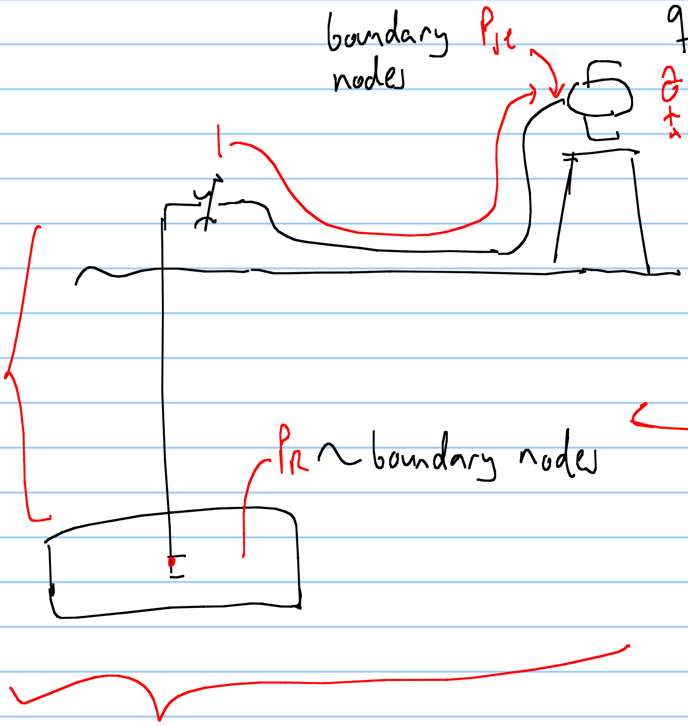
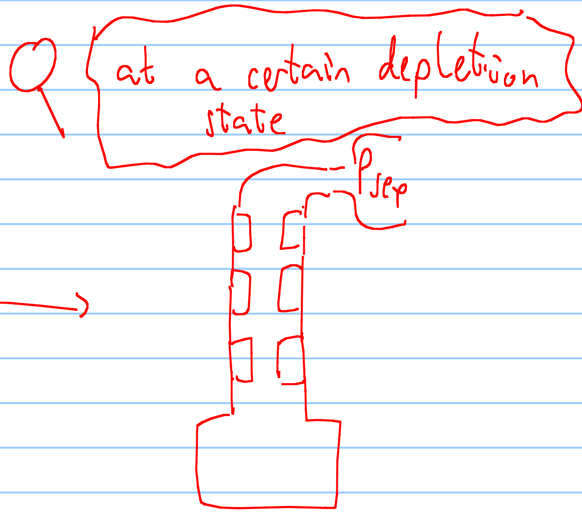
flow equilibrium ⟶ performance of a production system (field)

$q_f(t)$, $p(t)$, $T(t)$.





- Reservoir (model) ~ simpler than reservoir simulator

well
- Pressure and temperature drop in circular/annular sections of pipe, accessories (restriction, slots, valve)

choke
- Δp, ΔT in the choke

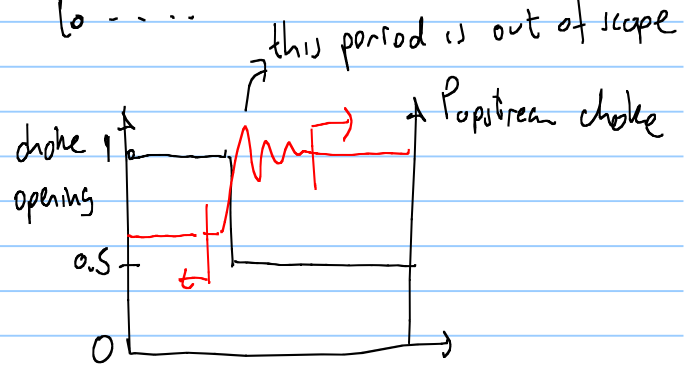
pipeline
- p, T drop calculations in circular sections of pipes, accessories, valve

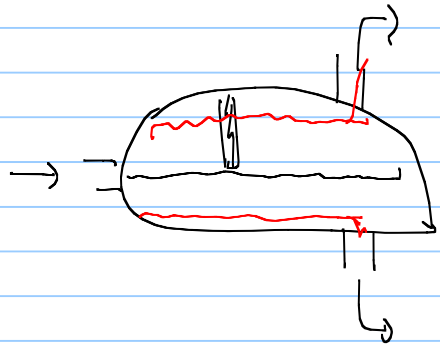
production system simulator
- set of equations
  - Δp
  - ΔT
- fluid behavior
  - $PV = nRT \cdot Z$ EOS
    - Redlich-Kwong
    - Peng-Robinson
    - ....
  - BO model
- → steady state analysis

$\frac{\partial}{\partial t}$

- well testing
- flow assurance

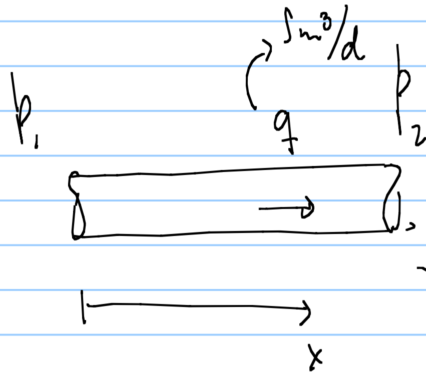
} transient models





example of multiphase flow transient
slugging arriving to a separator

Analogy for available and required pressure curves



gas flowing through a pipe

three calculation options:

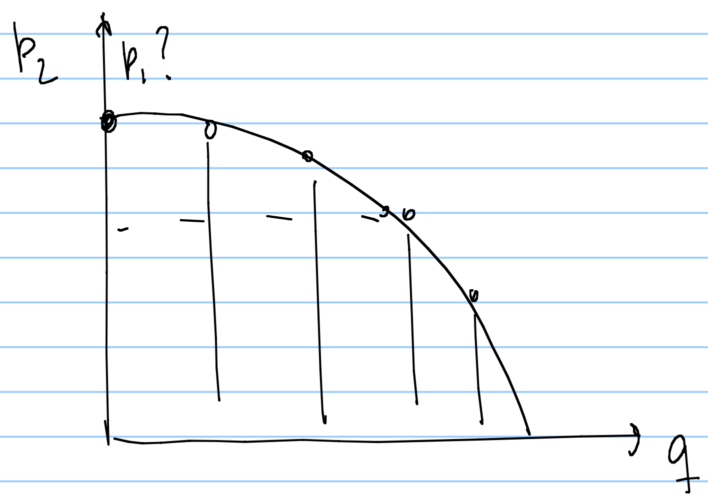
① $p_1, p_2 \rightsquigarrow q$

② $p_1, q \rightsquigarrow p_2$

③ $p_2, q \rightsquigarrow p_1$

$$\left.\frac{dp}{dx}\right|_{TOTAL} = \left.\frac{dp}{dx}\right|_{friction} + \left.\frac{dp}{dx}\right|_{hydrostatic} + \left.\frac{dp}{dx}\right|_{acceleration}$$

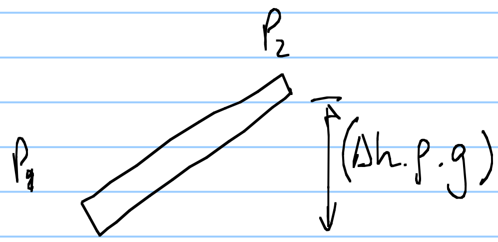
p_1 fixed $\quad$ q changing $\quad$ $q \uparrow \quad \Delta p \uparrow \quad p_2 = p_1 - \Delta p$



available pressure curve

in this case when $q = 0$

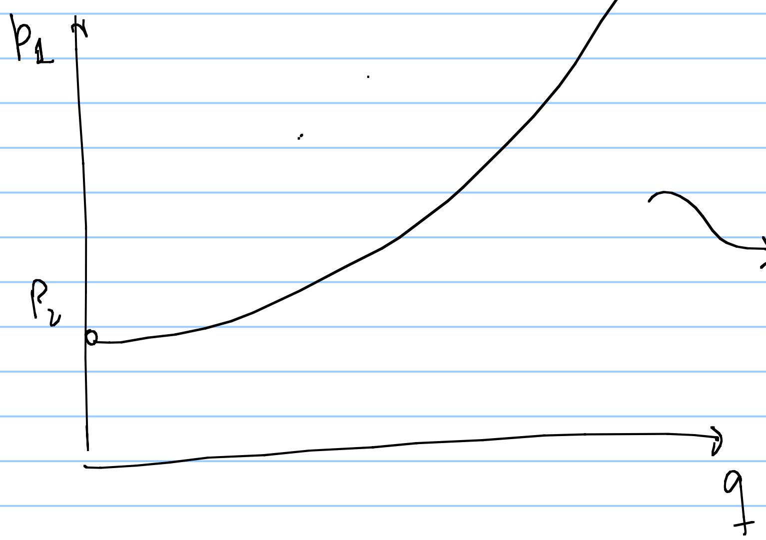
$P_2 \neq P_1$



P_2 constant $\quad q \uparrow$

$\Delta p = f(q)$ ← non linear

$P_1 = P_2 + \Delta p$

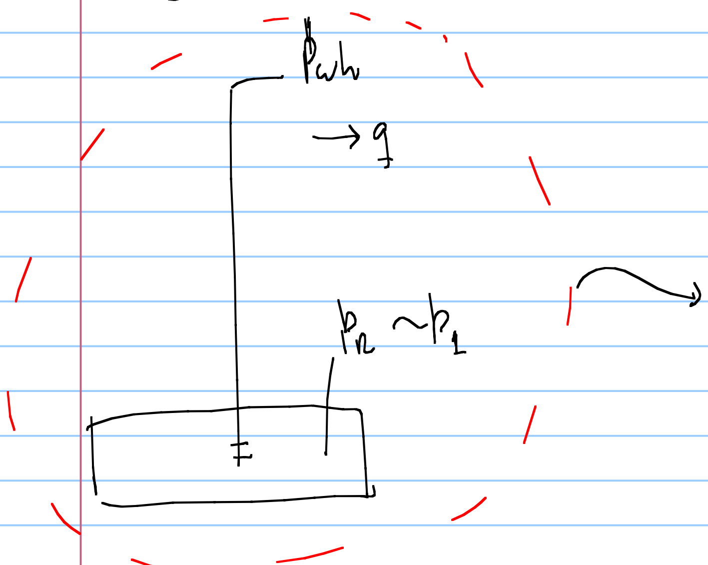


→ required pressure curve.

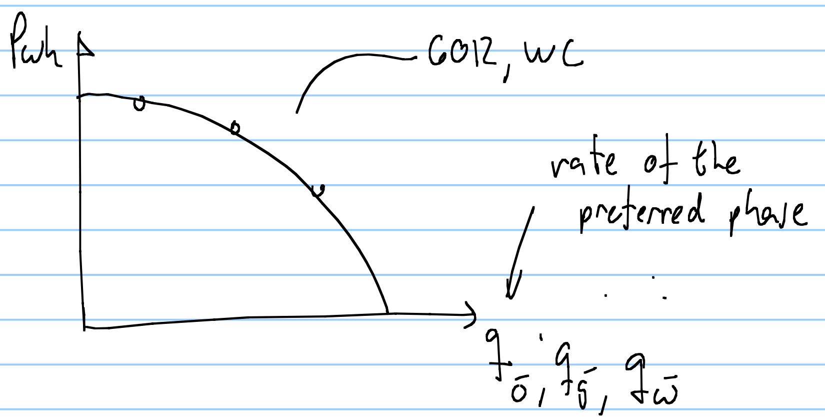
- Bilal
- Elshad

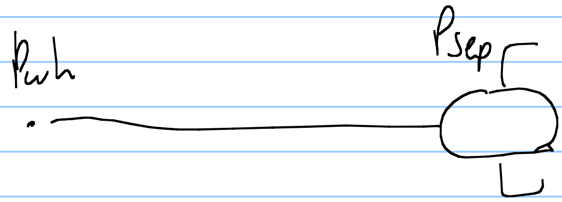
} reference group.

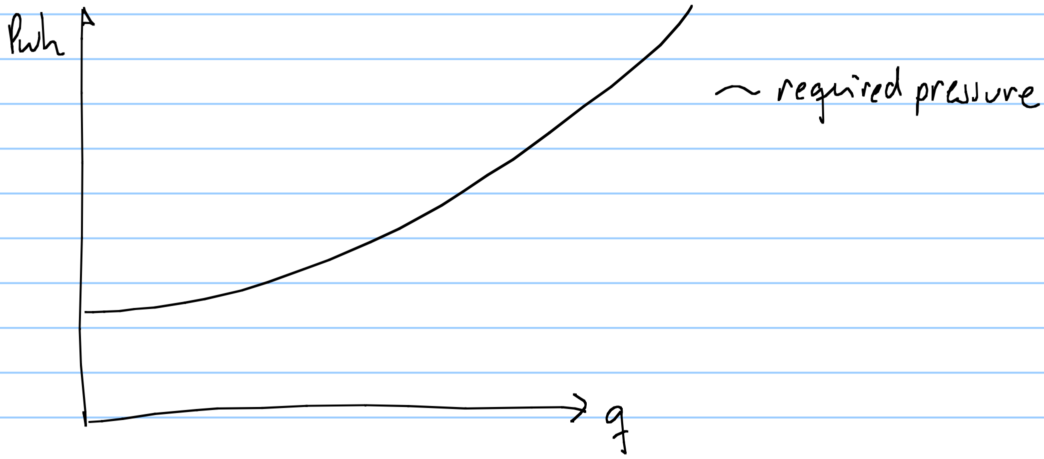
going back to our production system



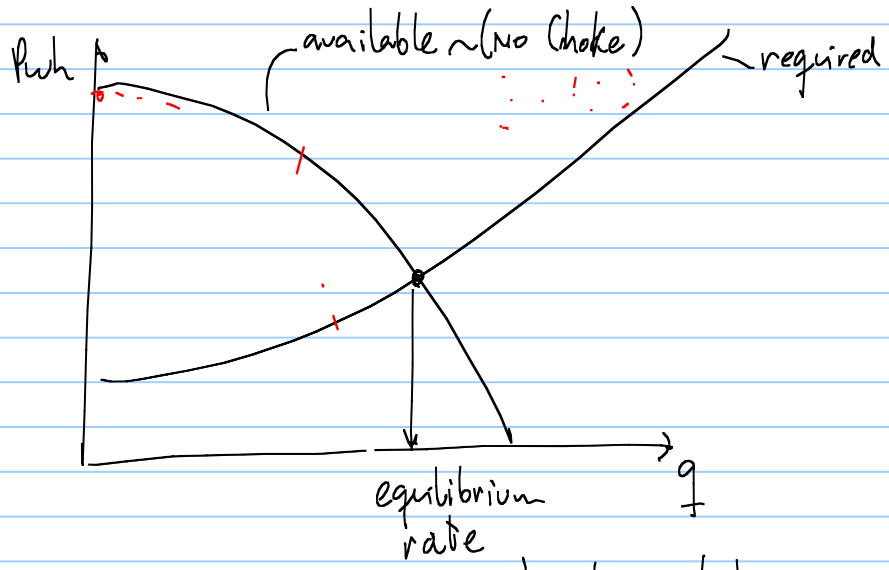
one point in time (Q_p)



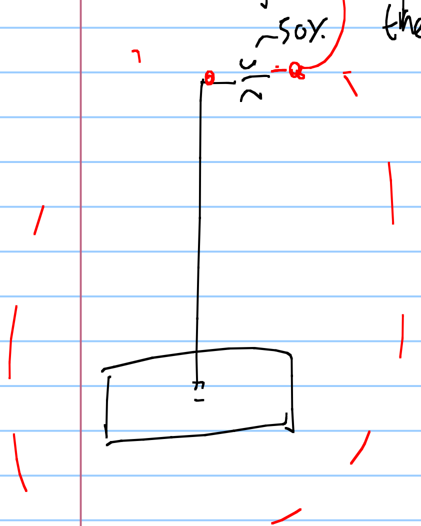




how to calculate the equilibrium flow rate



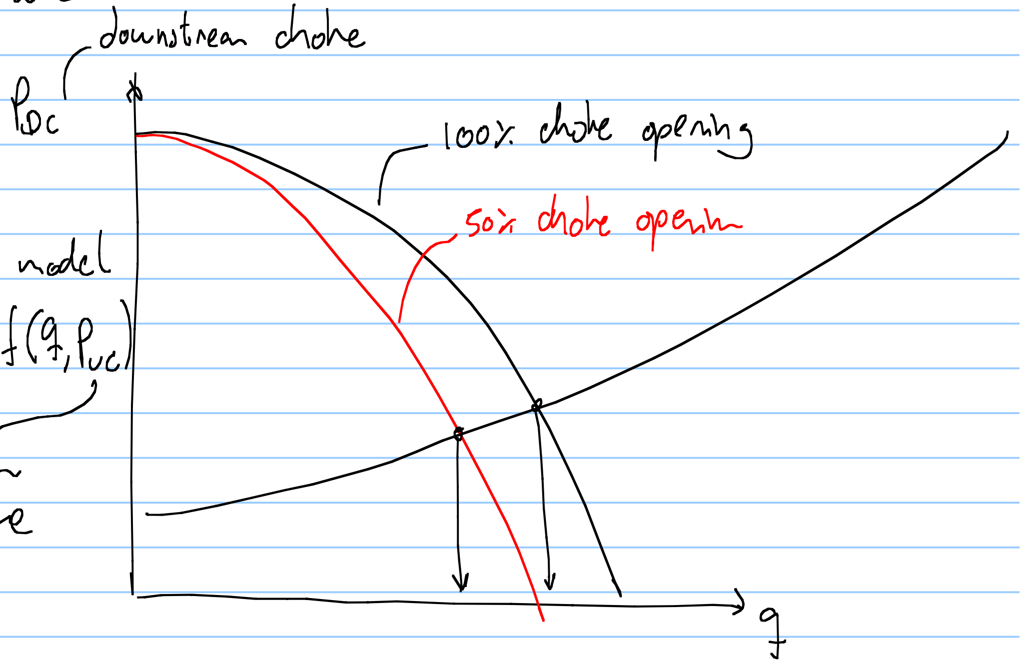
what if we include the choke



choke model

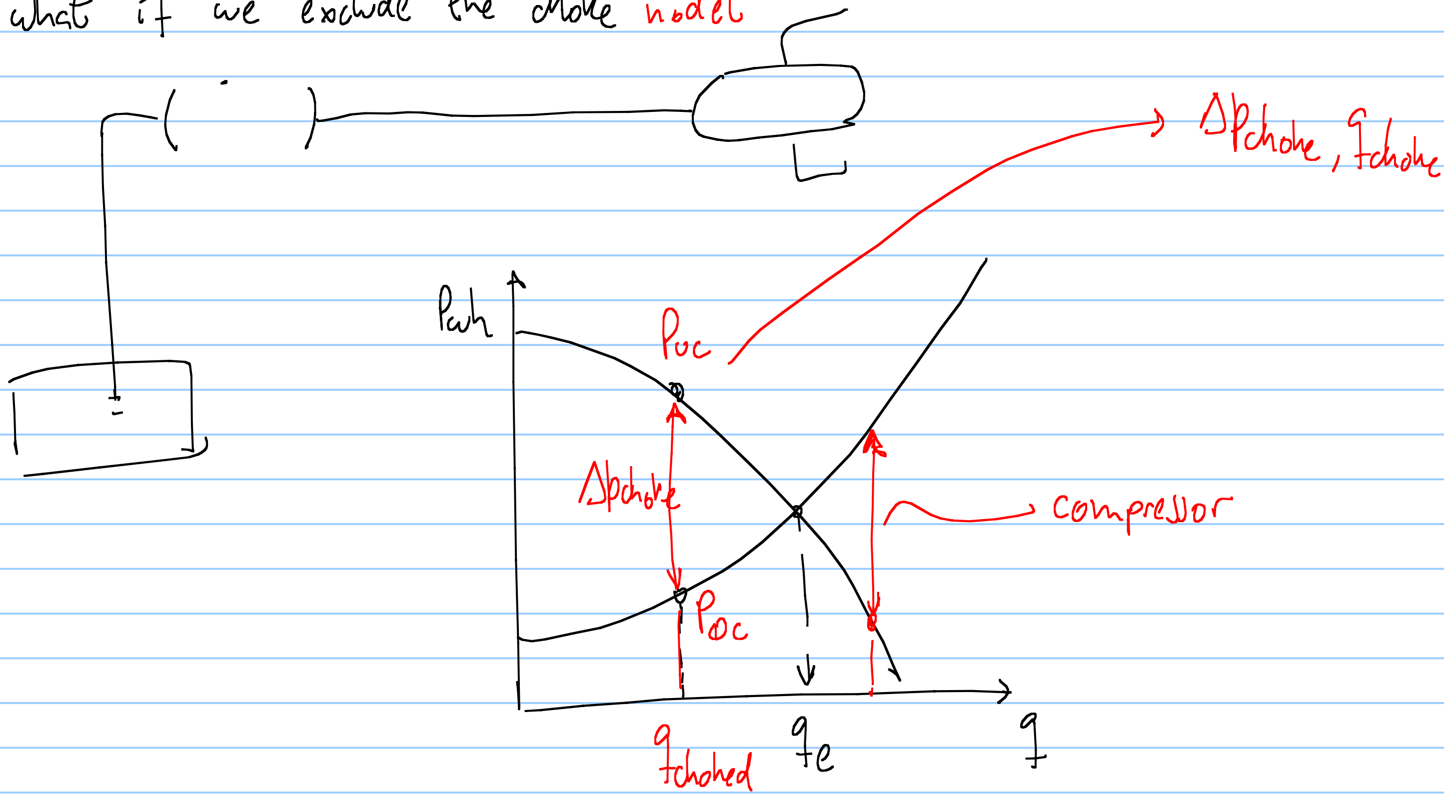
$\Delta p = f(q, P_{uc})$

upstream choke



what if we exclude the choke model

useful for design
not so accurate models



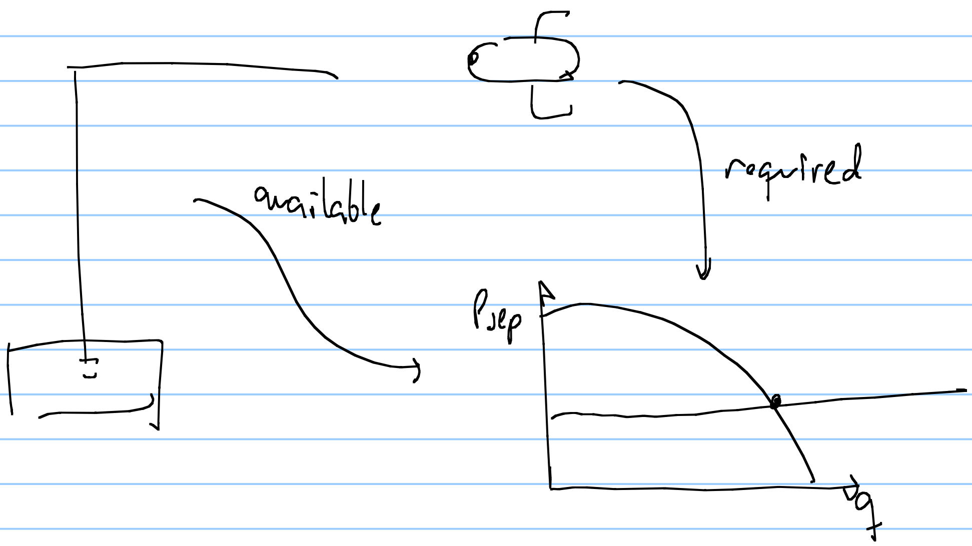
where to do equilibrium

bottomhole

- Boosting desig
- artificial lif design
- control reservoir simulator

wellhead

- allocation
- field desig
- condition monitoring



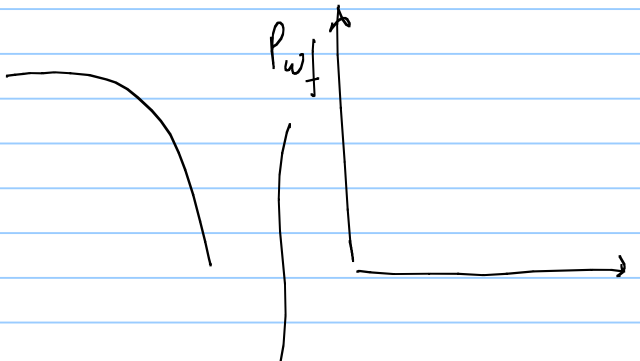
look in detail into the components of the production system

- Reservoir deliverability

$\rightarrow$ IPR $\begin{cases} \text{equation} \\ \text{collection of points} \end{cases}$

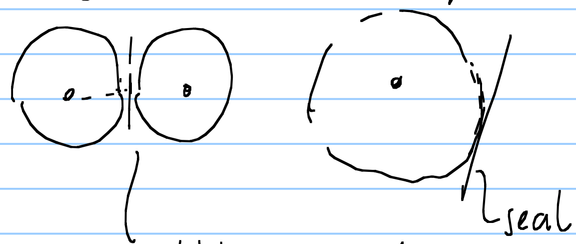
inflow performance relationship

(representation of the (pseudo) steady state of the well



flowing bottomhole pressure.

- information about conditions away from the wells, boundary



- flow restrictions in the formation k, μ, ρ

near wellbore $\begin{cases} \text{skin damage} \\ \text{perforations} \\ \text{fracks} \end{cases}$

- convergence effect

how do we get IPR $\rightarrow$ analytical derivation radial well undersaturated

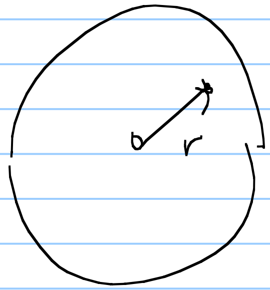
compressibility

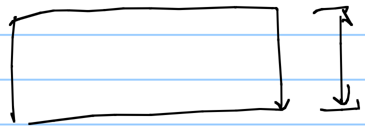
$$\sim\!\!> \frac{K}{\mu} 2\pi h \frac{\partial}{\partial r}\left(r \frac{\partial p}{\partial r}\right) = 2\pi h \, q \, c \, r \left(\frac{\partial p}{\partial t}\right)$$

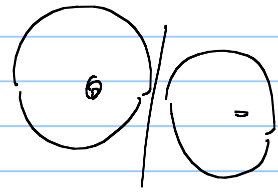
~> PDE partial differential equation,

Boundary condition (BC)

- Fixed pressure
  - · injection
- no flow boundary





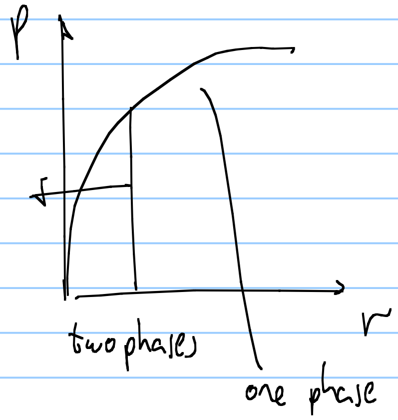


$$q_o = \frac{kh(p_R - p_{wf})}{141.2\mu_o B_o \ln(0.61 r_e / r_w)}.$$

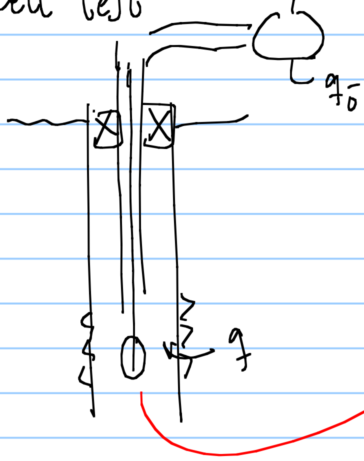
wellbore radius

outer bound radius

oil formation volume factor



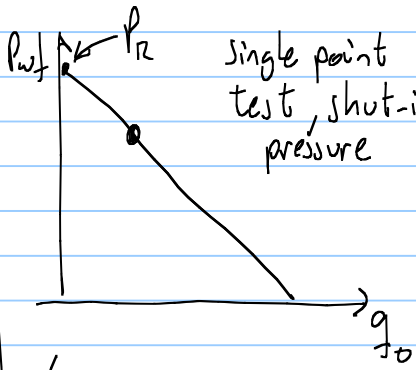
· well test



Downhole pressure transducer

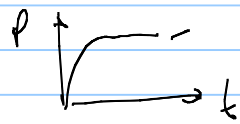
How does the IPR looks like?

Undersaturated oil

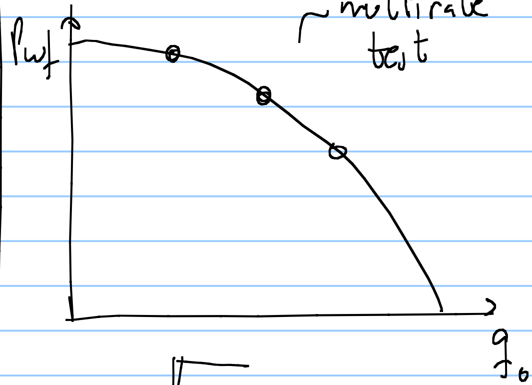


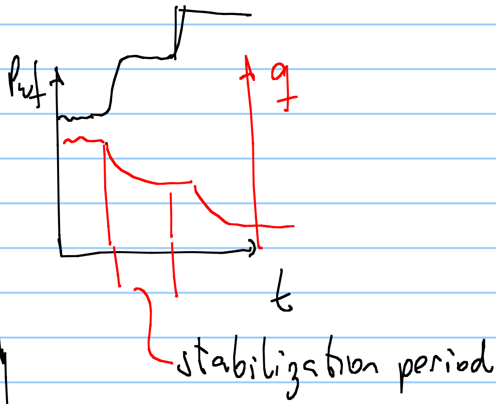
$$q_o = J(P_R - P_{wf})$$

productivity index



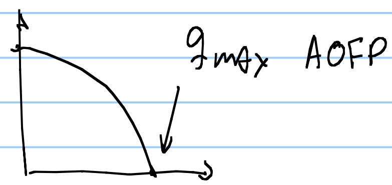
gas, saturated oil





Vogel equation (sat. oil)

$$\frac{q}{q_{max}} = 1 - 0.2\frac{P_{wf}}{P_R} - 0.8\left(\frac{P_{wf}}{P_R}\right)^2$$



Backpressure equation (gas)

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

$$0.5 \leq n < 1$$

how to find C and n for the backpressure equation from a collection of points?

well test results

P_{wf}	q	$P_{wf\,calc}$	ε
P_R	0		
P_{wf_1}	q_1	$\boxed{\ } P_{wf_1 cal}$	$(P_{wf} - P_{wf\,cal})^2$
P_{wf_2}	q_2	$P_{wf_2 calc}$	
P_{wf_3}	q_3	$P_{wf_3 calc}$	
			$\Sigma\varepsilon$

$C = \boxed{\ }$

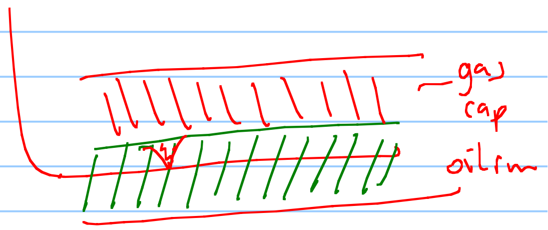
$n = \boxed{\ }$

program UDF P_{wf} vs q

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

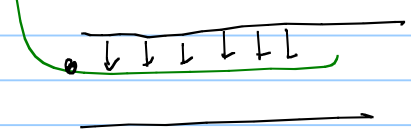
$GOR_1 \neq GOR_2$

$q_g = GOR \cdot q_o$

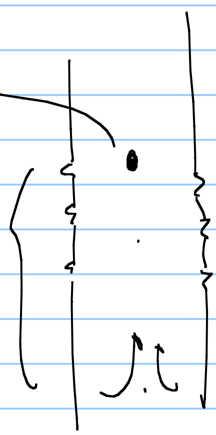


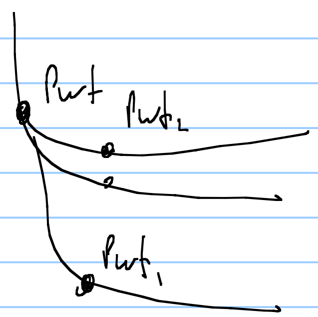
critical coning P_{wf}

How do we define bottom-hole pressure → vertical well { in front of the perforation



last point where there is fluid coming from the formation



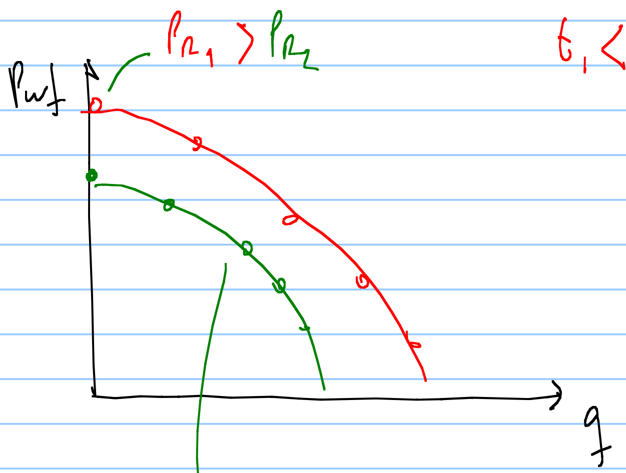


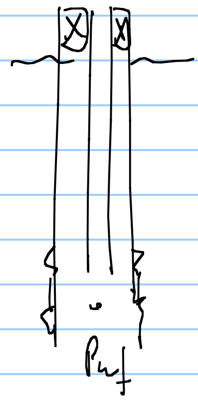
in these cases the IPR has information about the flow in the wellbore

Sometimes is better to use
a collection of points GOR, wc (f) Pwf

Pwf	q_o	q_g	q_w

IPR does it change with time? ~> IPR changes with time but





for single phase gas an undersaturated liquid the equation coefficients remain constant

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

are going to remain constant with depletion

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

constant

• tubing equation (flow in a circular conduit)

single phase liquid

single phase gas

$$\left.\frac{dp}{dx}\right|_{TOTAL} = \left.\frac{dp}{dx}\right|_f + \left.\frac{dp}{dx}\right|_h + \cancel{\left.\frac{dp}{dx}\right|_a} \rightarrow 0$$

along the pipe

V, $Re = \frac{\rho V D}{\mu}$

$f(\rho, \Delta h)$

$f(p, T)$

Tubing flow Equation-Dry gas

$T_{sc} = 15.56\,°C$

$p_{sc} = 1.01325$ bar

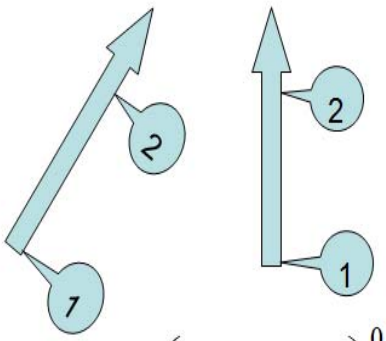
z

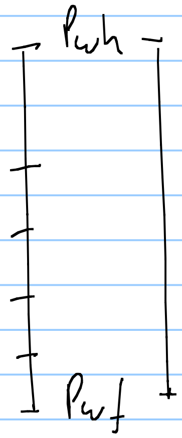
universal gas constan

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

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

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



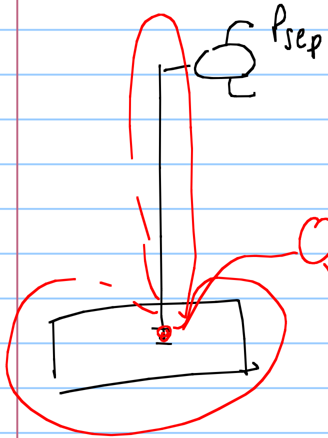


$$p_{\text{inlet}} = p_1 = e^{s/2}\left(p_2^2 + \frac{q_g^2}{C_T^2}\right)^{0.5} \qquad p_{wh} = p_2 = \left(\frac{p_1^2}{e^s} - \frac{q_g^2}{C_T^2}\right)^{0.5}$$

$p_1 = f(p_2, q_g)$ ~ single phase gas, constant inclination.

Exercise in excel.

Well hydraulic equilibrium equilibrium point bottom hole



Approximation $P_{wh} \simeq P_{sep}$

equilibrim point

(−)

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

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

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

Eva no 3					
pR	304	bara	290	bara	
C inflow	104	Sm3/d/(bar^2n)			
n, exponent	0.9				
Tubing, C_t	4.25E+04	Sm3/d/bar			
s-Elevation factor	0.155				
pwh=	35	50	85	bara	
		IPR		**TPR**	
				pwh=35 bara	
		pwf	**q**	**pin**	**error**
		bara	**Sm3/d**	**bara**	**(bar^2)**
		304	0.00E+00	38	
		254	1.04E+06	46	
		204	1.79E+06	59	
		154	2.35E+06	71	
		104	2.74E+06	79	
		82	2.86E+06	82	7.47E-12
		54	2.98E+06	85	
		4	3.06E+06	87	

p_{in}