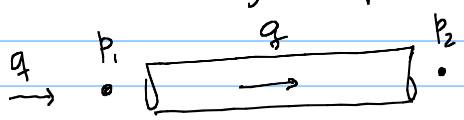
Day 2 03.12.2019

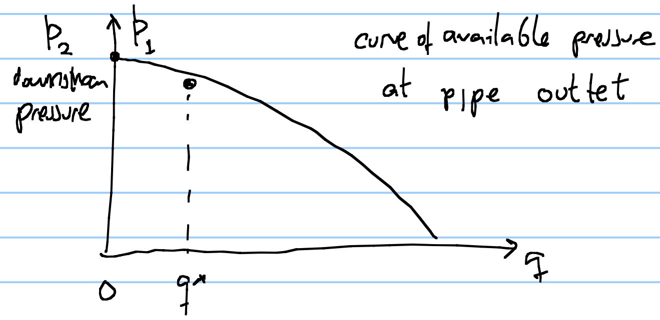
flow equilibrium

horizontal pipe

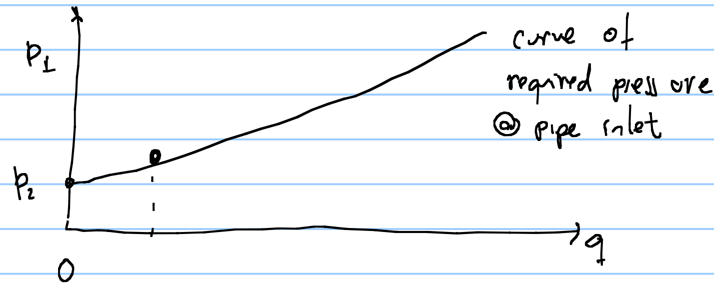


$$\Delta p_f = f \frac{L}{\phi} \frac{v^2}{2g}$$

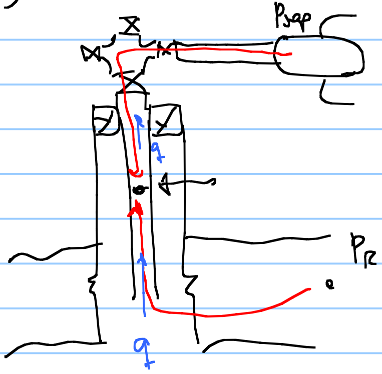
1) Fixed upstream pressure, P_1, change q

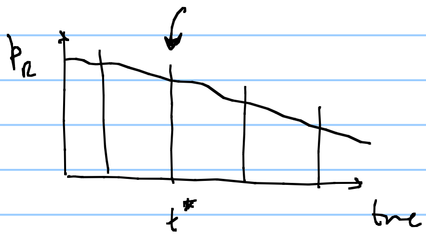


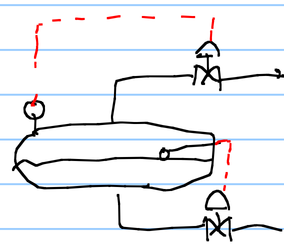
2) fixed downstream pressure P_2, vary the rate



looking back at our production system

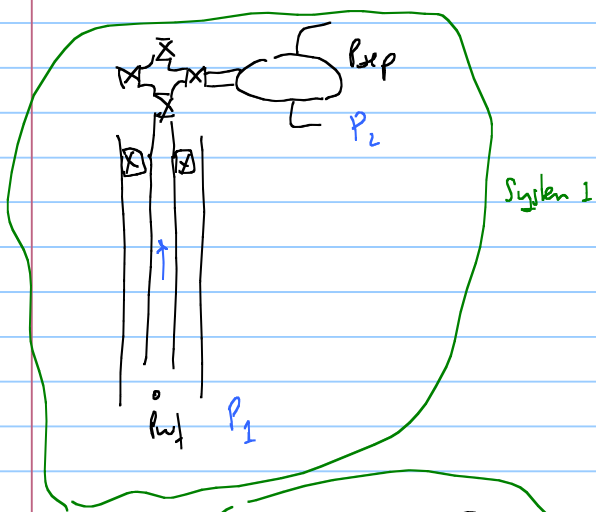






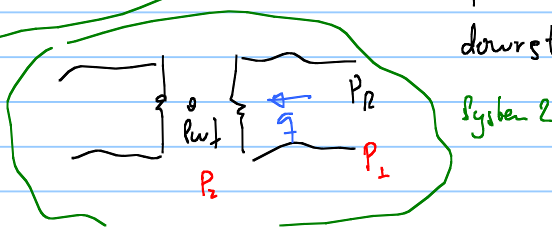
to determine flow rate of petroleum systems we usually use equilibrium analysis

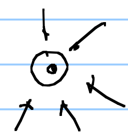
- select an equilibrium point (wellhead P_{wh} / bottom-hole P_{wf}) → chokes → pumps

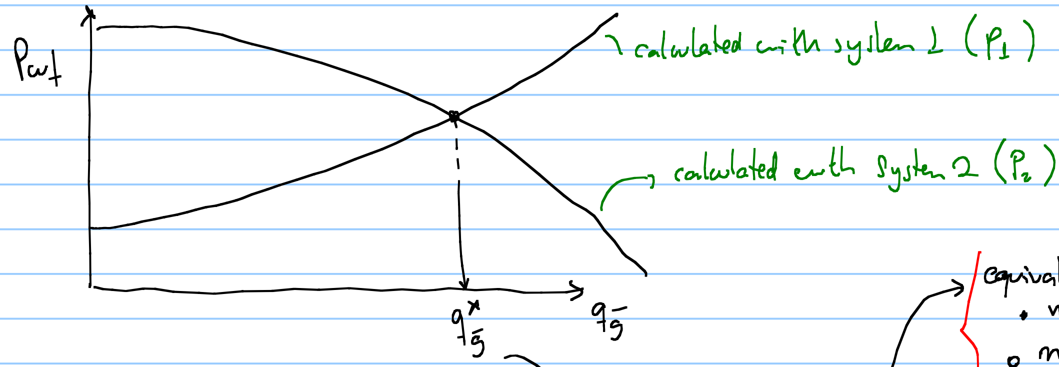


- plot the available pressure curve calculated from the upstream boundary with constant pressure

- plot the curve of required pressure from the downstream boundary with constant pressure

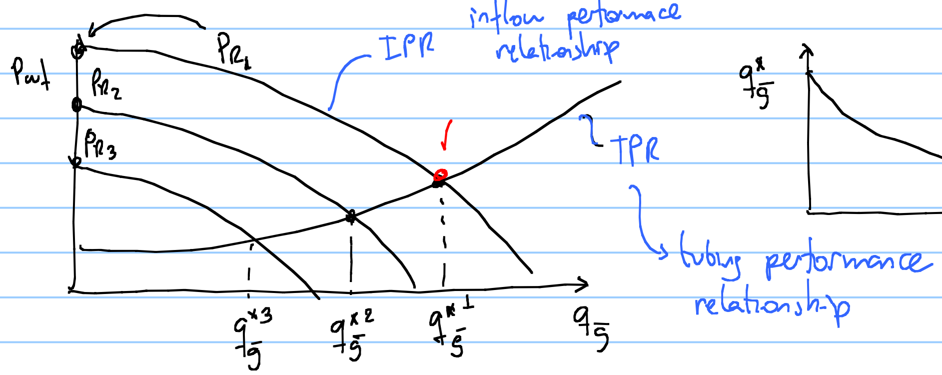


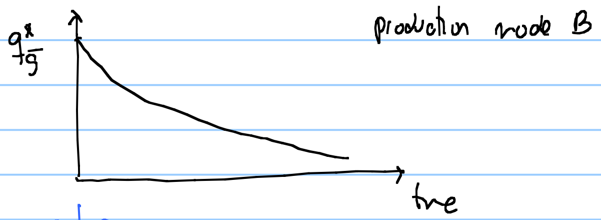




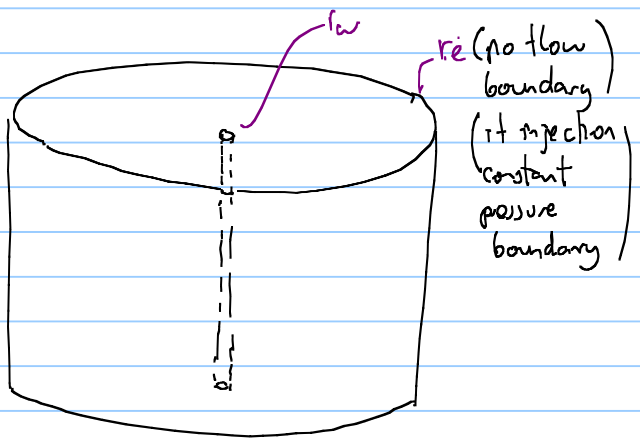
equilibrium rate → equivalent to solve:
- mass conservation eq
- momentum conservation eq
- energy conservation eq

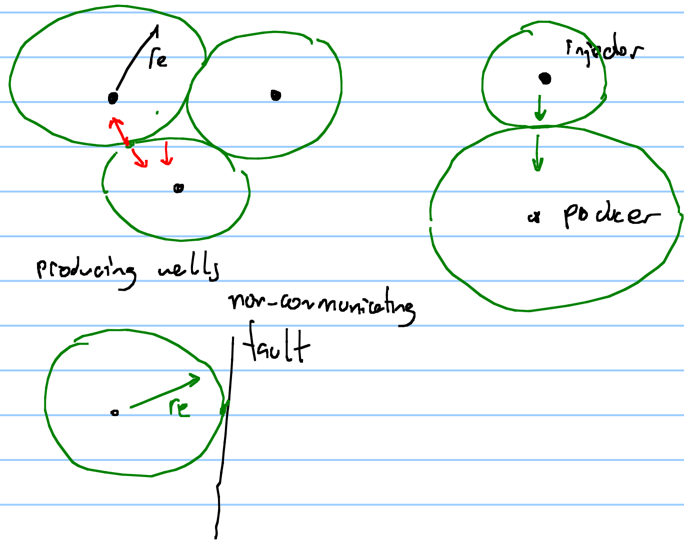
in time P_R usually declines. how does the intersection change? $q_{\bar{g}}^*$



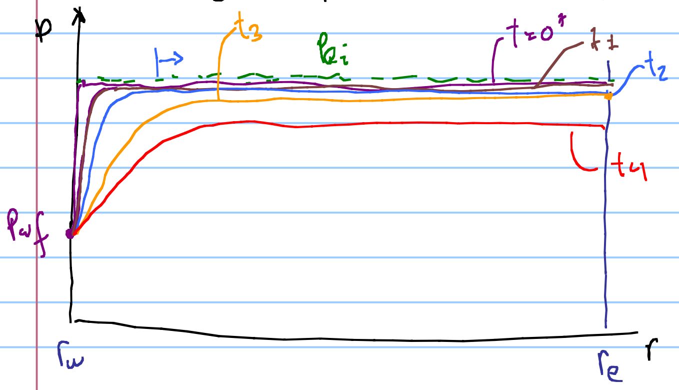


IPR:





initially, no production, everything @ P_{Ri}



so at time $t=0$ $\quad P_{(r=r_w)} = P_{wf}$ const

@ t_3 the pressure change reaches the boundary

two distinct regimes

$t=0 \rightarrow t_3$ "infinite acting" transient

$t_3 \rightarrow$ forward PSS pseudo steady state

for PSS, IPR equations can be written as a function of $q_{\bar{g}}$, P_R, P_{wf} only

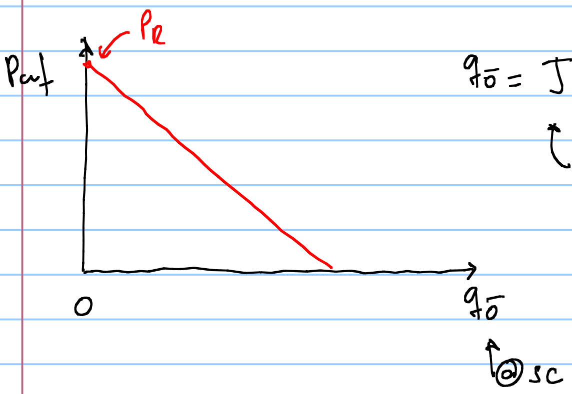
for II, IPR equations must be a function of time, $q_{\bar{g}}$, P_{Ri}, P_{wf}

1 for conventional reservoirs where K (permeability) is medium-high, the infinite acting $t=0 \rightarrow t_3$ is very short (hours → days). Therefore, most of the production occurs in PSS

→ we will work with PSS equations in class

2 However for unconventional reservoirs tight reservoir, shale reservoir, K low to super low, the infinite acting period $t=0 \rightarrow t_3$ might take months → years. Therefore most of the production occurs in II
↳ IPR must consider time

PSS IPRs for oil (undersaturated), Gas, oil+gas



$$q_{\bar{o}} = J\,(P_R - P_{wf})$$

↑ productivity index

$$J = \frac{2\pi \cdot k \cdot h}{\mu_o \cdot B_o \cdot \left[\ln\left(\frac{r_e}{r_w}\right) - 0.75\right]}$$

h: height of reservoir layer

undersaturated oil

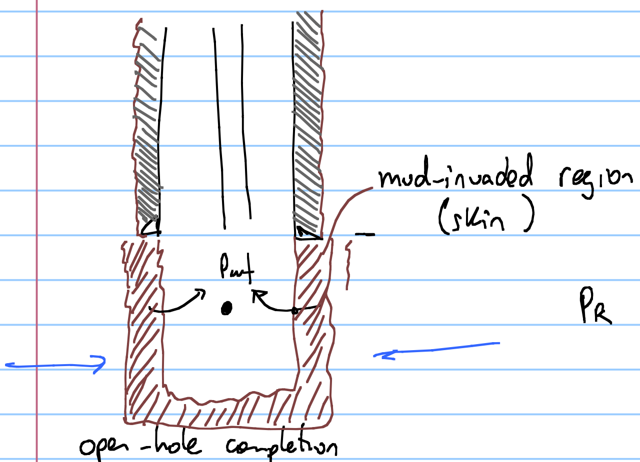
for dry gas

$$q_{\bar{g}} = C\,(P_e^2 - P_{wf}^2)^n$$

n → back pressure exponent (0.5 – 1) turbulence of flow

dry gas backpressure equation for medium-low pressure

C ↳ backpressure coefficient

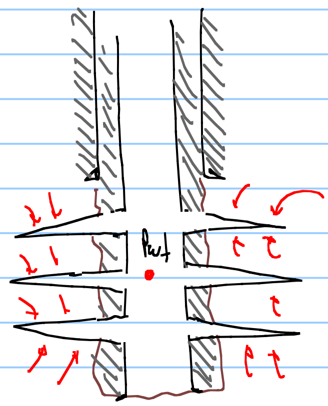


to capture the effect of skin, a factor S is included in the IPR. For example, for liquid

$$J = \frac{2\pi\, k\, h}{B_o\, \mu_o \left(\ln \frac{r_e}{r_w} - 0.75 + S\right)}$$

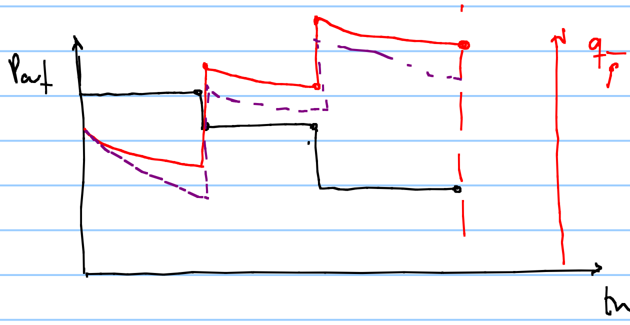
$$q = J\,(P_R - P_{wf})$$

S: usually consider near well flow impairment "restrictions".



cased and perforated completion

well testing



in programs $q_g = f(t, P_{Ri}, K, \phi, \mu_o, P_{wf}, h, r_e)$

$q_{g\,measured} \neq q_{g\,simulated}$

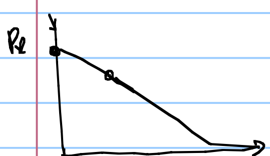
find reservoir properties (h, K, ϕ) such that

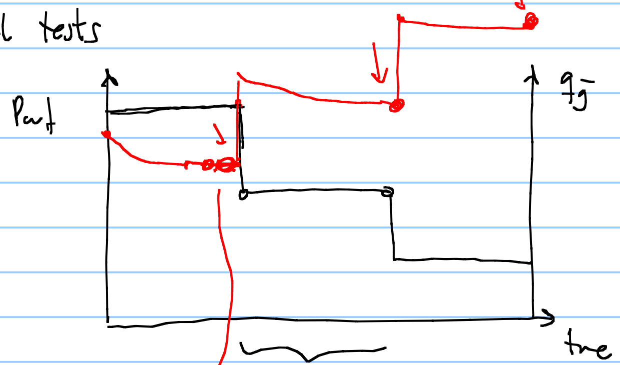
$q_{g\,measured} = q_{g\,simulated}$

$$q_g = \underbrace{\frac{\cancel{2}\pi K h}{\left[\ln\frac{r_e}{r_w} - 0.75 + S\right]} \frac{T_{sc}}{T_R\, P_{sc}} \left(\frac{1}{\mu z}\right) \frac{1}{\cancel{z}}}_{C,\ \text{back pressure coefficient}} \left(P_R^2 - P_{wf}^2\right)$$

IPR's can be estimated from analytical equations derived for simple cases or can be derived from stabilized well tests

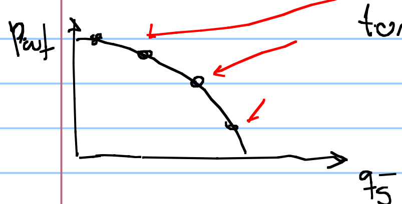
$q = J(P_R - P_{wf})$





depending on reservoir mins → hrs → days

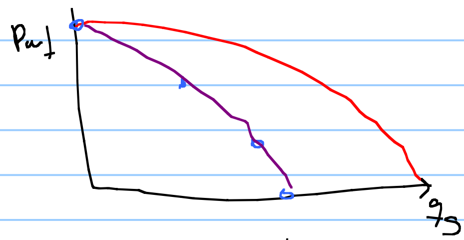
$q = C\left(P_R^2 - P_{wf}^2\right)^n$?



tune C and n to reproduce test results

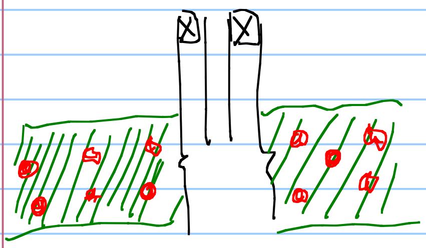
C □
n □

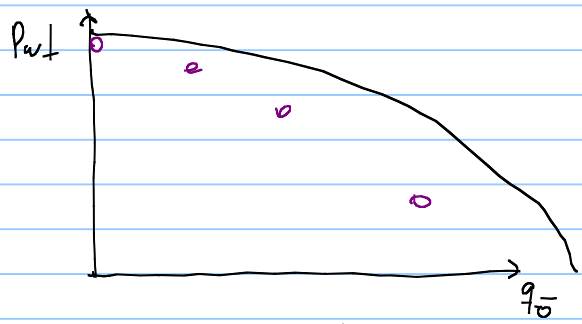
P_{wf}	q_g
□	□
□	□
□	□



change C, n until passes through

Saturated oil (simultaneous flow of oil and gas near wellbore)

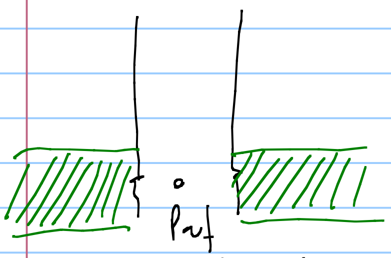




analytical expressions are more complex, but people typically use Vogel

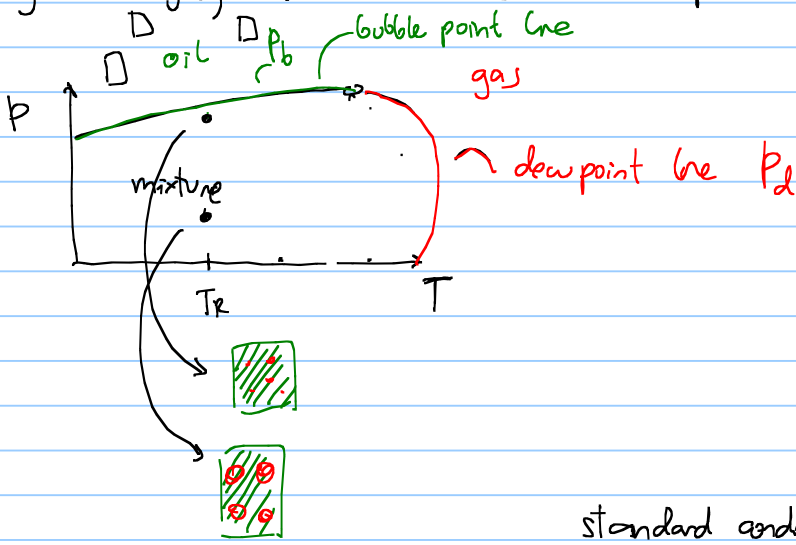
$$\frac{q_{\bar{o}}}{q_{\bar{o}max}} = 1 - 0.2\frac{P_{wf}}{P_R} - \frac{P_{wf}^2}{P_R^2}$$ tune $q_{\bar{o}max}$ to measurements

How to compute other phases? e.g. gas, water when well is oil producer?

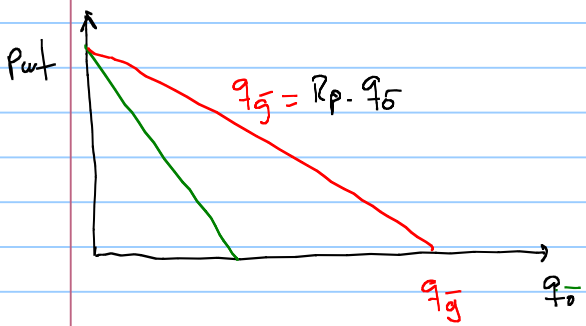


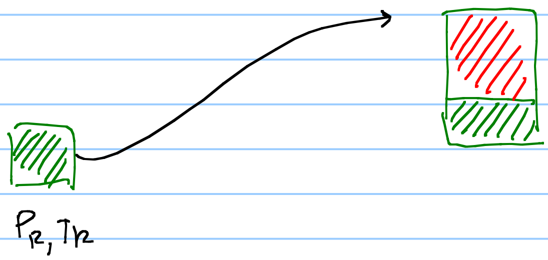
undersaturated oil

$P_{wf} > P_b @ T_R$



standard conditions P_{sc}, t_{sc}



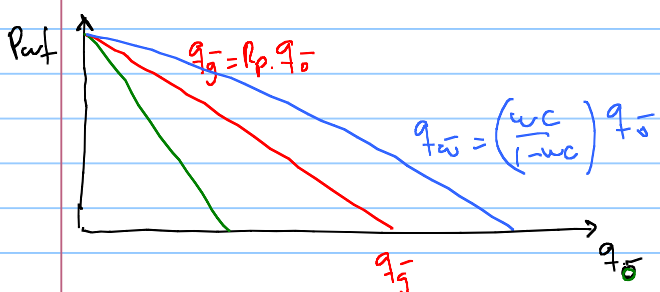


GOR,

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

$$WC = \frac{q_{\bar{w}}}{q_{\bar{o}} + q_{\bar{w}}} \Rightarrow q_{\bar{w}}(1-WC) = q_{\bar{o}}\,WC$$

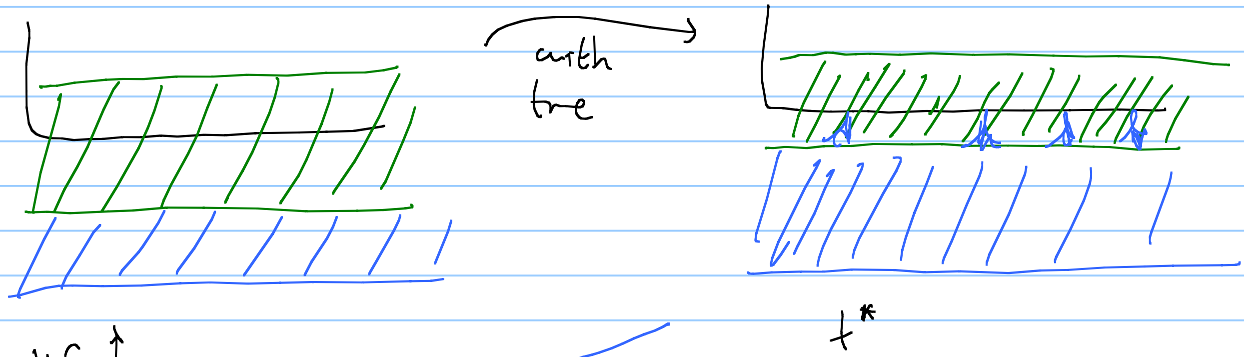
$$q_{\bar{w}} = q_o\left(\frac{WC}{1-WC}\right)$$

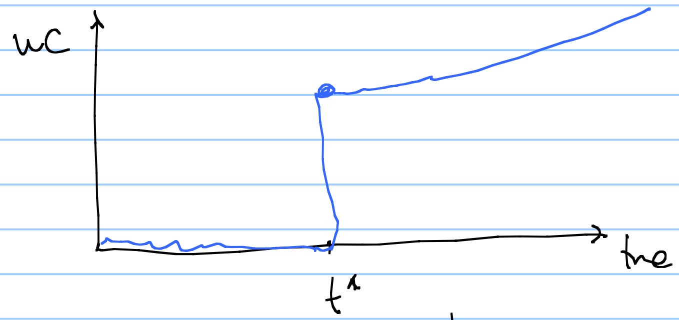


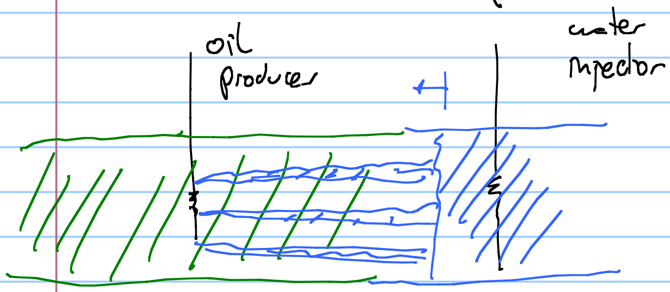
R_p and WC might change with time!

for example

for example wc migh change with water cusping







"Available" curve (IPR)

required curve (TPR) tubing performance relationship

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

tubing coefficient

elevation coefficient (NOT skin)

$$P_1 = \left[\left(\left(\frac{q_g}{C_T}\right)^2 + P_2^2\right) e^s\right]^{0.5}$$

$$P_2 = \sqrt{\frac{P_1^2}{e^s} - \left(\frac{q_g}{C_T}\right)^2}$$

Tubing flow Equation-Dry gas

K 15.56 + 273.15 K

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

Universal gas constant $R = 8.314 \frac{J}{kmol\,K}$

M = molecular weight

$MW_{air} = 28.97$

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

height difference

g: 9.81 m/s^2

T_{av}: $\frac{T_{wh} + T_{wf}}{2}$

$Z_{av} = \frac{Z_{wf} + Z_{wh}}{2}$

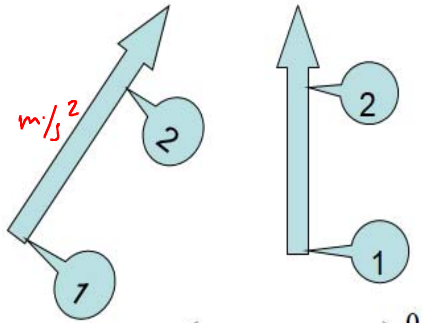
γ_g gas specific gravity

$\gamma_g = \frac{MW_g}{MW_{air}}$

CH_4 12+4 = 16

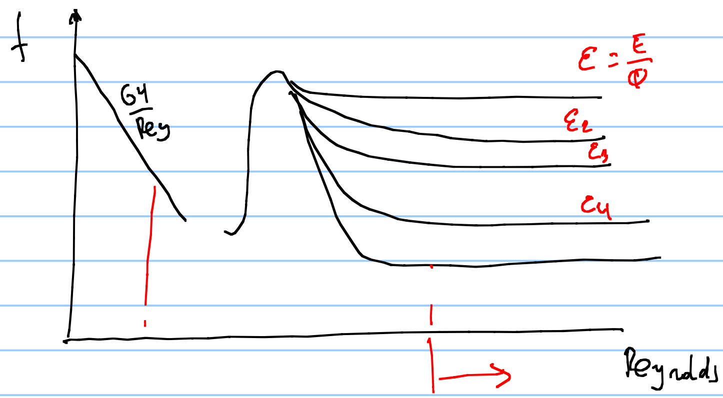
$\gamma_{g\,CH_4} = \frac{16}{28.97}$

$\gamma_{g\,CH_4} = 0.55$



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

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



$Re = \frac{v \rho \Phi}{\mu}$ ✓

Re are usually very high

v are high

μ are very low

liquid 1E-3 Pa s

gas 1E-5 Pa.s

gas is usually in the fully turbulent region

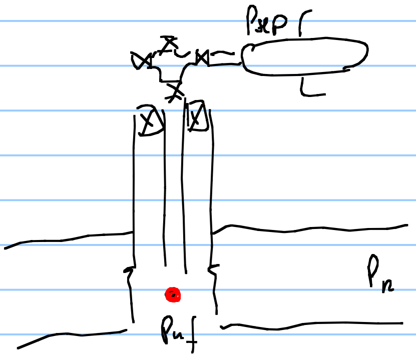
$f \neq F(Re)$

$f = F(\epsilon)$

$\epsilon = f(\Phi)$

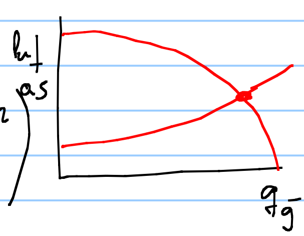
$$f_M = \frac{0.01748}{D^{0.224}\cdot\left(|1\,m|\cdot\left|\frac{39.37\,in}{1\,m}\right|\right)^{0.224}} = \frac{0.0077}{D^{0.224}}$$

Class exercise



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

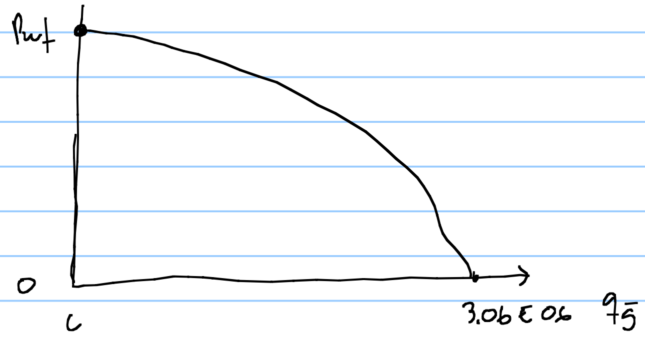
$P_{wf} = \left(P_R^2 - \left(\frac{q_g}{C_R}\right)^{1/n}\right)$

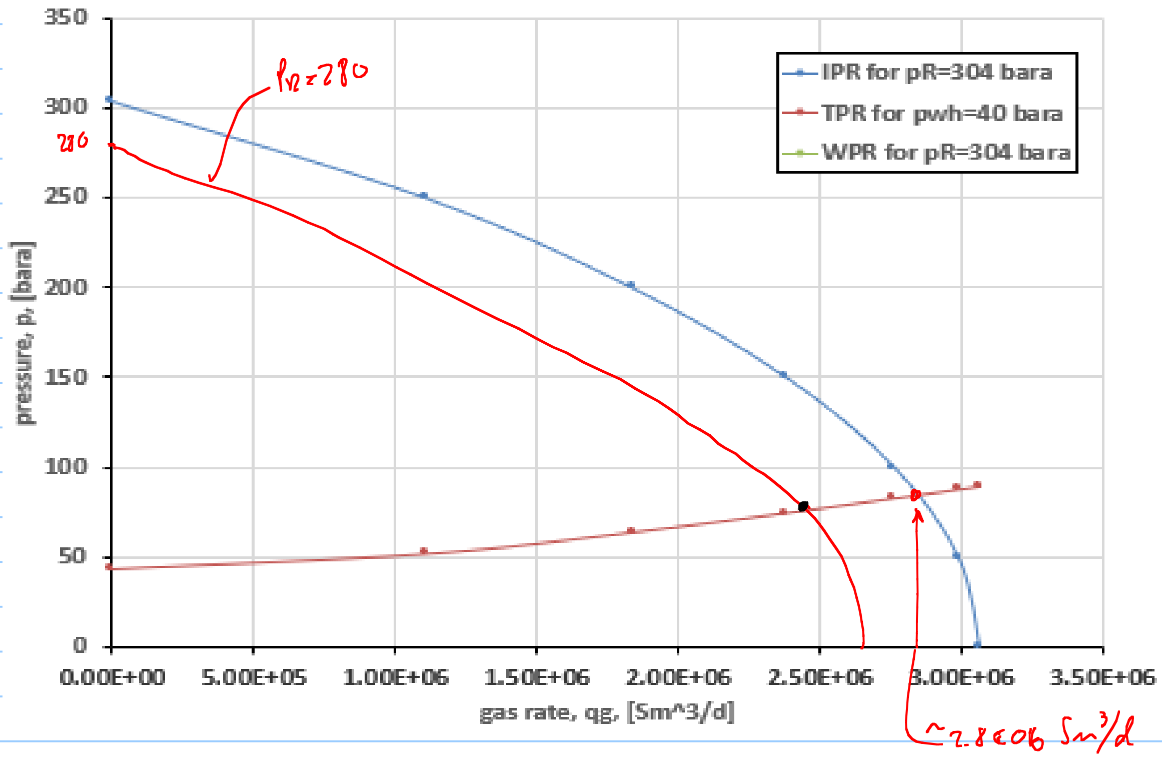


from pxp → Pwf

$$p_{wf} = \left[\left(\left(\frac{q_g}{C_T}\right)^2 + p_{wh}^2\right) e^s\right]^{0.5}$$

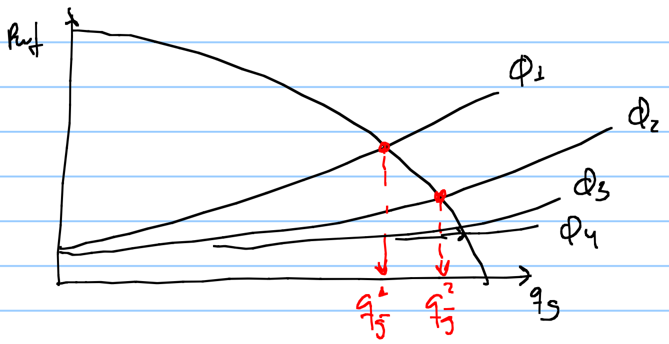
	IPR
pwf_avail	qg
[bara]	[Sm^3/d]
304	0.00E+00
250	1.11E+06
200	1.84E+06
150	2.38E+06
100	2.76E+06
50	2.99E+06
0	3.06E+06





How do we decide on tubing size (Φ) NOT POROSITY!

Φ ↑



Φ2 > Φ1

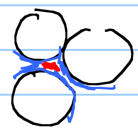
Φ↑ also costs more

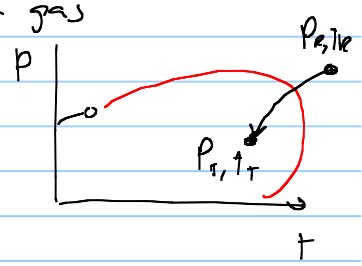
Φ3 and Φ4 don't give a substantial increment in rate

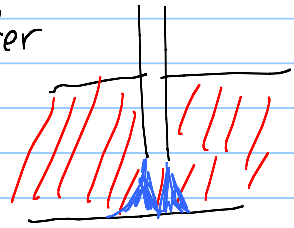
Usually wells produce not only gas, but liquid → oil condensing from gas

↳ water condensing out of gas

↳ coning from aquifer







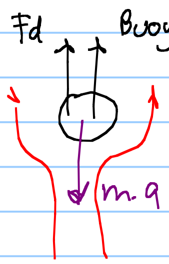
the gas must evacuate the liquid from well

gas velocity V_g must be high enough to drag liquid out of well

If Φ $V_g \downarrow$ then liquid dragging capacity will be reduced ! ⇒ liquid loading

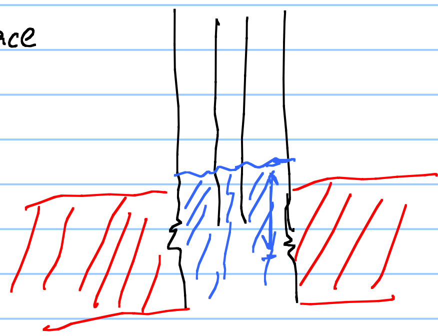
choose a diameter that assures liquid is carried to surface

V_g should be high enough



liquid droplet

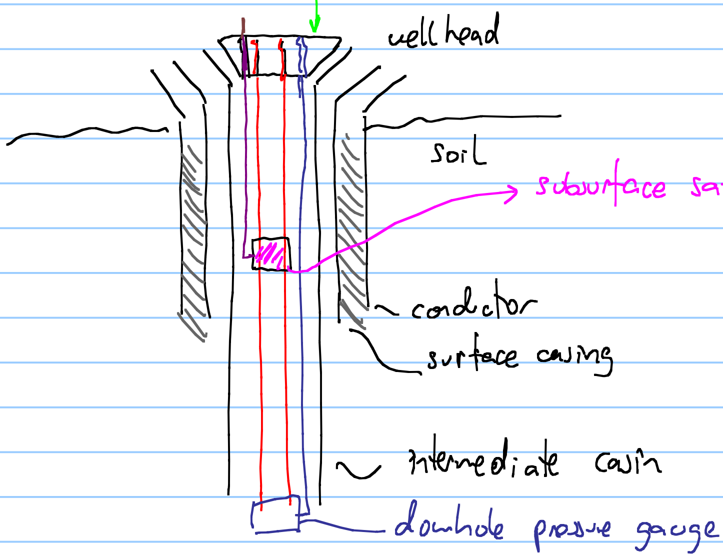
$F_d + F_B = F_{weigh} \Rightarrow V_g^{Turner}$

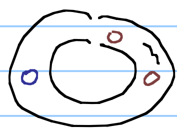


- Erosion usually wells produce particles and liquid, if Φ is too small this can cause erosion.

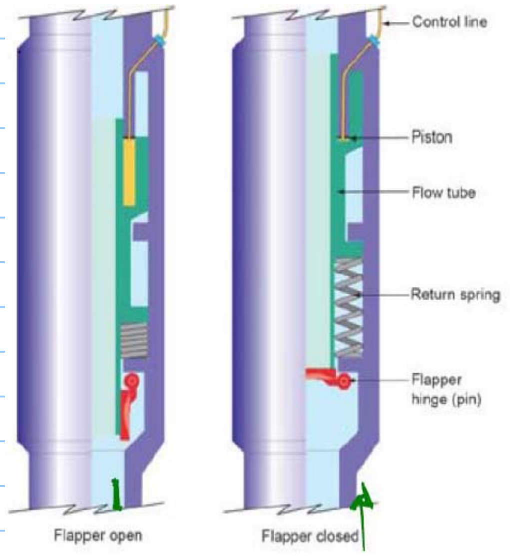
$V_g < V_{erosional} \rightsquigarrow$ API 14E

- tubing hangar





leave enough space in the hanger



how to find the equlibrium point

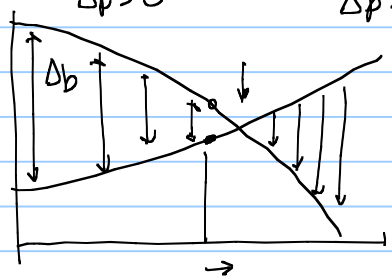
$f_1(x)$ find x^* such that $f_1(x^*) = f_2(x^*)$

$f_2(x)$

$f_3 = f_1 - f_2$ find x^* such that $f_3(x^*) = 0$

root finding

$\Delta p > 0$ $\Delta p < 0$



	IPR	TPR	
pwf_avail	qg	pwf_req	pwf_avail-pwf_req
[bara]	[Sm^3/d]	[bara]	[bara]
304	0.00E+00	43.2	260.8
250	1.11E+06	51.6	198.4
200	1.84E+06	63.7	136.3
150	2.38E+06	74.4	75.6
100	2.76E+06	82.5	17.5
50	2.99E+06	87.4	-37.4
0	3.06E+06	89.1	-89.1

the solution is between these two. When $P_{wf avail} - P_{wf req}$ equals zero

Goal seek

	IPR	TPR	
pwf_avail	qg	pwf_req	pwf_avail-pwf_req
[bara]	[Sm^3/d]	[bara]	[bara]
304	0.00E+00	43.2	260.8
250	1.11E+06	51.6	198.4
200	1.84E+06	63.7	136.3
150	2.38E+06	74.4	75.6
84.3784	2.85E+06	84.4	0.0
50	2.99E+06	87.4	-37.4
0	3.06E+06	89.1	-89.1

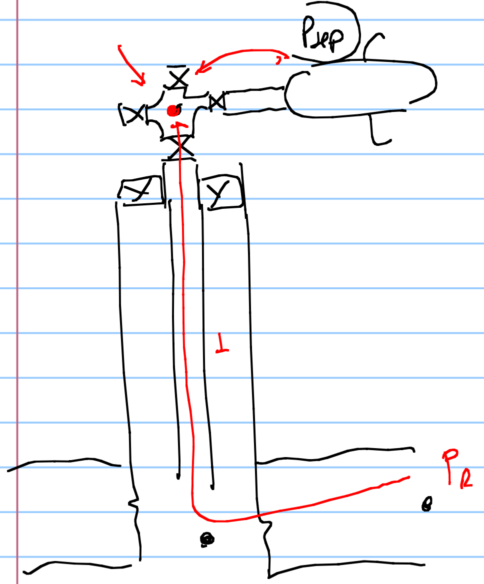
← equilibrium rate $q_g = 1.85\ E06\ Sm^3/d$

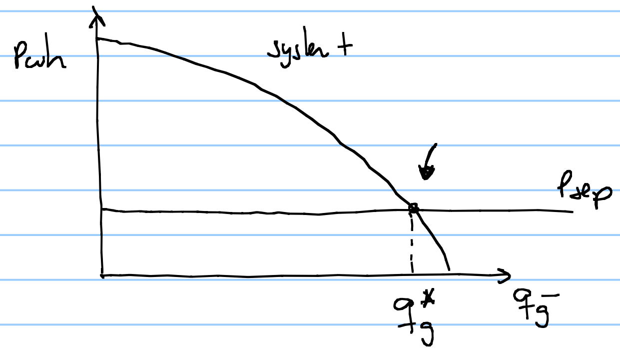
$P_{wf} = 84.37$ bara

$$q_g = C_R \left(P_R^2 - P_{wf}^2\right)^n \qquad q_g = C_T \left(\frac{P_{wf}^2}{e^S} - P_{wh}^2\right)^{0.5}$$

Two equations with two unknowns

- change equilibrium point ⇝ at wellhead



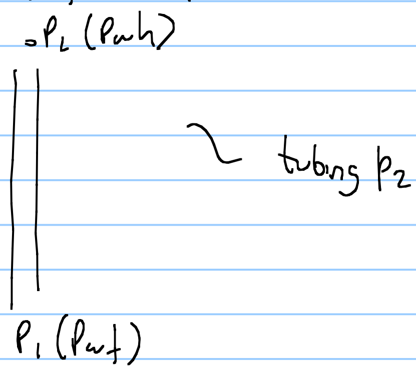


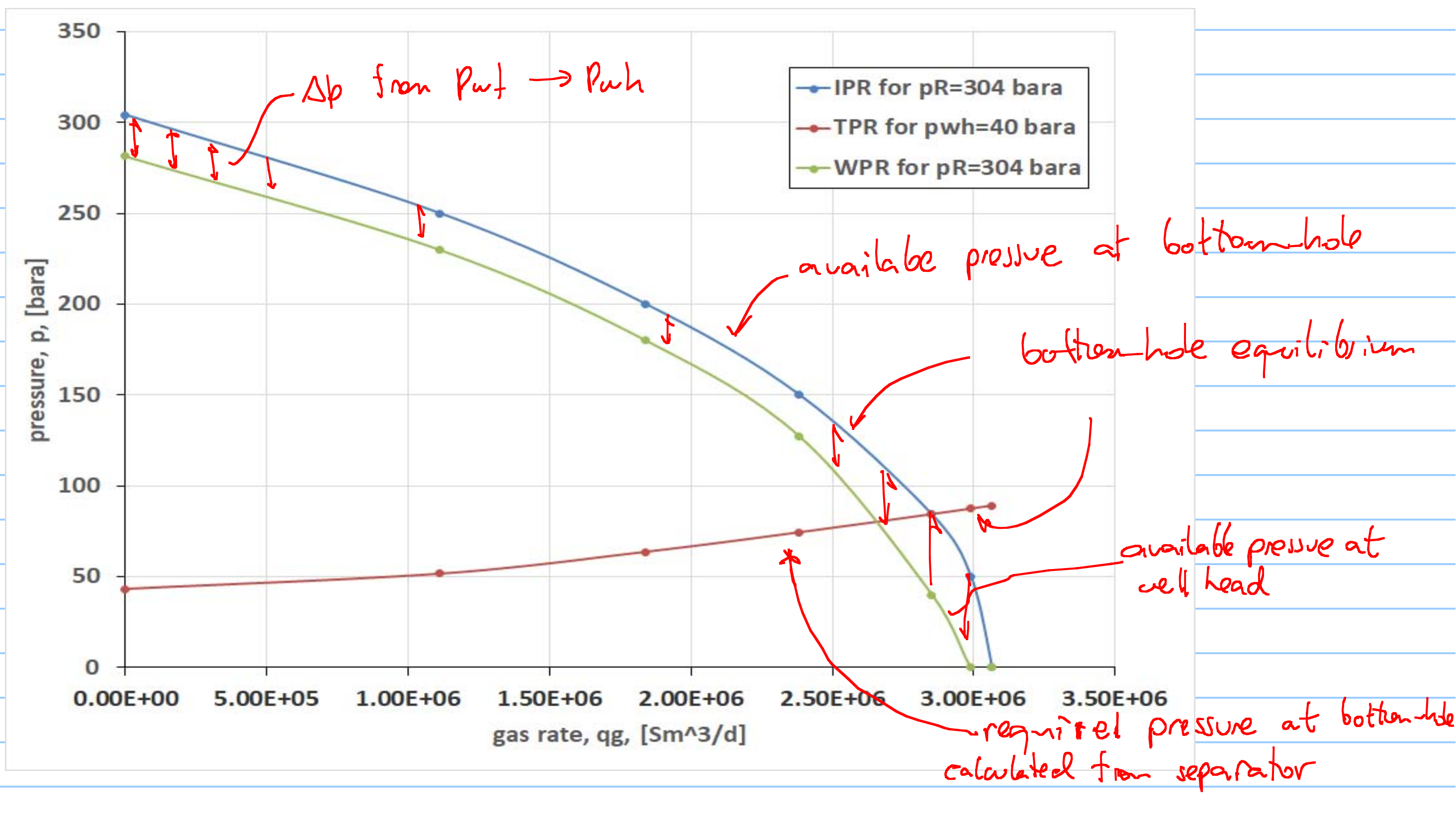
very close to wellhead, therefore Δp friction at flowline is neglected

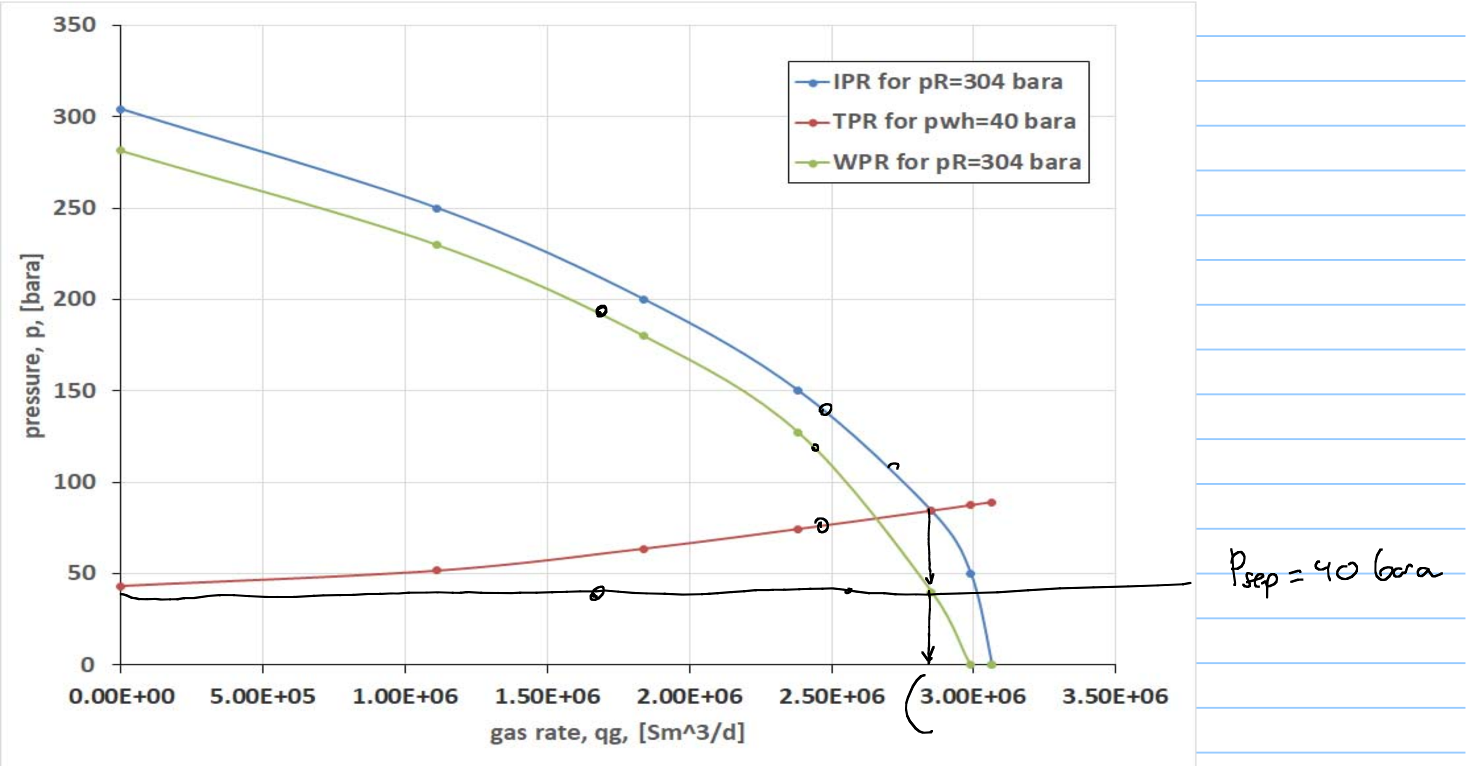
↳ 2.85 E06 Sm³/d same system!

the system is the same regardless of equilibrium point

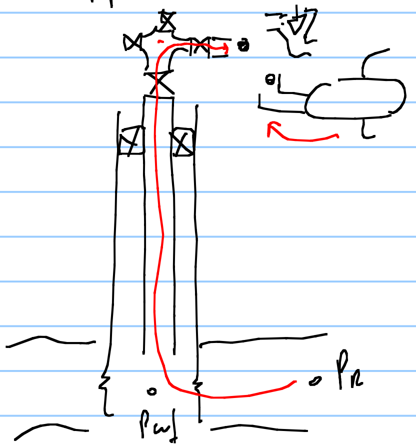
move from Pwf ⇝ Pwh



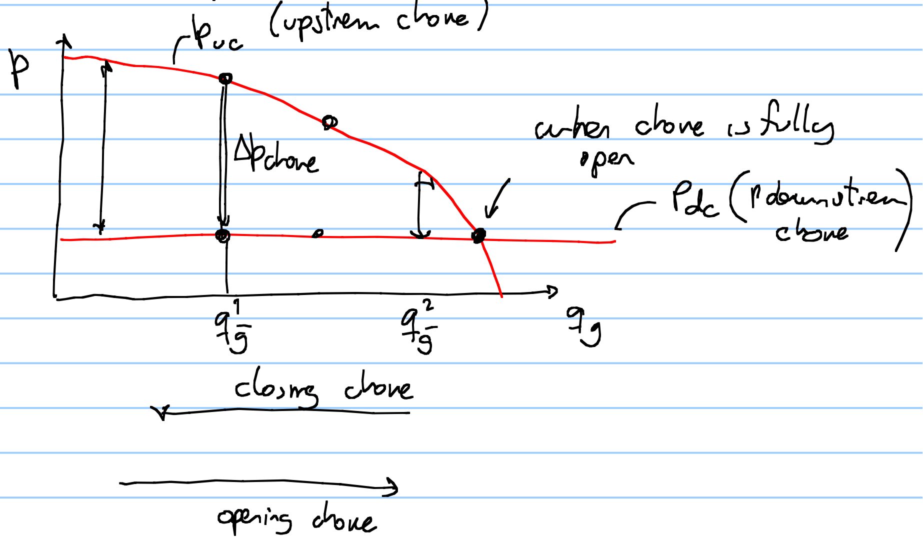


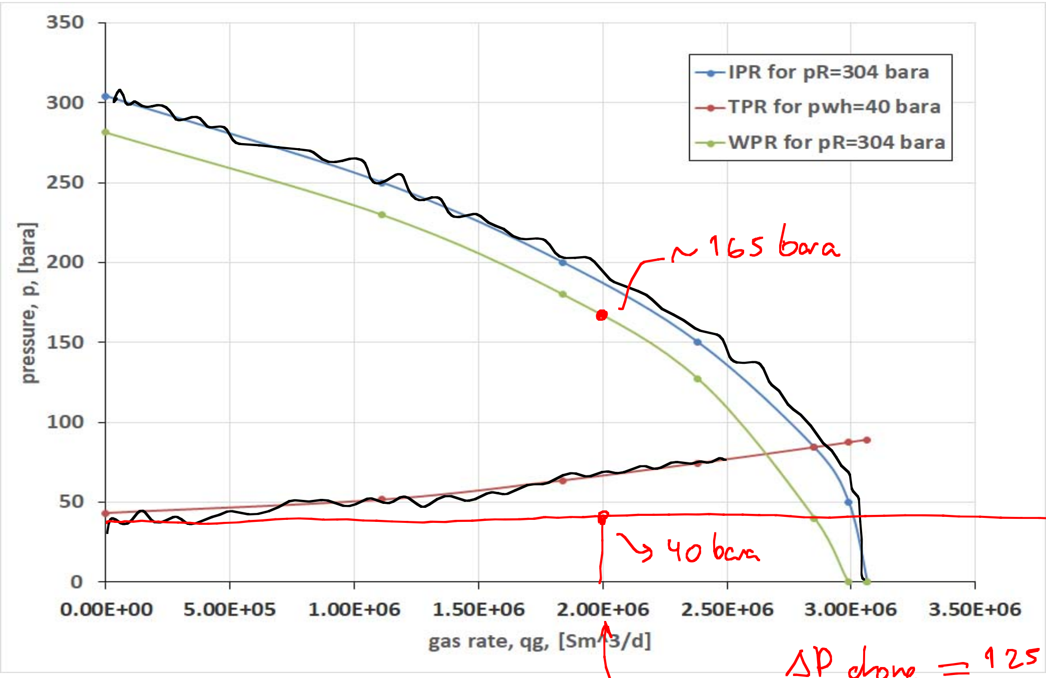


what happens when there is a choke?



- remove choke
- compute available pressure at choke inlet and required pressure at choke outlet

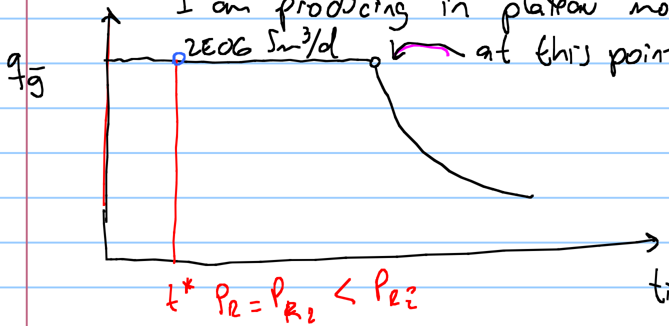




what choke Δp is needed to produce $q_g = 2E06\ Sm^3/d$?

ΔP choke $= 125$ bara

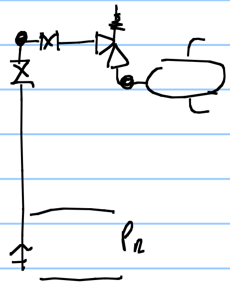
I am producing in plateau mode

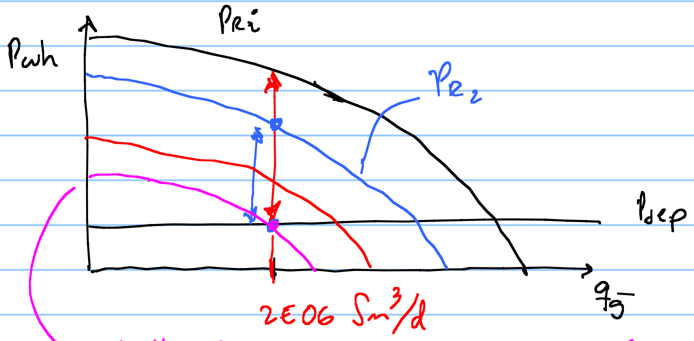


at this point choke is fully open!

t^* $P_R = P_{R_2} < P_{Ri}$

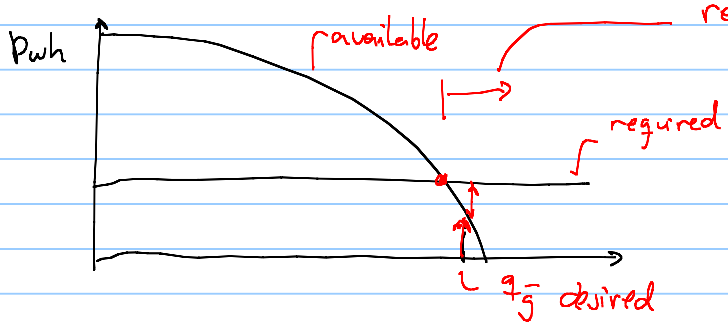
$\Delta p_{choke_2} < \Delta p_{choke_i}$





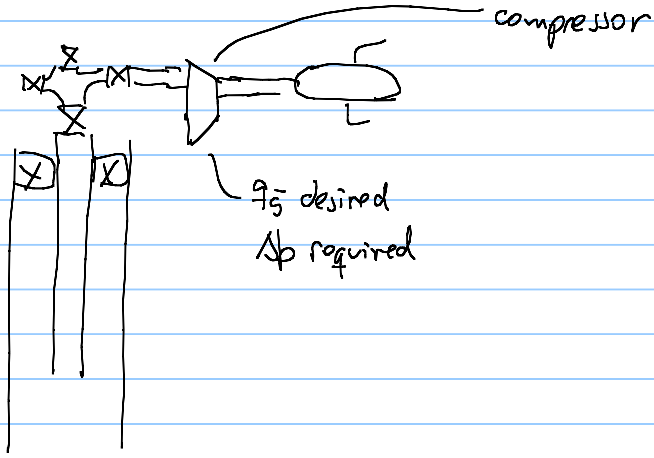
at this P_R, there is no need for choke

what if i need a rate bigger than equilibrium rate ?



required energy is greater than available!

to place a component that gives energy, like a compressor or a pump


compressor
q_g desired
Δp required