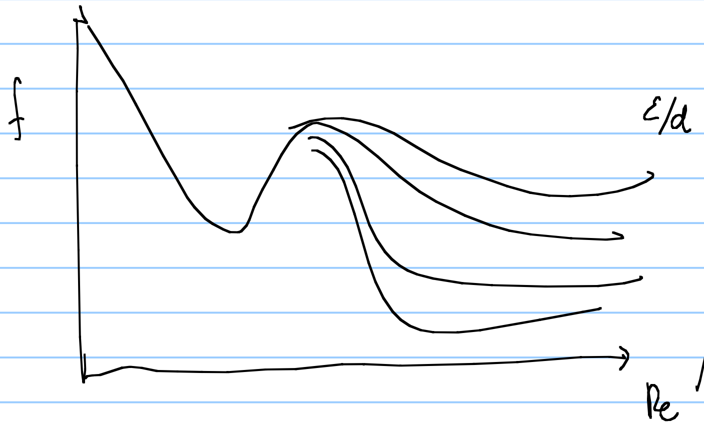
Pwh known and calculate Pwf for q_o = 1000 stb/d

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

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

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





u_m ρ_m

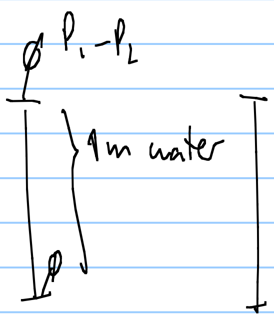
$$\frac{V \cdot \rho \cdot \phi}{\mu}$$

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

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

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

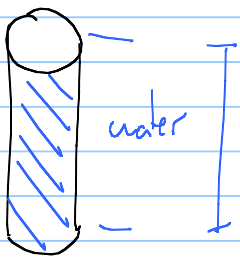
QC Quality control



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

$$10.000 \text{ Pa}$$

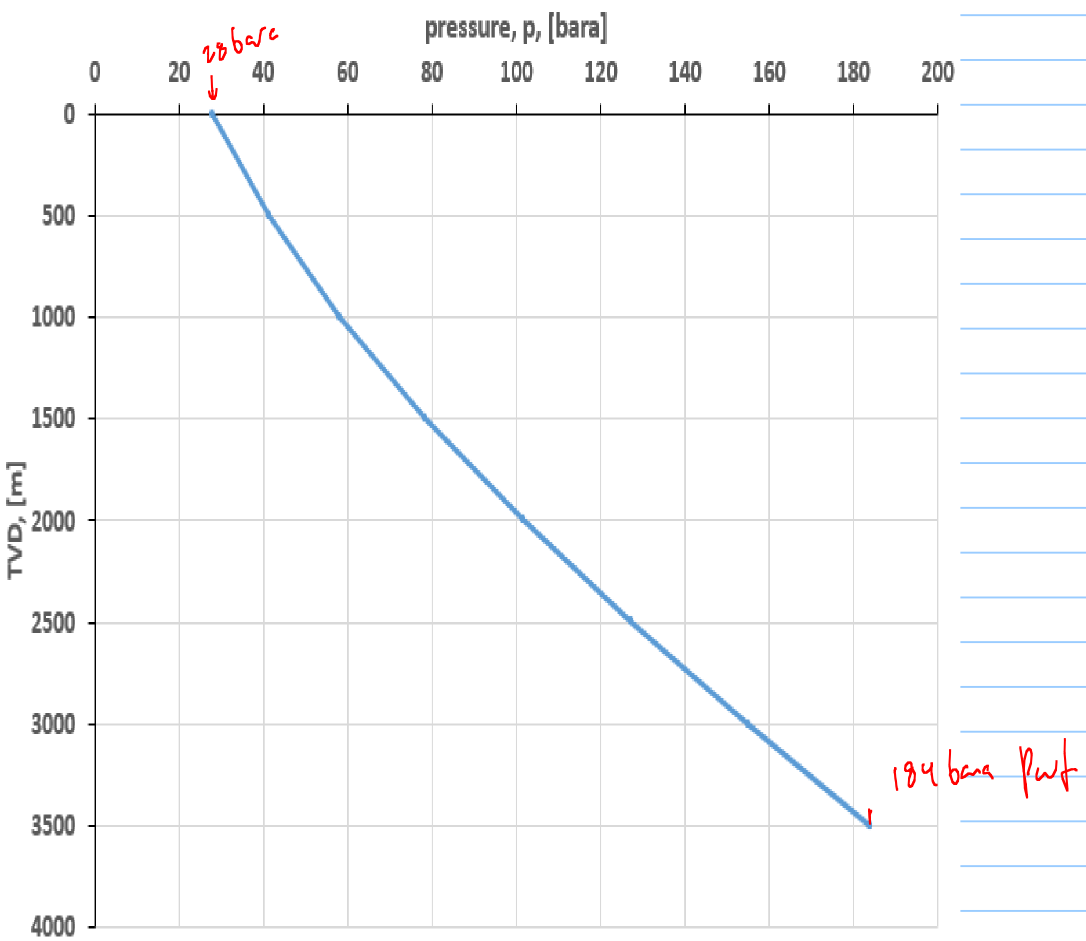
$$\approx 0.1 \text{ bar}$$

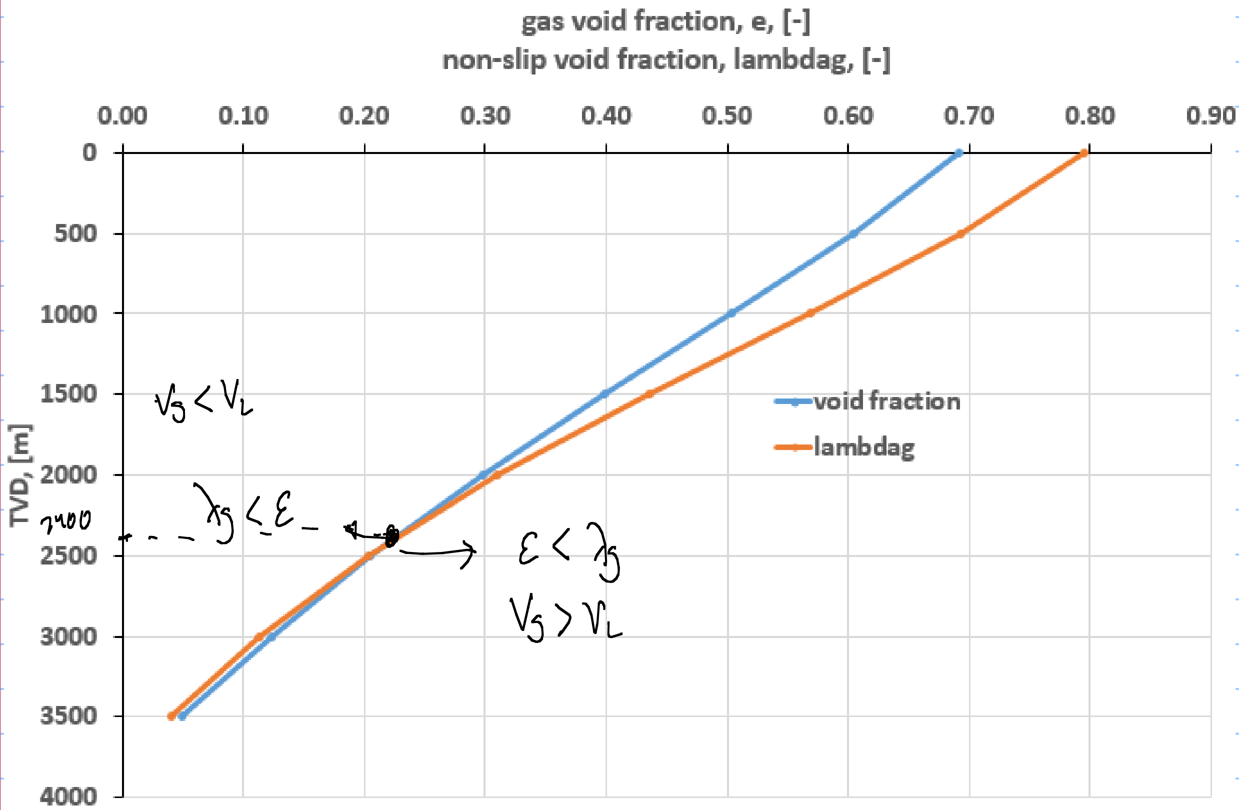


$$\Delta p = \rho_w \cdot \Delta L \cdot g = 10 \cdot 1 \cdot 1000 = 10000 \text{Pa} \cdot \frac{1 \text{bar}}{10^5 \text{Pa}} = 0.1 \text{ bar}/m$$

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. <

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

THANK YOU FOR YOUR ACTIVE PARTICIPATION!

--THE END--