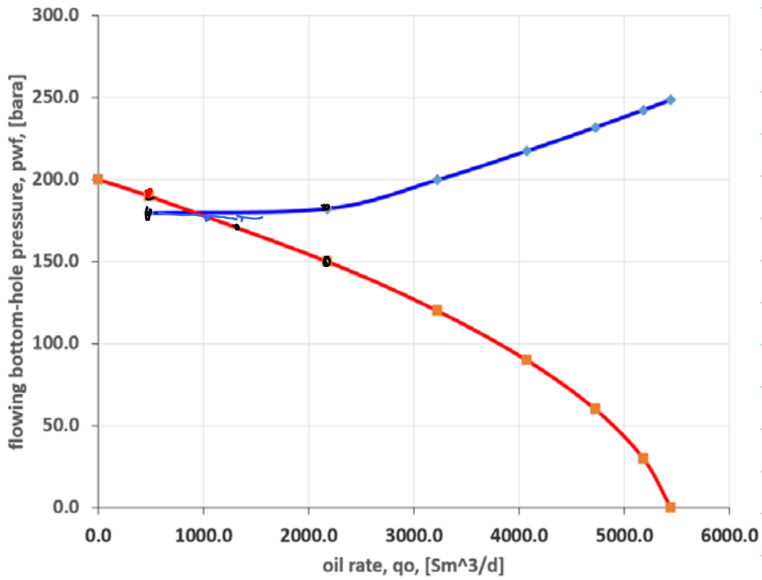
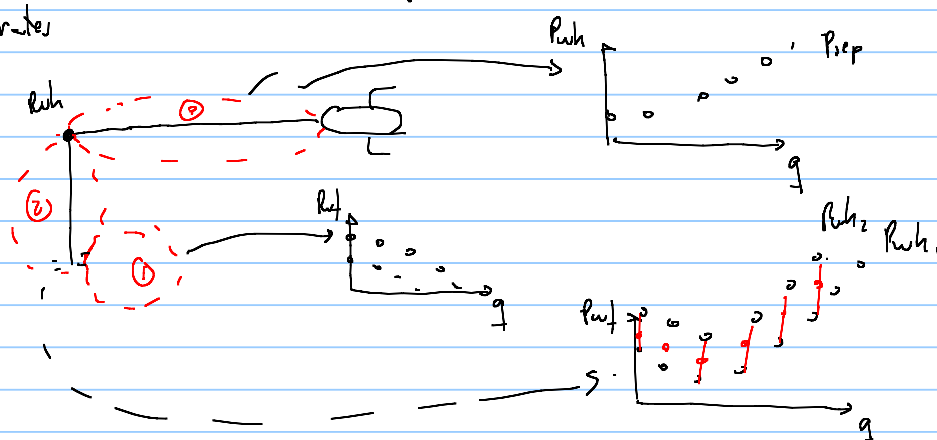
Class 6

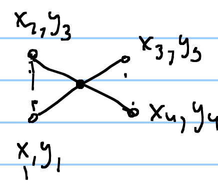
Solution of class exercise - flow equilibrium in a saturated oil well:



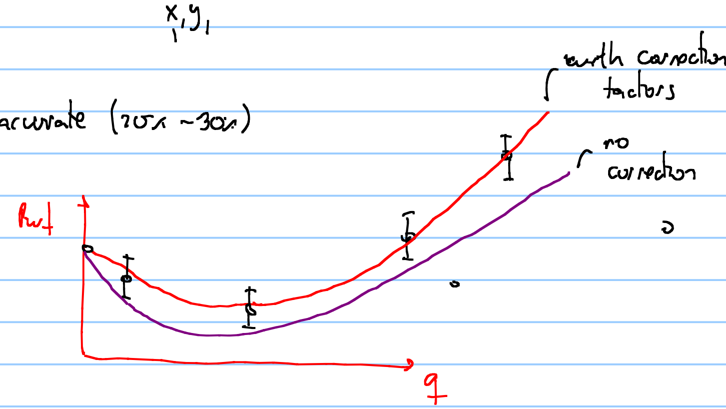
in commercial software, performance curves are often precomputed and later the collection of points is used to find operating rates



the intersection is found by intersecting two straight lines

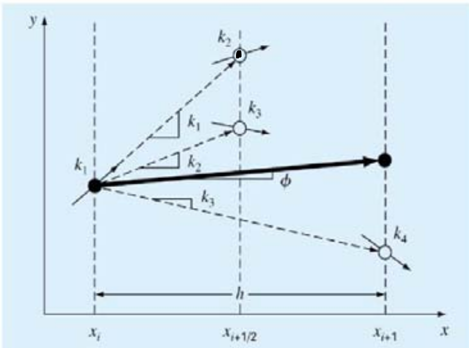


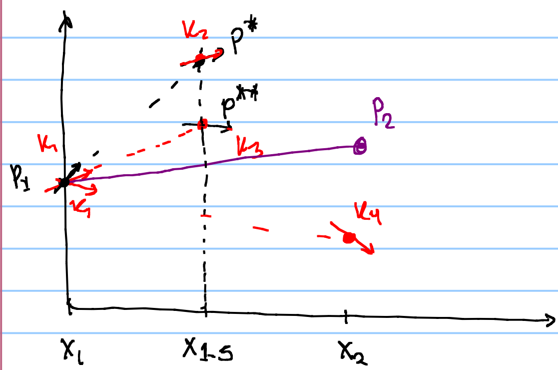
in most cases multiphase $\frac{dp}{dx}$ models are not 100% accurate (20% - 30%)



$$\left.\frac{dp}{dx}\right|_{\text{PART}} = - \underset{C_1}{\rho_{mix}} \cdot g \cdot \sin\theta - \underset{C_2}{\rho_{mix}} \cdot f \frac{V_m^2}{D \cdot 2}$$

Classic 4th-order Runge-Kutta Method





① $\left.\frac{dp}{dx}\right|_{P_1, x_1} = k_1$ Euler's

② $\frac{p^* - P_1}{\Delta x \cdot 0.5} = k_1 \rightsquigarrow p^*$

③ @ $p^*, x_{1.5} \rightsquigarrow \left.\frac{dp}{dx}\right|_{p^*, x_{1.5}} \rightsquigarrow k_2$

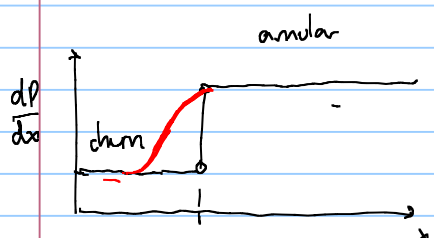
④ $\frac{p^{**} - P_1}{\Delta x \cdot 0.5} = k_2 \rightsquigarrow p^{**}$

⑤ @ $p^{**}, x_{1.5} \rightsquigarrow \left.\frac{dp}{dx}\right| = k_3$

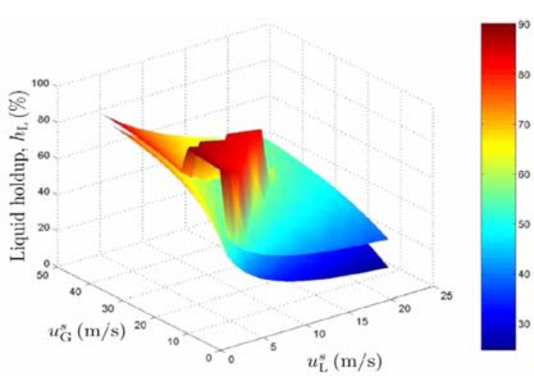
⑥ $\frac{P_2' - P_1}{\Delta x} = k_3 \rightsquigarrow P_2'$

⑦ @ P_2', x_2 $\rightsquigarrow \frac{dp}{dx} = k_4$

⑧ $y^*(t_0 + h) = y^*(t_0) + \frac{k_1 + 2k_2 + 2k_3 + k_4}{6} h \rightsquigarrow P_2$



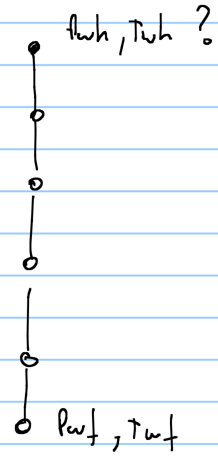
flow pattern based dp model looks like



what happens with integration of p, T ?

$\frac{dp}{dx}$ momentum balance multiphase

$\frac{dT}{dx}$ energy balance (high GOR gas wells)



$\rightsquigarrow \frac{dp}{dx}, \frac{dT}{dx}$

$\frac{dp}{dx}$ is often a function of T

$$\frac{\partial p}{\partial x} = f(T, \ldots)$$

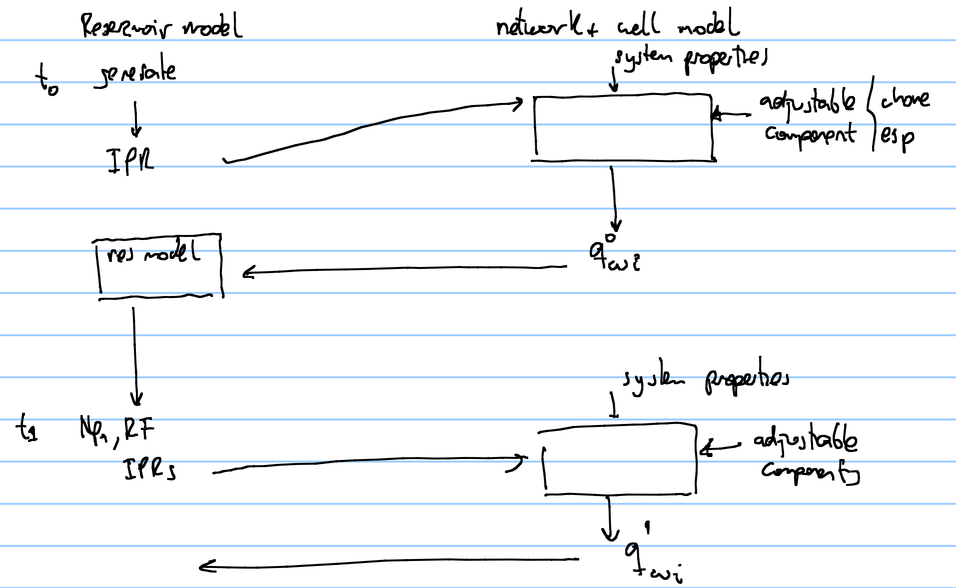
$$\frac{\partial T}{\partial x} = f(p, \ldots)$$ e.g. Joule Thomson coefficient

coupled system of differential equations

luckily $\frac{\partial p}{\partial x} = f(T)$ is weak

$\frac{\partial T}{\partial x} = f(p)$ is weak

<u>field performance</u>



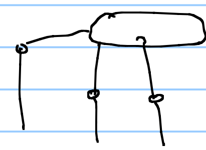
coupling of reservoir and network models

SPE 65159

Linking reservoir and surface simulators: how to improve the coupled solutions
C. C. Barroux, Institut Francais du Petrole, P. Duchet-Suchaux, TotalFinaElf S.A., P. Samier, TotalFinaElf S.A., R. Nabil, Gaz de France

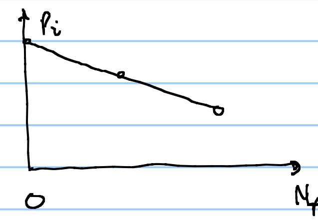
- undersaturated oil reservoir strong aquifer support → no multiphase flow in the formation during life of field
- field produced with ESPs

- well are standalone (no surface network)



- well are identical

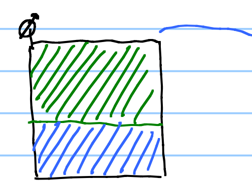
Material balance



Reservoir model $P_R = P_i - A \cdot N_p$ — B_o, C_R, V, V_A

initial oil in place — compressibility

$$\frac{1}{A} = \frac{\left(N \cdot B_{oi} \cdot c_o \cdot + N \cdot B_{oi} \cdot \frac{c_w \cdot S_w + c_f}{S_o} + V_a \cdot \phi_a \cdot (c_w + c_f) \cdot B_w\right)}{B_o(p)}$$



well model $q_o = J \cdot (P_R - P_{wf})$

ESP can operate down to a minimum bottomhole pressure $P_{suc} > P_b(T_R)$

$P_{wf\,min}$

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

for "N_w" number of identical wells

$$q_{field} = N_w \cdot J\,(P_R - P_{wf\,min})$$

$$q_f = N_w\, J\,(P_i - A \cdot N_p - P_{wf\,min})$$

$$q_f = -N_w \cdot J \cdot A \cdot N_p + \underbrace{N \cdot J\,(P_i - P_{wf\,min})}_{\text{initial maximum production}}$$

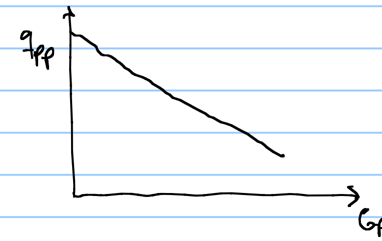
$$q_f = -N_w \cdot J \cdot A\,N_p + q_{of}$$

max field rate @ N_p

$q_f = q_{pp}$ field production potential

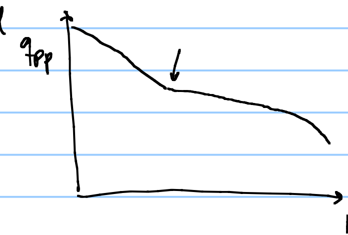
$q_{pp} = -m\, N_p + q_{opp}$ → field production potential @ initial reservoir pressure

for other cases • dry gas and network

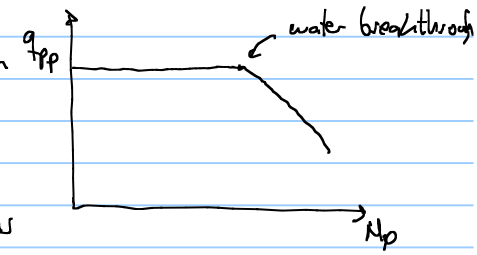


production potential is calculated by,
@ a given N_p, run model to obtain maximum production → open choke
→ ESP, Pwfmin, frequency
→ gas lift → optimization
→ multiphase booster → max frequency

• saturated + undersaturated



• undersaturated + water injection $P_R \simeq$ constant

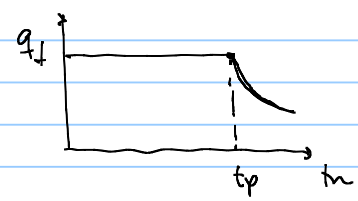


$$\int_0^t q_f \cdot dt$$

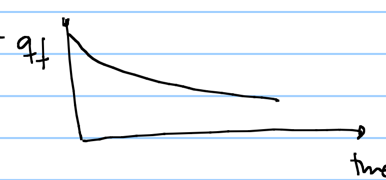
$\{ q_{pp} = -m\, N_p + q_{ppo} \}$ — Pwf min, inital conditions

m → A → reservoir (size, structure, fluid properties)
→ N_w → number wells
→ J → well productivity

field are typically produced in two modes → plateau



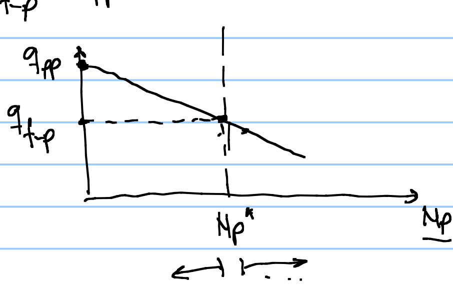
→ potential



$q_f = f(t)$?

$$q_f \begin{cases} q_{f-p} & \text{if } t \leq t_p \\ q_f = q_{pp} & \text{for } t > t_p \end{cases}$$

plateau will end when $q_{f-p} = q_{pp}$



for $N_p > N_p^*$ I cannot maintain desired plateau

for $N_p \leq N_p^*$ I can produce plateau

N_p^* $[Sm^3]$ $\qquad q_{f-p}$ $[Sm^3/d]$ $\qquad 0 \to N_p^*$

$$t_p = \frac{N_p^*}{q_{f-p}} \quad \frac{[Sm^3]}{[Sm^3/d]} \quad \frac{1}{\text{uptime}} \qquad (1)$$

uptime ; number of operational days in a year $\left[\frac{day}{year}\right]$

$$q_{p-f} = q_{pp} = -m N_p^* + q_{ppo}$$

$$N_p^* = \left[\frac{q_{ppo} - q_{pf}}{m}\right] \qquad (2)$$

$$t_p = \frac{q_{ppo} - q_{p-f}}{m \cdot q_{f-p}\ \text{uptime}} = \frac{1}{m}\frac{1}{\text{uptime}}\left(\frac{q_{ppo}}{q_{f-p}} - 1\right)$$

for $t > t_p$

$$t_p = \frac{1}{N_w \cdot A \cdot J}\left[\frac{N_w J(P_R - P_{wf,min}) - 1}{q_{f-p}}\right]$$

$$t_p = \frac{1}{A \cdot J}\left[\frac{J(P_R - P_{wf,min})}{q_{f-p}} - \frac{1}{N_w}\right]$$

$$q_f = q_{pp} = -m\int_0^t q_f\,dt + q_{ppo}$$

$$q_f = -m\int_0^{t_p} q_{p-f}\,dt - m\int_{t_p}^t q_f\,dt + q_{ppo}$$

$$q_f = -m\, q_{p-f}\, t_p - m\int_{t_p}^t q_f\,dt + q_{ppo}$$

$$q_f = -\frac{\cancel{m}}{\cancel{m}}(q_{ppo} - q_{pf}) - m\int_{t_p}^t q_f\,dt + q_{ppo}$$

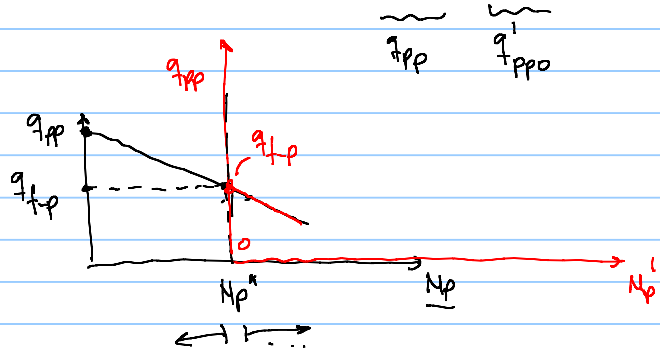
$$\underbrace{q_f}_{q_{pp}} = \underbrace{q_{p-f}}_{q'_{ppo}} - m\underbrace{\int_{t_p}^t q_f\,dt}_{N'_p}$$

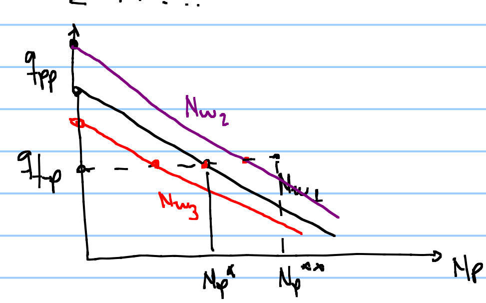
https://en.wikipedia.org/wiki/Integrating_factor

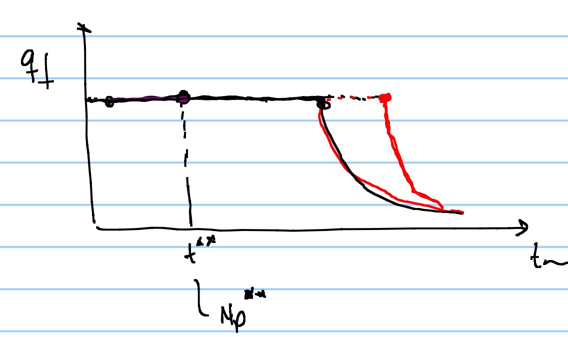
a solution is:

$$q_f = q_{f-p} \cdot e^{-m(t-t_p)}$$

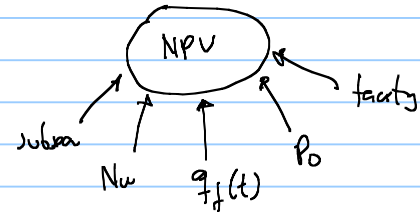
$A \cdot J \cdot N_w$







in the field development process decision $\rightarrow$ NPV



time	expenditures	Revenue	$\boxed{\text{Cash flow}}$	$\boxed{\text{DCF}}$
0			Revenue − Expenditure	
1				
2				
3				
4				
5				

$PV = \frac{FV}{(1+i)^n}$ — n: year counter, i: interest rate

$\sum DCF = NPV$

find q_{fp} such as NPV is maximum $\uparrow q_{f-p}$ increase revenue $\uparrow$ $\uparrow$ CAPEX $= f(q_{f-p})$?

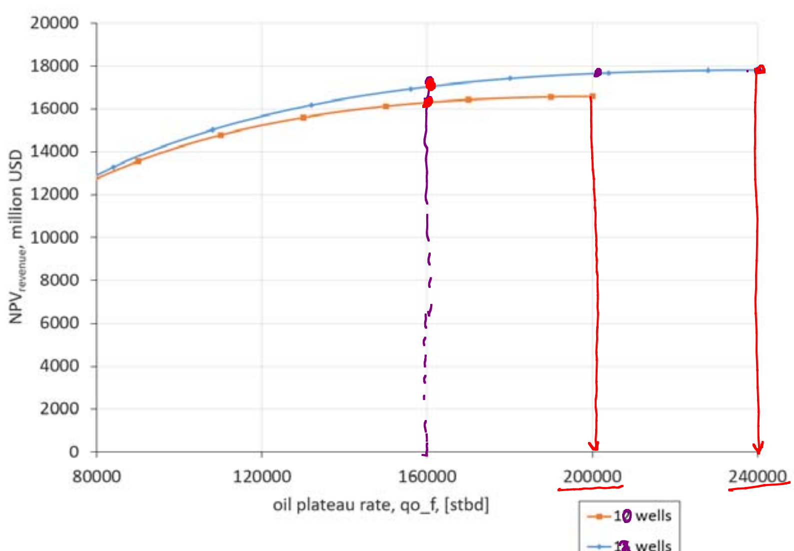
$$PV\ Revenue = \int_0^t \frac{P_o \cdot q_f}{e^{it}}\, dt$$

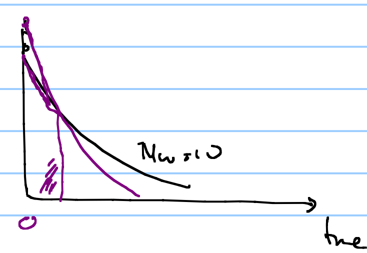
discrete discounting $\frac{1}{(1+i)^n}$

continuous discounting $\frac{1}{e^{it}}$

$$PV_{revenue} = P_o \left[\int_0^{t_p} \frac{q_{f-p}}{e^{it}} \cdot dt + \int_{t_p}^{t} \frac{q_{f-p}\, e^{-m(t-t_p)}}{e^{it}}\, dt \right]$$

$$PV_{revenue}(t) = q_{fp} \cdot P_o \left[\frac{m+i - m\, e^{-\left(\frac{q_{ppo}}{q_{fp}} - 1\right)\frac{i}{m}} - i\, e^{-(m+i)t + \left(\frac{q_{ppo}}{q_{fp}} - 1\right)}}{i\,(m+i)} \right]$$





$\frac{1}{e^{it}}$