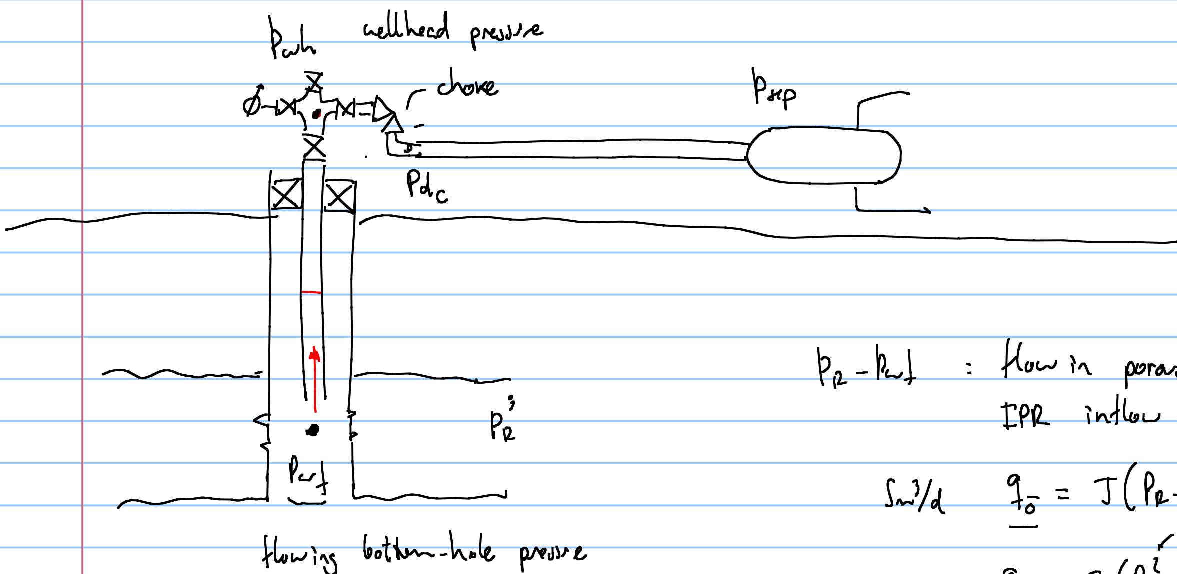
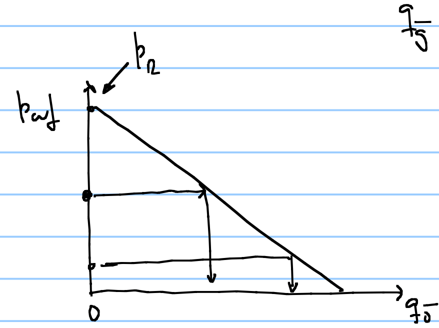
Flow equilibrium in dry gas production systems



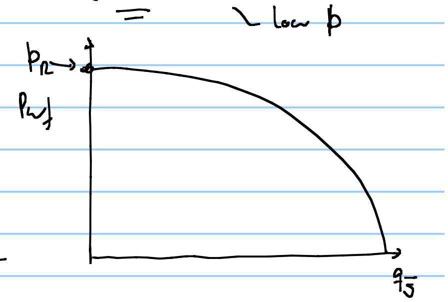
$p_R - P_{wf}$: flow in porous media
IPR inflow performance relationship

Sm^3/d $\quad q_o = J(P_R - P_{wf})$ PSS

$q_g = C(P_R^2 - P_{wf}^2)^n$ PSS — low p



undersaturated oil, water injection



Dry gas
saturated oil
saturated gas

$P_{wf} \rightarrow P_{wh}$
flow in tubing (pipe)

① ——— ②

$Re = \frac{\rho \phi V}{\mu}$, $\varepsilon = \frac{e}{\phi}$

$$\underbrace{z_1 + \frac{P_1}{\rho \cdot g} + \frac{V_1^2}{2g}}_{h_1} = \underbrace{z_2 + \frac{P_2}{\rho \cdot g} + \frac{V_2^2}{2g}}_{h_2} + f\frac{L}{\phi}\frac{V^2}{2g}$$

A. The Tubing Rate Equation in Vertical and Deviated Gas-Wells

Author: Prof. Michael Golan

Derivation from first principles (pure SI system)

page 133 ~ Compendium.

$$p_{wf}^2 = p_t^2 \cdot e^S + \frac{8 \cdot f_M}{\pi^2 \cdot D^5 \cdot g \cdot \cos(\alpha)} \cdot \left(\frac{p}{T}\right)_{sc}^2 \cdot (Z_{av} \cdot T_{av})^2 \cdot (e^S - 1) \cdot q_{sc}^2 \quad \text{Eq. A-19}$$

Multiplying and dividing the second term on the right-hand side with:

$$S = 2 \cdot \frac{M_g \cdot g}{Z_{av} \cdot R \cdot T_{av}} \cdot L \cdot \cos(\alpha) = 2 \cdot \frac{28.97 \cdot \gamma_g \cdot g}{Z_{av} \cdot R \cdot T_{av}} \cdot L \cdot \cos(\alpha) \quad \text{Eq. A-20}$$

α

$$p_{wf}^2 = p_t^2 \cdot e^S + \frac{28.97}{R} \cdot \left(\frac{p}{T}\right)_{sc}^2 f_M \cdot L \cdot \gamma_g \cdot Z_{av} \cdot T_{av} \cdot \frac{(e^S - 1)}{S \cdot D^5} \cdot q_{sc}^2 \quad \text{Eq. A-21}$$

Solving for the flow rate:

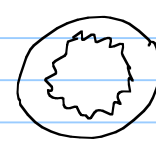
$$q_{sc} = \left(\frac{\pi}{4}\right) \cdot \left(\frac{R}{M_{air}}\right)^{0.5} \cdot \left(\frac{T_{sc}}{p_{sc}}\right) \cdot \left(\frac{D^5}{f_M \cdot L \cdot \gamma_g \cdot Z_{av} \cdot T_{av}}\right)^{0.5} \cdot \left[\left(p_{wf}^2 - p_t^2 \cdot e^S\right) \cdot \left(\frac{S}{e^S - 1}\right)\right]^{0.5} \quad \text{Eq. A-22}$$

friction moody

$Re \sim V$

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

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



$\Lambda\Lambda = e$

$\varepsilon = \frac{e}{\phi}$

$Re = \frac{\rho Q V}{\mu}$

Gas in fully turbulent regime,

$$f_F = \frac{0.00437}{D^{0.224}}$$

fanning

$f_m = \frac{f_F}{4}$

tubing constant

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

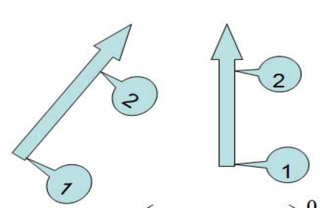
$\phi \uparrow, C_T \uparrow$

Tubing flow Equation-Dry gas

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

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

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



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

$P_{wh} \to P_{dc}$ (downstream of choke) $\rightsquigarrow$ eq. $f(q_g, P_{wh}, P_{dc})$

page 140 in Compendium

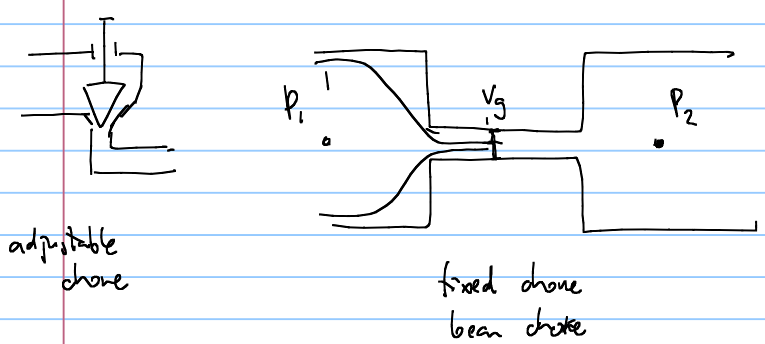
B. Choke Equations

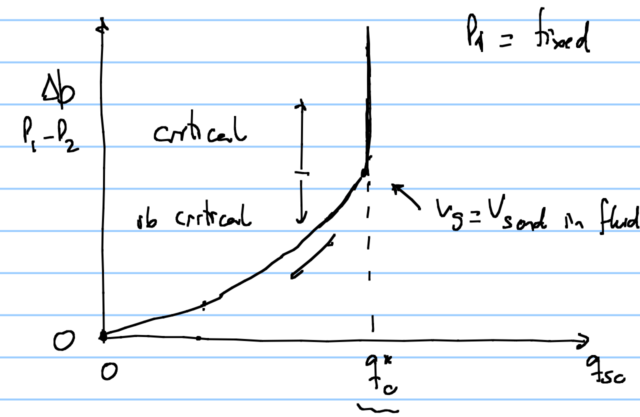
Undersaturated Oil Flow

Based on a frictionless flow contraction from an upstream point 1 to a downstream point 2.

The single-phase Bernoulli equation for steady state frictionless flow along a streamline, neglecting elevation changes, is:

$$\frac{dp}{\rho} + V \cdot dV = 0 \qquad \text{Eq. B-1}$$





empirical constant to account for vena contracta effect

$$q_{sc} = c_d A_2 p_1 \left(\frac{T_{sc}}{p_{sc}}\right) \sqrt{2\frac{R}{M_g Z_1 T_1}} \sqrt{\left(\frac{k}{k-1}\right)\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{k}} - \left(\frac{p_2}{p_1}\right)^{\frac{k+1}{k}}\right]}$$

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

$P_{dc} \to P_{sep}$ flow in pipeline (pipe, conduit)

$$q_g = C_{FL}\left(\frac{P_{dc}^2}{e^s} - P_{sep}\right)^{0.5}$$

if horizontal line? $s = 0$

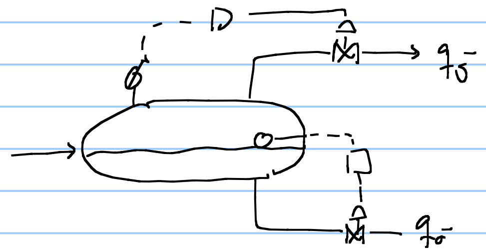
$$q_g = C_{FL}\left(P_{dc}^2 - P_{sep}^2\right)^{0.5}$$

C_{FL} = const. $\frac{s e^s}{e^s - 1}$ | $s = 0$

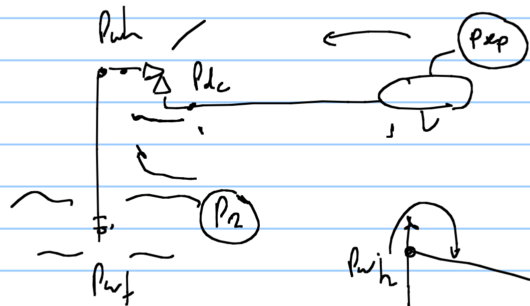
L'Hopital

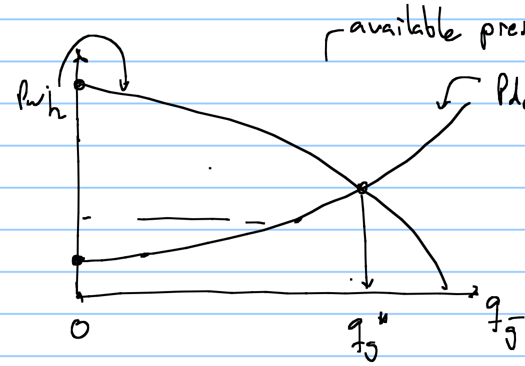
$$\lim_{s \to 0} \frac{s e^s}{e^s - 1} = 1$$

		unknowns	equation
IPR	$q_g = C\left(p_R^2 - p_{wf}^2\right)^n$	2	1
tubing	$q_g = C_T\left(\frac{p_{wf}^2}{e^s} - p_{wh}^2\right)^{0.5}$	1	1
choke	$f(q_g, p_{wh}, p_{dc})$	1	1
pipeline	$q_g = C_{PL}\left(p_{dc}^2 - p_{sep}^2\right)^{0.5}$		1
		4	4



Graphical solution





if no choke

$p_{wh} \approx p_{dc}$

q_g^*

$$q_g = C\left(p_R^2 - p_{wf}^2\right)^n \quad (1)$$

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

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

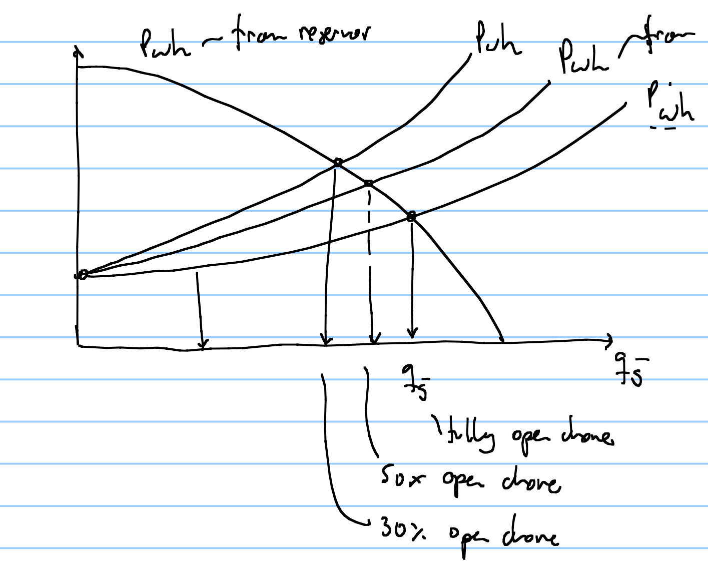
substitute (2) in (1)

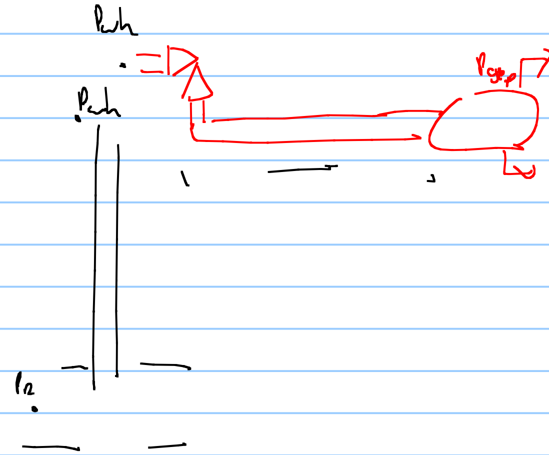
$$q_g = C\left(p_R^2 - e^s\left(p_{wh}^2 + \left(\frac{q_g}{C_T}\right)^2\right)\right)$$

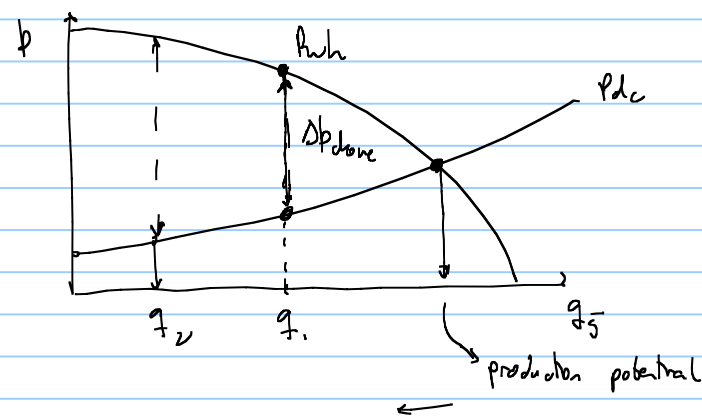
if $q_g = 0$ $\quad p_{wh}^2 = \frac{p_R^2}{e^s}$

$$q_g = \left(p_{dc}^2 - p_{sep}^2\right)^{0.5} \cdot C_{PL}$$

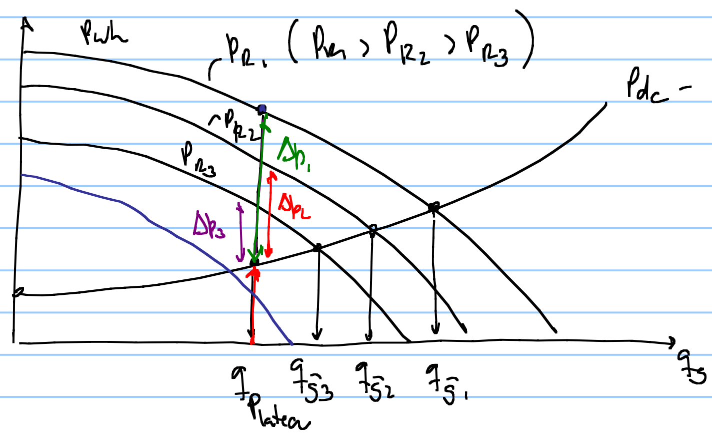
$$p_{dc} = \left(p_{sep}^2 + \left(\frac{q_g}{C_{PL}}\right)^2\right)^{0.5}$$







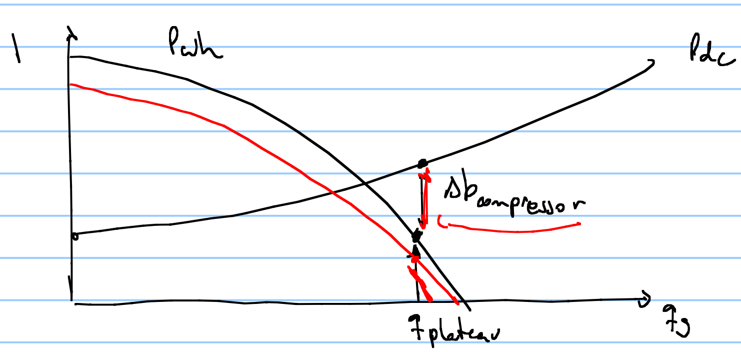
what happens with time?

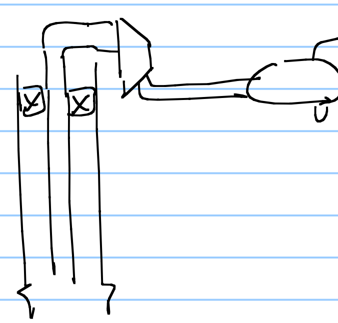


t_1, p_{R1}, Δp_1

t_2, $G p_2$, p_{R2}, Δp_2

t_3, $G p_3$, p_{R3}, Δp_3

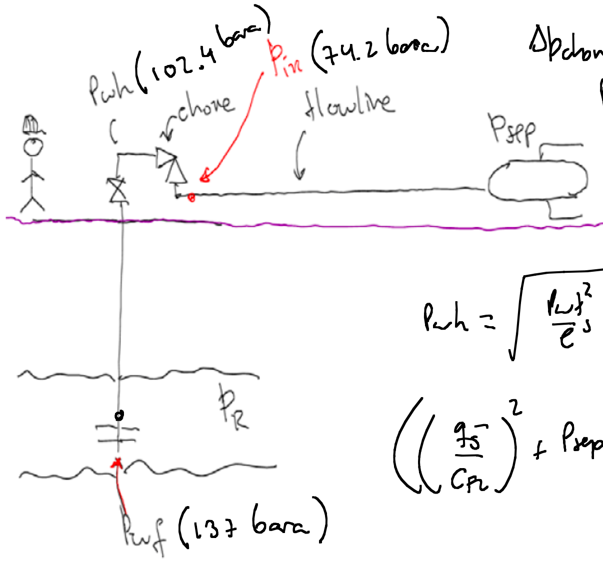




find a compressor q_s plateau, $\Delta p_{compressor}$.

Class exercise

1. For the dry gas production system shown in the figure below, what is the choke pressure drop required (in bar) for the system to deliver a rate of 2.5 E6 Sm³/d.



$\Delta p_{choke} = 28.14$ bar

$\frac{P_{in}}{P_{wh}} = 0.72$

$$P_{wh} = \sqrt{\frac{P_{wf}^2}{e^S} - \left(\frac{q_g}{C_T}\right)^2}$$

$$\left(\left(\frac{q_g}{C_{FL}}\right)^2 + P_{sep}^2\right)^{0.5} = P_{in}$$

Inflow equation:

$$q_{\bar{g}} = C_R \cdot \left(p_R^2 - p_{wf}^2\right)^n$$

With

C_R = 104 Sm³/d/bar^2n

n= 0.9

p_R = 304 bara

Tubing equation:

$$q_{\bar{g}} = C_T \cdot \left(\frac{p_{wf}^2}{e^S} - p_{wh}^2\right)^{0.5}$$

C_T = 4.41 E4 Sm³/d/bar

S = 0.31

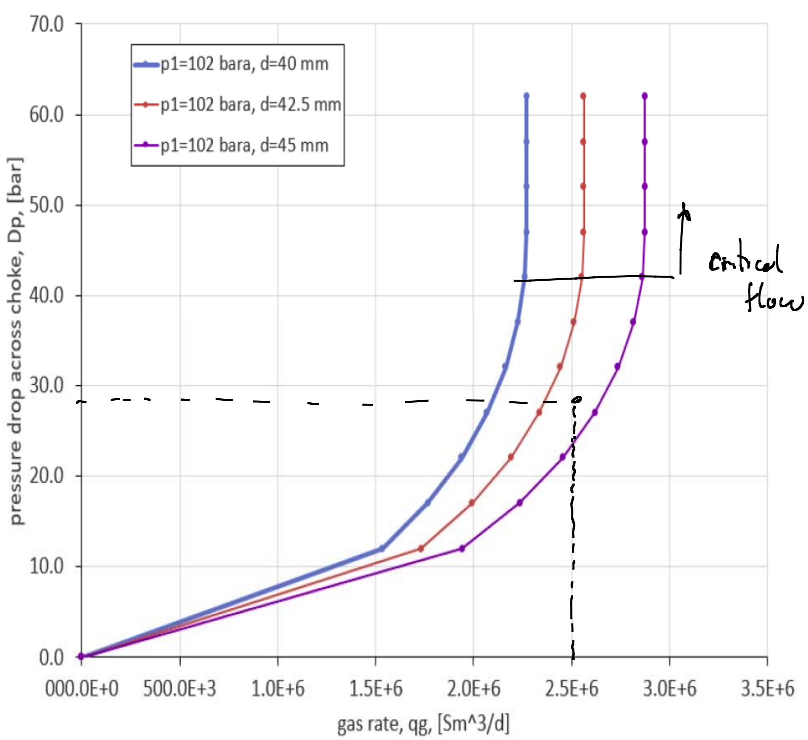
Flowline wellhead-separator:

$$q_{\bar{g}} = C_{FL} \cdot \left(p_{in}^2 - p_{sep}^2\right)^{0.5}$$

C_{FL} = 4E4 Sm³/d/bar

p_{sep} = 40 bara

2. Based on the choke performance maps shown below, what is (approximately) the required choke diameter (in mm) to provide the desired rate of 2.5 E6 Sm³/d. Use the wellhead pressure and choke pressure drop calculated in exercise 2. Will the choke operate in the critical or subcritical regime?



rule of thumb

critical flow occurs when

$\frac{P_{dc}}{P_{wh}} \leq 0.5 - 0.6$

$\Delta p_{critical} = P_{wh} - P_{dc}$

$P_{wh} - 0.6 \cdot P_{wh}$

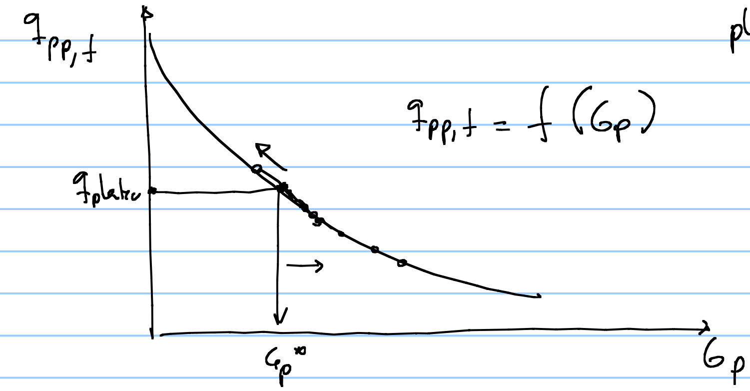
$0.4\, P_{wh}$

$\Delta p = 0.4 \cdot 102$

$= 40.8$ bar

for open choke $q_g = 2.67$ E6 Sm³/d

Production potential of field



$q_{pp,f} = f(G_p)$

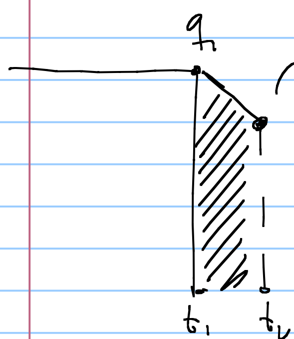
plateau period is over when
$q_{plateau} = q_{pp,f}$

for $t > t_p$, produce at potential

$t < t_p$, produce at plateau

how can this curve be used for predicting post plateau profile?

$q_{field} = q_{pp,f}$



$q_2 = q_{pp,f}$

$(G_{p_2} - G_{p_1}) = (t_2 - t_1)(q_1 + q_2) \cdot 0.5$

assume q_2 ($< q_1$)

compute G_{p_2}

calculate $q_{pp,f}$ with G_{p_2}

check if $q_{pp,f} = q_2$?

no

yes

solution