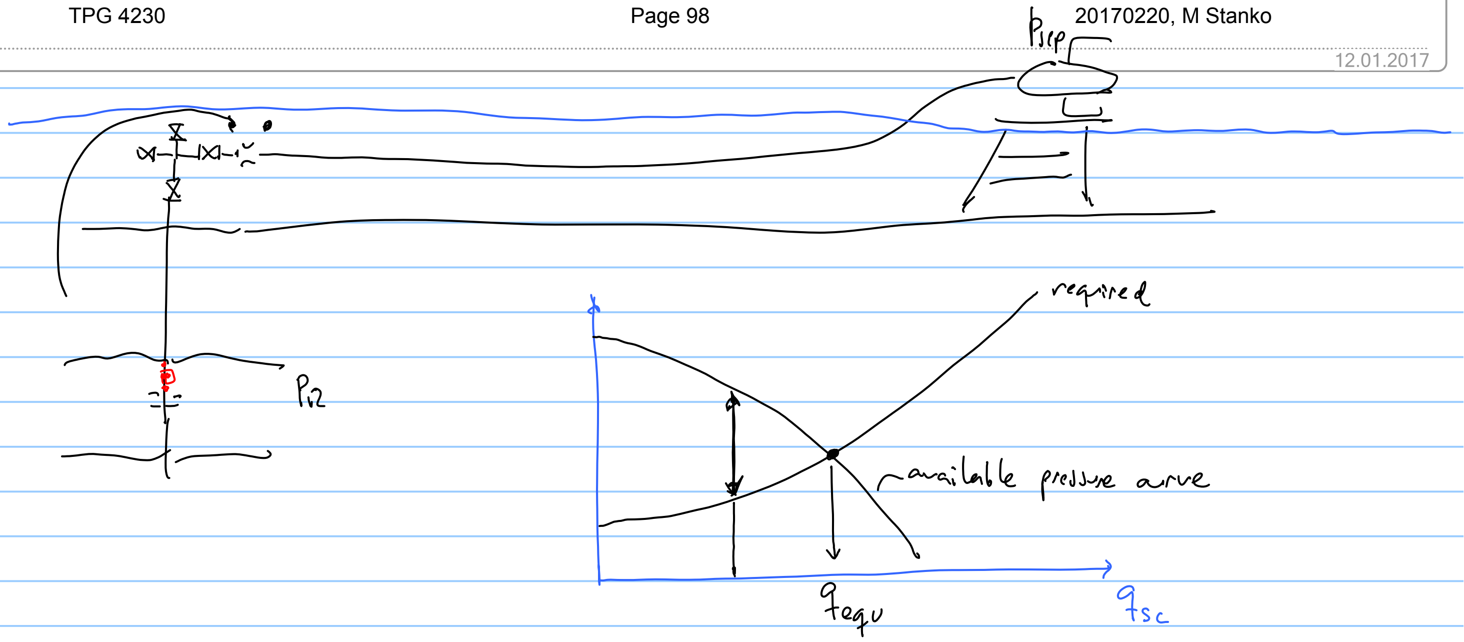
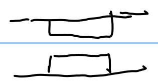


when we have adjustable elements in my production system:
choke, pump (the rotational speed can be changed)
gas lift the gas lift injection rate can be changed:

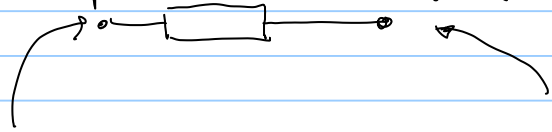
Fixed choke
bean choke



adjustable choke

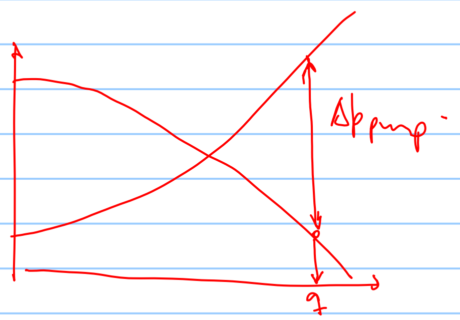
there are two ways to calculate equilibrium

1: Removing the component from the system and applying equilibrium exactly at that location



is useful for design. (when a new component will be acquired or replaced)
when the numerical model is not available or is very uncertain and complex
e.g. multiphase boosters ←
multiphase chokes

ESP design

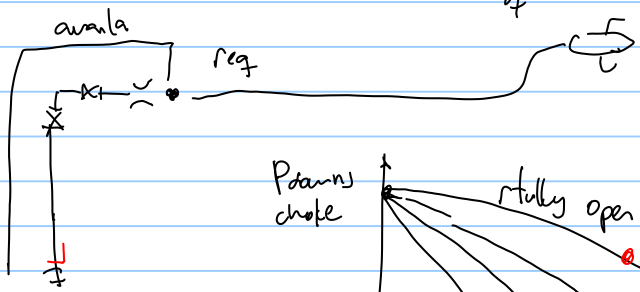


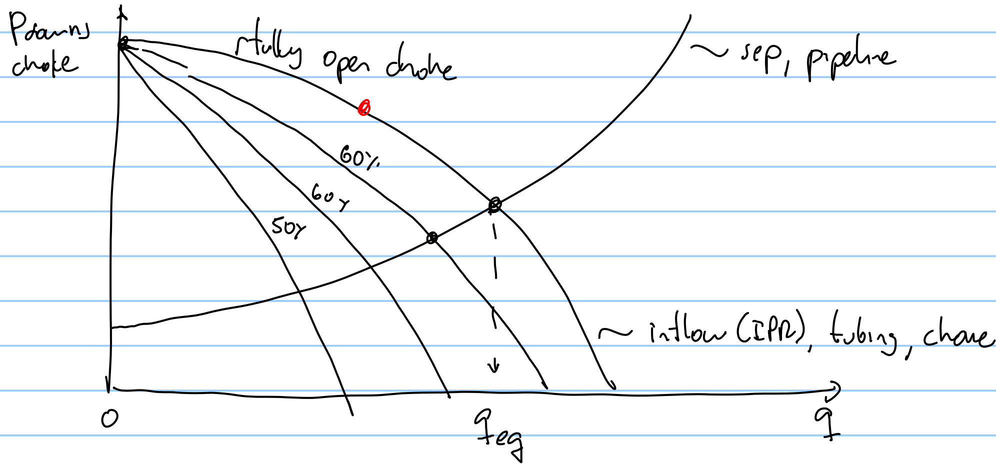
the desired rate and Δp have to be verified against the equipment afterwards

ESP power

300 Hp → 2000 Hp

2: Including the component in the available or required pressure curves





if a particular model is available
and an equation is also available

ESP – $\Delta p = a(f)\, q_{act}^2 + b(f)\, q_{act} + c(f)$

choke $\Delta p = d \cdot q_{act}^2$

actual local volume rates at p, T at inlet of the components

commercial software use this mode
Pipesim, gap, prosper, Reo, pipephase

solving for a desired rate

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

for a dry gas well with a choke.

- assume an opening.
- calculate the intersection ~ q^*
- check if $q^* = q_{desired}$?
- if yes → finish
- if not

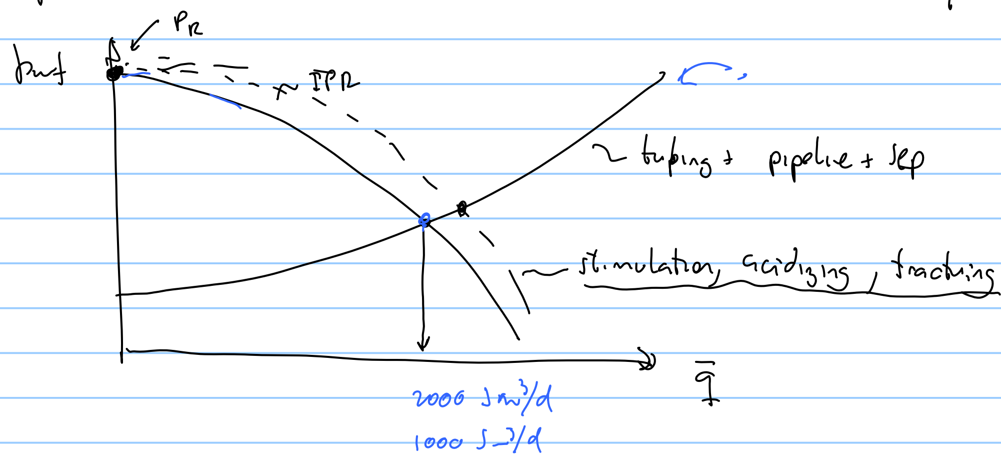
— newton method

wrongly called optimization in commercial software

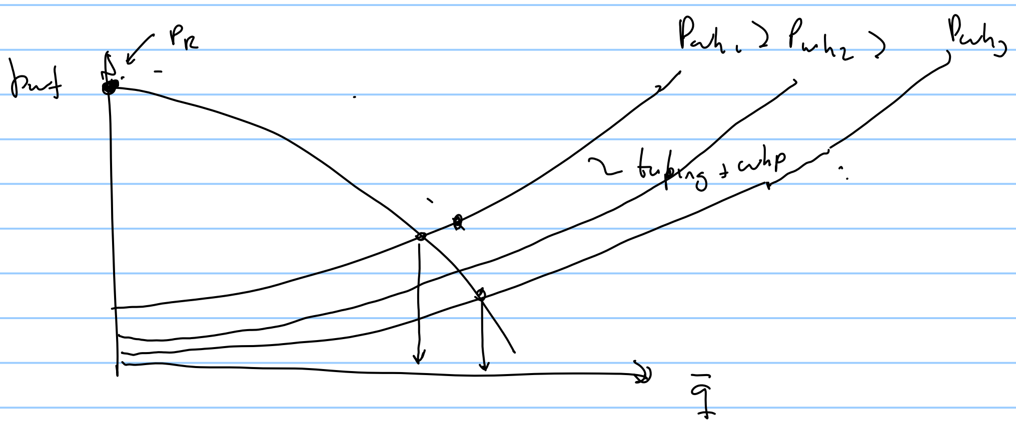
(−) the component model is usually highly non-linear

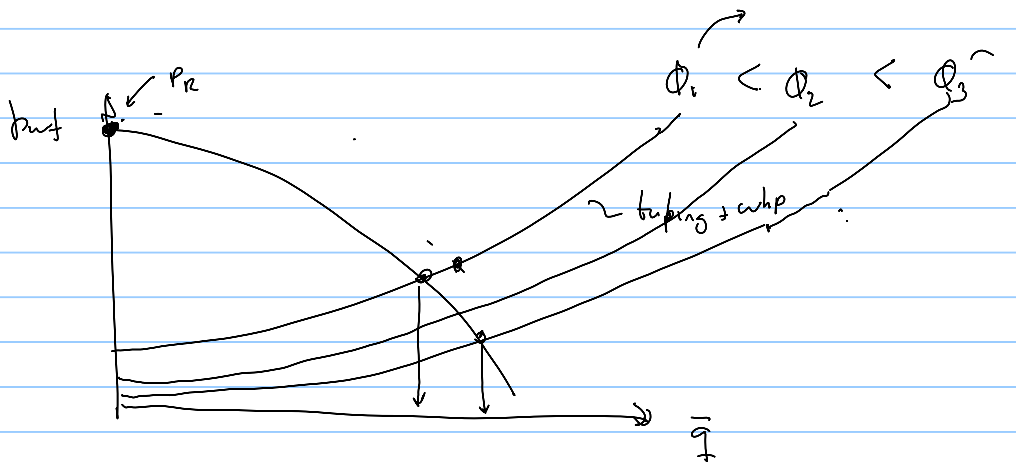
(−) takes more time to evaluate

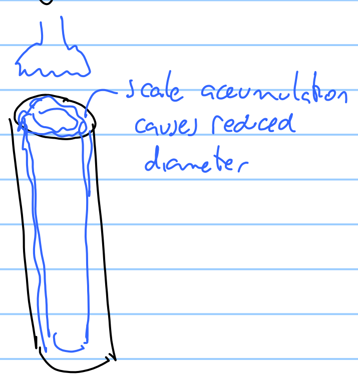
- the operator (engineer) can affect the available and required pressure curves



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







Equilibrium analysis can be performed for diagnosis!

During the field design process

① Reservoir engineers use reservoir simulator with $P_{wf\,min}$, target rate

Repeat simulation find optimum N_{well}, RF, max NPV

define for each well ($q(t)$)

back and forth communication

when the production layout is defined! →

② Production engineers, is that rate feasible?

the rate is not feasible!

the rate is feasible :)

Reservoir simulator + production simulator
$\underbrace{\hspace{6cm}}_{\text{coupling}}$

- what happens when we have multiphase flow? simultaneous flow of gas, oil and water in parts of the production system

IPR

$q_{\bar{g}} = q_{\bar{o}} \cdot GOR$

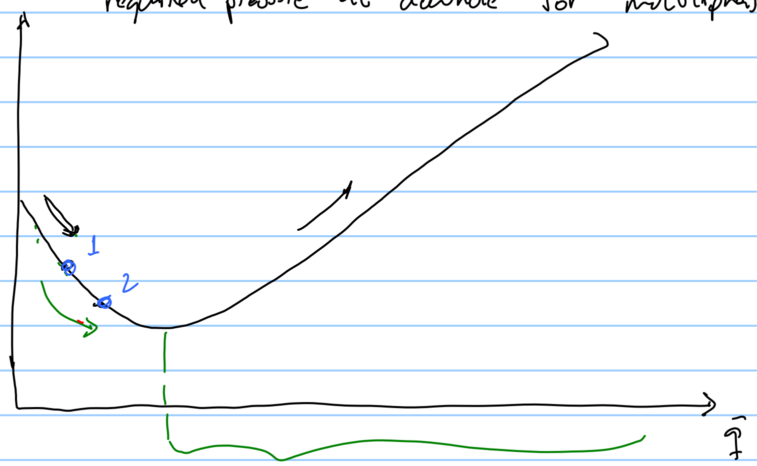
$q_{\bar{w}} = q_L \cdot wc = (q_{\bar{o}} + q_{\bar{w}})\, wc$

$q_{\bar{w}} = \dfrac{q_{\bar{o}}\, wc}{(1 - wc)}$ wc is a fraction $(0-1)$

what happens with the flowing conduits? Ole Jørgen Mydal

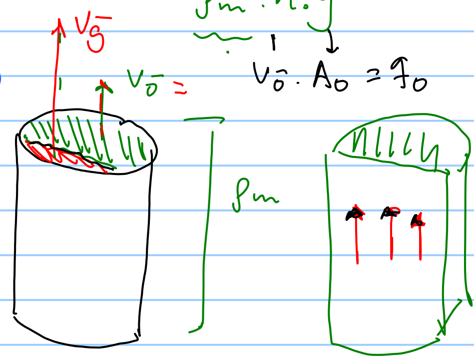
required pressure at downhole for multiphase flow

P_{wf}

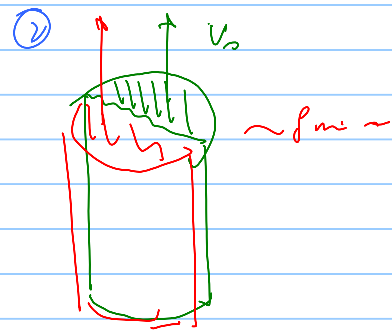


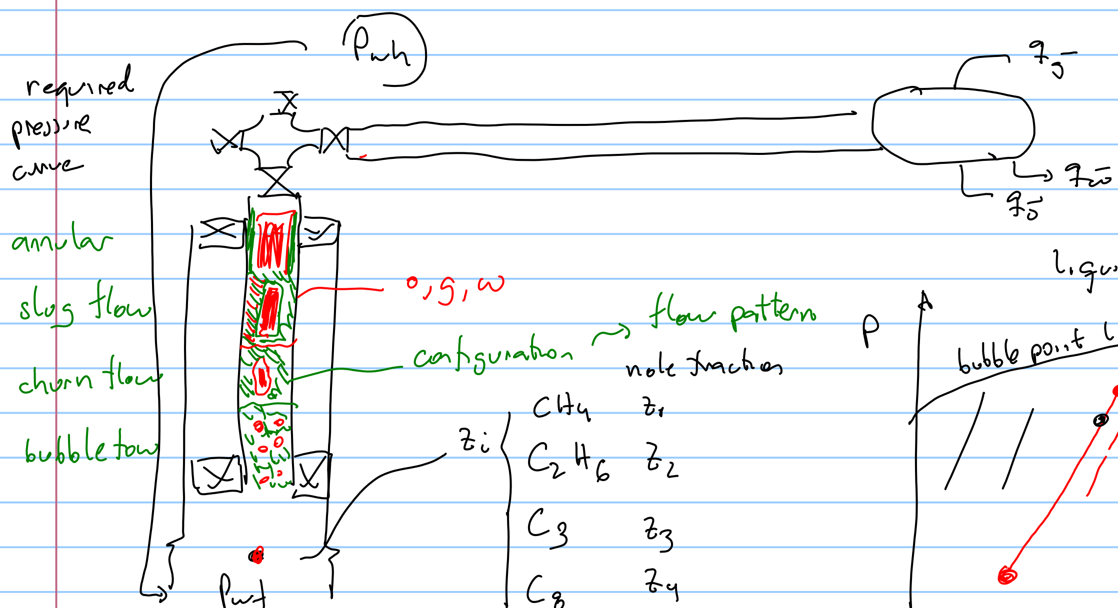
$\Delta p_{tubing} = \underbrace{\Delta p_{hydrostatic}}_{\rho_m \cdot h \cdot g} + \Delta p_{friction}(q)$

① $v_{\bar{o}} =$ $v_{\bar{o}} \cdot A_o = q_o$



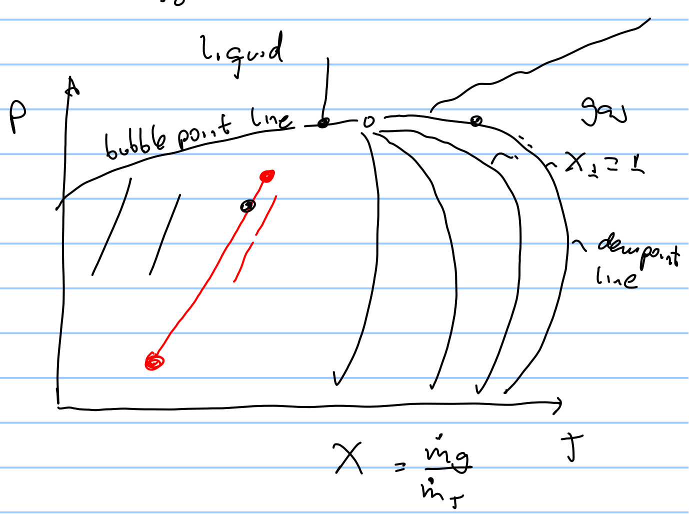
the gas velocity is high enough such that it starts pulling the liquid up, reducing the gas velocity and increasing the liquid velocity



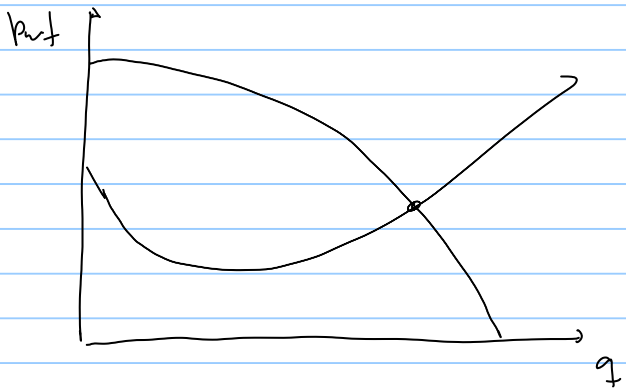


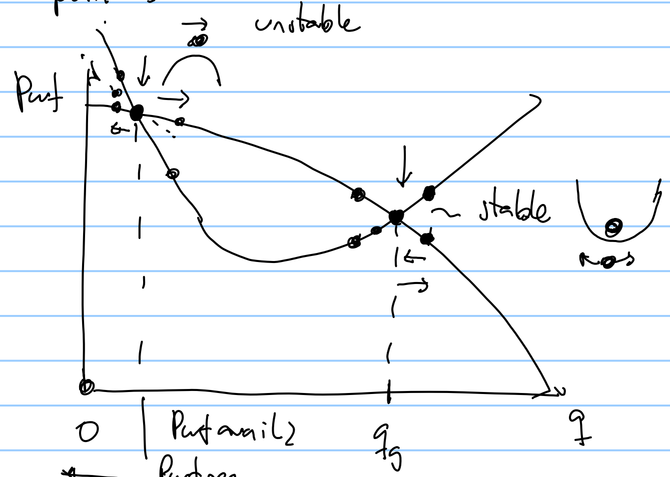
mole fraction

z_i { CH_4 z_1, C_2H_6 z_2, C_3 z_3, C_8 z_4, ⋮ ⋮



what are the consequences for the equilibrium point?





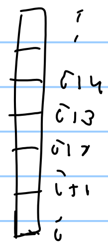
$P_{wf\,avail} > P_{wf\,req}$ ← q is increased

$P_{wf\,req} > P_{wf\,avail}$, q is reduced

→ $P_{wf\,req} > P_{wf\,avail}$, q is reduced

→ $P_{wf\,avail} > P_{wf\,req}$, q is increased

for muliphase flow pressure drop calculations are time consuming
- stepwise maner
- flash ~> determining amount of oil and gas
- determine slip between phases
- ↳ calculate ΔP

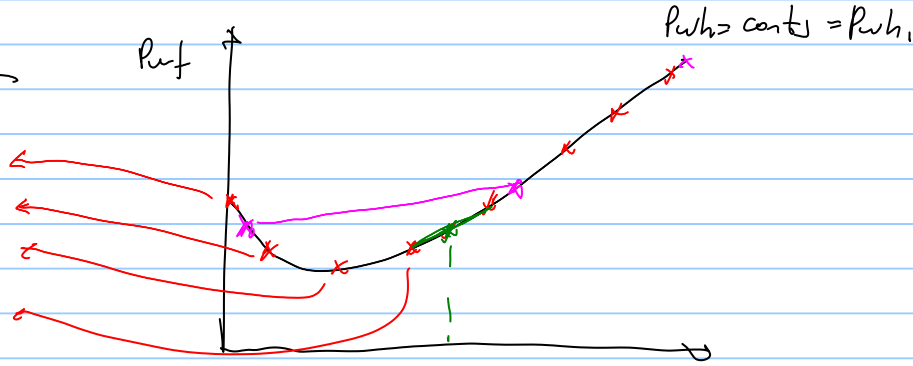


to save time, TPR is pre computed and stored in tables beforehand

Tubing table VLP vertical lift performance
TT

$P_{wh} = P_{wh_1}$

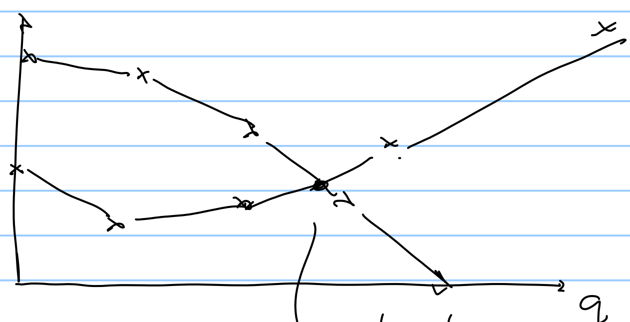
q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–



Later we use the table as our multiphase proxy.
perform interpolation on the table

there has to be a appropriate number of points on the table such as $P_{wf\,interpolated} \simeq P_{wf\,calc}$

Linear interpolation is fast and cheap :)



intersection of two straigh lines ~> computionally cheaper than non linear solver there will be several tables for different wellhead pressures

$P_{wh} = P_{wh_1}$

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_2}$

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

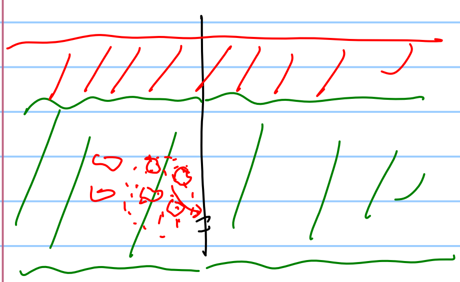
$P_{wh} = P_{wh_3}$

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

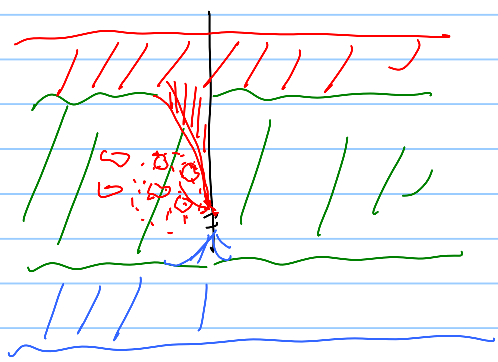
$P_{wh} = P_{wh_4}$

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

with time the well GOR changes, WC change



with the depletion
$S_g \uparrow$ $K_{rg} \rightarrow$ more gas flow towards the wellbore the GOR $\uparrow$
around wellbore



gas coning
water coning

So usually it is necessary to build tables for different GORs and WCs

$P_{wh} = P_{wh_1}$ GOR_1, WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_2}$ GOR_1, WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_3}$ GOR_1, WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_4}$ GOR_1, WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_1}$ GOR_2 WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_2}$ GOR_2 WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_3}$ GOR_2 WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

$P_{wh} = P_{wh_4}$ GOR_2 WC_1

q_o	q_g	q_w	P_{wf}	T_{wh}
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–
–	–	–	–	–

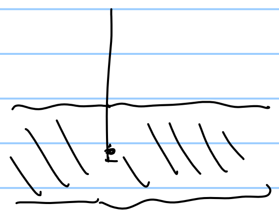
this increases the number of tables required significantly

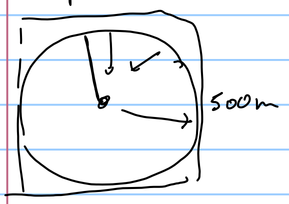
$$N_{points} = \underbrace{N_{rates}}_{\text{typically } \sim 10} \times \underbrace{N_{Pwh}}_{\sim 6} \times \underbrace{N_{GORs}}_{\sim 8} \times \underbrace{N_{WCs}}_{\sim 5} = 1440 \text{ runs } !$$

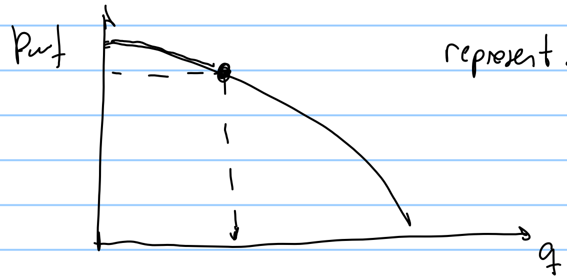
Inflow deliverability

Inflow performance relationship:

for a given time, for a given P_R, for a given depletion state

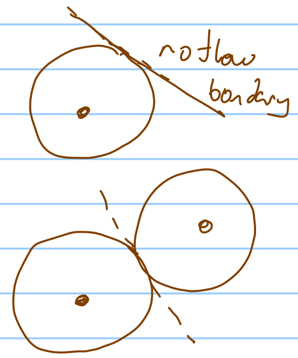






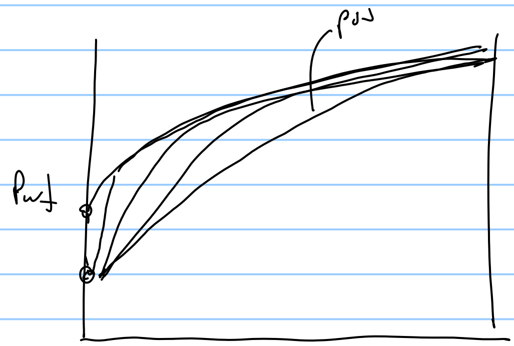
represents the flow behavior of the near wellbore formation

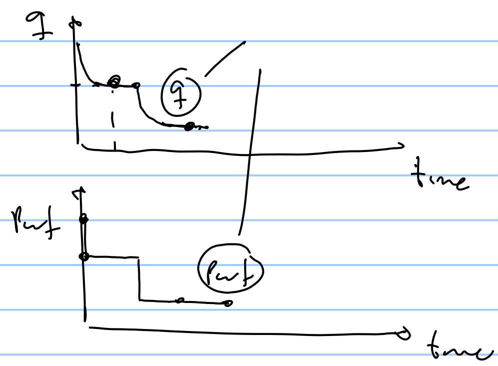
Reservoir engineers use reservoir simulator.



stabilized flow (pressure perturbation reaches the outer bound)

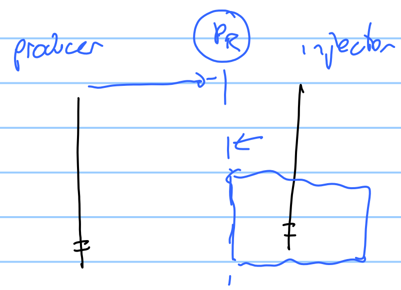
IPR applies usually for stabilized flow / pss pseudo steady state





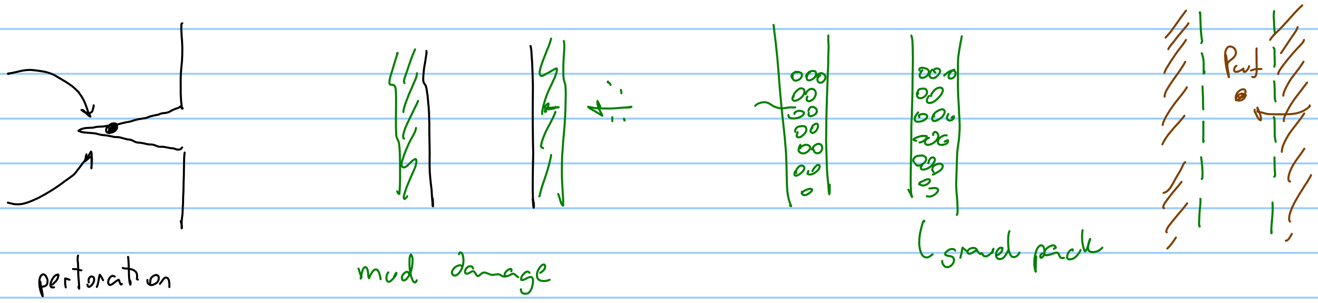
IPR: contains information about

- location and type of outer bound
  - no flow
  - constant pressure

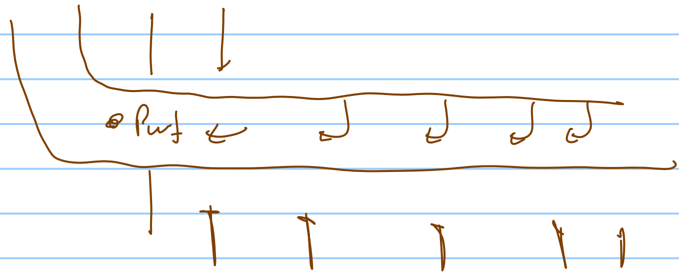


- permeability of formation (rock properties) k_z, k_x, k_y
- fluid properties and their variation with p, $\sim$ $v = \frac{k}{\mu}\frac{dp}{dr}$

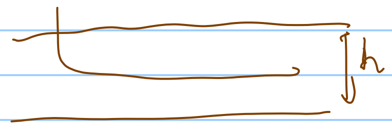
- oil, gas and water saturation in the drainage area ~> K_{ro}, K_{rg}, K_{rw}
  S_o, S_g, S_w
- Restricted flow towards the wellbore



- for horizontal well, the IPR captures sometimes flow in the wellbore



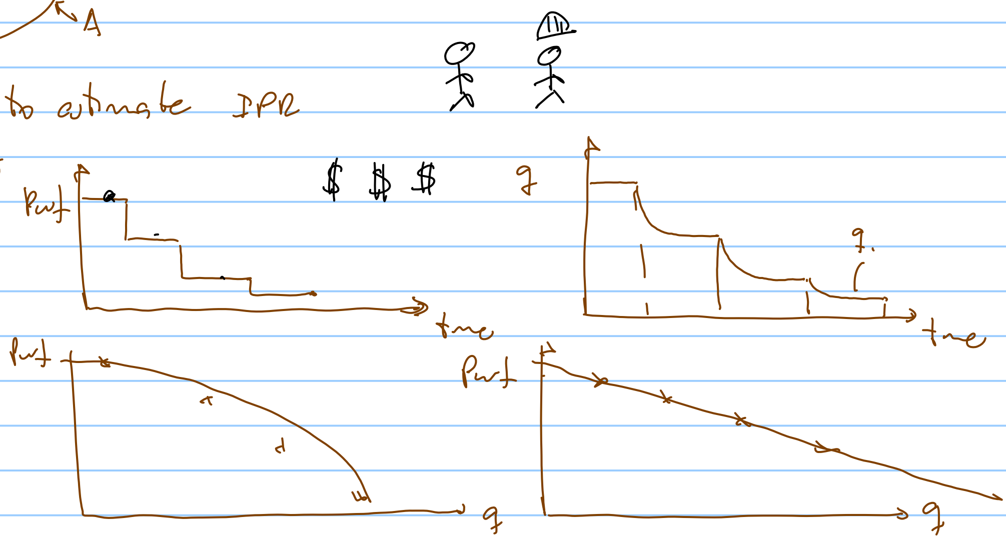
- well radius
- formation thickness



- Volume average pressure or the drainage area (P_R)
- high velocity effect (non Darcy) $v = \frac{k}{\mu}\frac{dp}{dr}$ $av + c v^2 = \frac{k}{\mu}\frac{\partial p}{\partial r}$
- the convergence effect of the flow towards the wellbore

two methods to estimate IPR

- well test



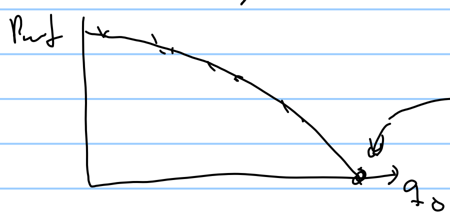
Some equation typically used are

- Linear IPR ~ (undersaturated oil + water) $q_L = J(P_R - P_{wf})$

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

- Backpressure equation (gas saturated oil) $q = C(P_R^2 - P_{wf}^2)^n$

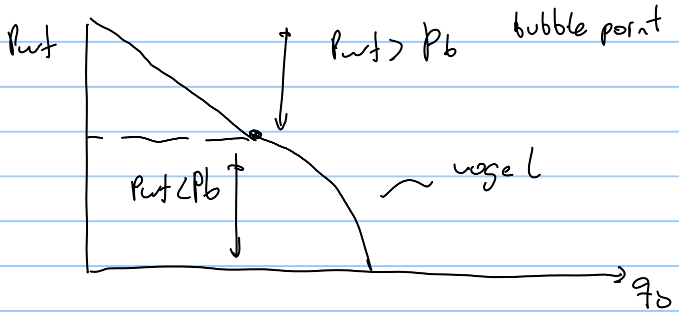
- Vogel equation (saturated oil) $q_{\bar{o}} = \underset{\sim}{q_{o\,max}} \cdot \left(1 - 0.2\,\frac{P_{wf}}{P_R} - 0.8\left(\frac{P_{wf}}{P_R}\right)^2\right)$



q_o @ $P_{wf} = 1$ bar

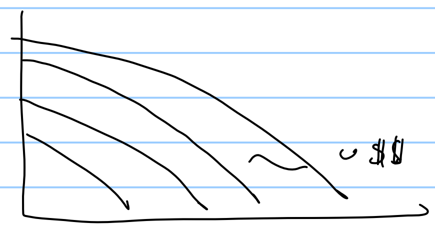
AOF: absolute open flow

- Composite IPR (saturated and undersaturated oil)



bubble point pressure → use linear IPR

- with time the IPR changes ~ it is necessary to run well test again



- IPR can be also estimated analytically. useful for field design (no test data is available) expression are derived from differential equations conservation of mass and

$$\frac{k}{\mu} 2\pi h \frac{\partial}{\partial r}\left(r \frac{\partial p}{\partial r} \right) = 2\pi h \phi c r \frac{\partial p}{\partial t}$$

customize the equation for each situation, well geometry. and solve it

some examples

for gas

unit conversion constant

$$q_g = \frac{\pi k h T_{sc} a}{T_R P_{sc} \left(\ln\left(\frac{r_e}{r_w}\right) - 3/4 + S \right)} \int_{P_{wf}}^{P_R} \left(\frac{2p}{\mu_g z} \right) dp$$

for oil

unit conversion constant

$$q_{\bar{o}} = \frac{2\pi k h a}{\ln\left(\frac{r_e}{r_w}\right) - 3/4 + S} \int_{P_{wf}}^{P_R} \frac{k_{ro}}{\mu_o B_o} dp$$

$k_{ro} = f(S_o)$

for undersaturated oil $k_{ro} \leq 1$ if you have connate water $\frac{k_o}{k}$

S_o = constant

k_{ro} = value less than 1

$\frac{k}{\mu_o B_o}$ = constant with P

$$\underbrace{q_{\bar{o}} = \frac{2\pi k h}{\left(\ln\left(\frac{r_e}{r_w}\right) - 3/4 + S \right)} \frac{1}{\mu_o B_o}}_{J} (P_R - P_{wf})$$