RESERVOIR RECOVERY METHODS

Note Title 9/3/2018

(A) DEVELOPMENT METHODS

① Smaller and often Onshore Projects

(HM)

(G&G) Drill – Discover (HCs) – Produce – Monitor – Modeling ⇒ Forecasting (& Today's optimization) q's p's

Theory
Eqs.
Num. methods
Data
Tune

History Matching

② Larger and Usually offshore Projects

G-G – Drill – Discover (HCs) – (Might Start Production Test) – Drill & Delineation –

(a) Modeling – Design – PDO
(???)
Planned Development Operation

Sensitivity Analysis
Statistics
Monte Carlo

(b)
– Development – Produce – Monitor – Modeling ⇒ (HM)
Forecasting (& Today's optimization)

(B) Modeling Methods $\quad p_R(Q_p) \quad N_p \quad N$

① (Volumetric) Material Balance : $p_R = f(p_{R_i}, Q_p, Q_i ; Q_{inj})$

Product Volumes $\quad \boxed{k \gtrsim 0.01 - 0.1} \quad$ g $\quad$ o $\quad G_p \quad$ IGIP G

[IOIP IGIP WIP]^{INITIAL} = Produced − Injected + Remaining

Sm^3 stb Mscf

(a)

e.g. Gas M.B. "Pot Aquifer"

$$\frac{p_R}{Z_{gR}}\left[1 - c_e(p_{R_i} - p_R)\right] = \left(\frac{p_{R_i}}{Z_{gi}}\right)\left(1 - \frac{G_p}{G}\right)$$

G_p = Cum. Gas (surface Gas Product) Produced

G = IGIP (—"—)

$p_R(Q_p)$

(b) Each and All RFUs

Aside : Reservoir Simulation of Depletion

$N_{cells} \simeq N_{RFU}$

if ands and buts (k sufficiently high)

$p_R \sim p(X, Y, Z)$

during Δt = 1–6 mo.

② Approximate Flow Equations

- Mainly Darcy (In reservoir w/reservoir rates / surface product rates)
- Depletion
  - Surface Rate Eq. $q_g = \dfrac{kh\,(p_{pR} - p_{pwf})}{T_R \cdot \Big[\underbrace{\ln \frac{r_e}{r_w}}_{7-10} + s + Dq_g\Big]} = \underbrace{\dfrac{dG_p}{dt}}$

$$p_p = 2\int_{p_{ref}}^{p} \frac{p'}{\mu Z}\,dp'$$

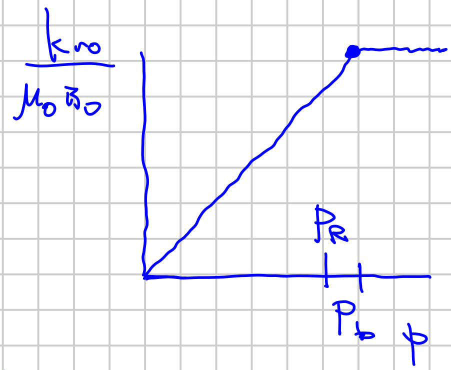
Single Phase Oil

$$\underset{\substack{STB/D \\ Sm^3/D}}{\frac{dQ_o}{dt}} = q_o = \frac{kh\,(\overset{M.B.}{p_R} - p_{wf})}{\mu_o B_o \left[\ln \frac{r_e}{r_w} + s\right]} = \frac{dN_p}{dt}$$

$-6 < s < +100$

S&D $\quad p_R < p_b$

$$q_o = \frac{k_{ro}\,kh\,(p_R^2 - p_{wf}^2)}{\mu_{ob} B_{ob} (2p_b) \left[\ln \frac{r_e}{r_w} + s\right]}$$

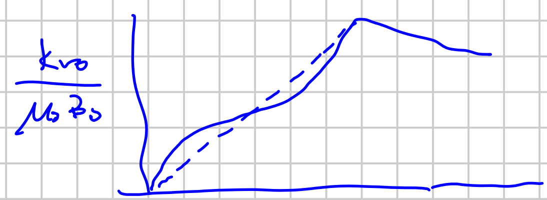


Fetkovich

Alt. ⇒ Vogel (100s of Simulations)

Muskat (1930s-40s)

Meyers



$$\begin{cases} MB: & p_R(Q_p) \\ Rate: & q = \dfrac{dQ_p}{dt} = \text{constant} = PI\,(p_R - p_{wf}) \end{cases}$$

$\boxed{q(t) \Rightarrow \text{Forecast} \quad \text{(Today's Optimization)}}$

Arp's Decline Curve Eq. : $\underbrace{MB}$ + $\underbrace{\text{"IPR"}}$ $\Rightarrow q(t)$

$$q = \frac{q_i}{[1 + bDt]^{1/b}}$$

$$q_i = PI(P_R - P_{wf}) = \text{constant}$$

$0 < b < 0.5$ — Single phase, low c oil; Low Pressure Gas; SGD

Decline Constant

$$D \equiv \frac{q_i}{\underbrace{(\underbrace{Q_i \cdot RF_{ult}}_{\text{"EUR"}})}} \cdot \frac{1}{1-b}$$

"Rate of Depletion"

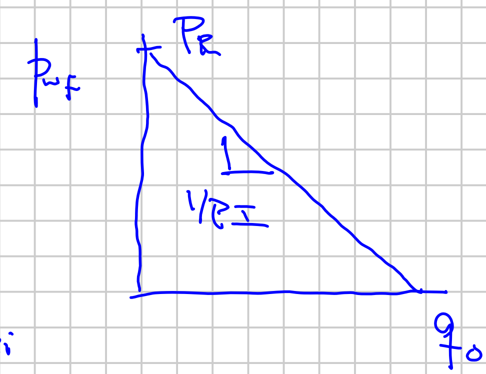
Contrast $\Rightarrow$ "Differential Depletion"

RFU_1 vs RFU_2

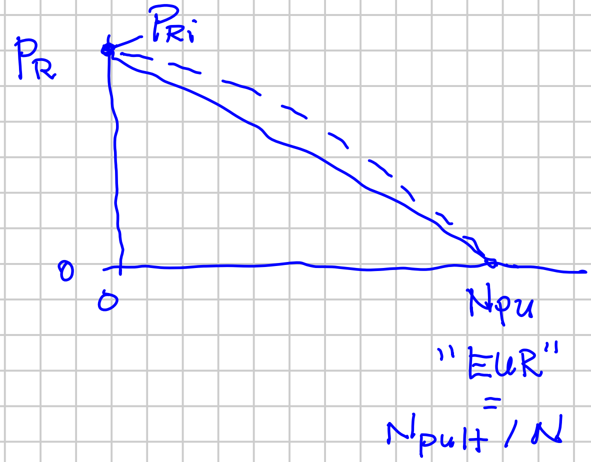
Homework Fun:

$$q_o = PI(\underbrace{P_R - P_{wf}}_{\text{const}})$$

$P_R(t)$



$$P_R = P_{Ri}\left(1 - \frac{N_p}{N_{pult}}\right)$$



$\Rightarrow$ Arp's Decline Eq.?

EOR : Displacent of Insitu Fluid by Injected Fluid

- Two or more wells ($I \rightarrow P_s$)
- $v_D = \frac{k}{\mu} \cdot \frac{dp}{dx}$ Darcy Velocity

  - Injected (w)
  - Produced (o)

$$v_{wD} = \underbrace{\left(\frac{k_w}{\mu_w}\right)}_{\lambda_w} \frac{dp_w}{dx} = k\left(\frac{k_{rw}}{\mu_w}\right)\frac{dp_w}{dx}$$

$$v_{oD} = \underbrace{\left(\frac{k_o}{\mu_o}\right)}_{\lambda_o} \frac{dp_o}{dx} = k\left(\frac{k_{ro}}{\mu_o}\right)\frac{dp_o}{dx}$$

@ Reservoir Conditions

$p_w \simeq p_o$

Mobility $\lambda \equiv \frac{k}{\mu}$ md/cp

Behind Front

$$M \equiv \frac{(k_{rw}/\mu_w)}{(k_{ro}/\mu_o)} = \underbrace{\left(\frac{k_{rw}}{k_{ro}}\right)}_{\text{Rock}}\underbrace{\left(\frac{\mu_o}{\mu_w}\right)}_{\text{Fluid}}$$

Mobility Ratio

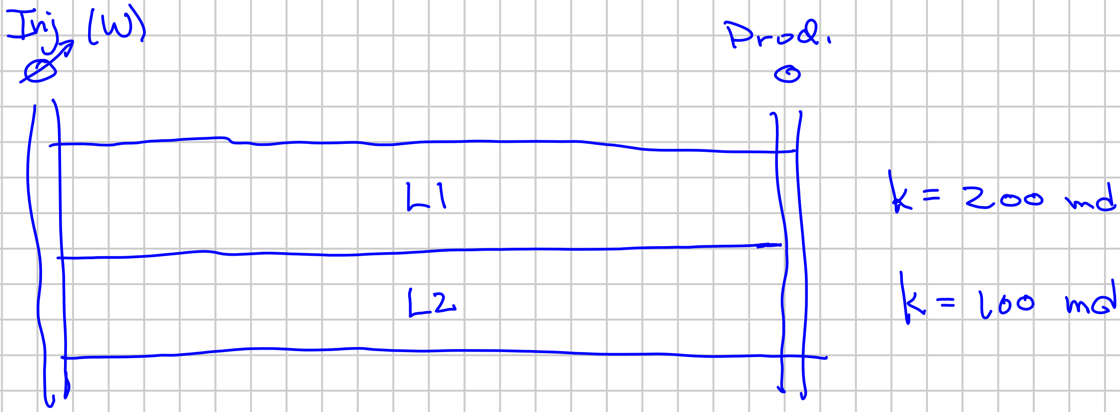
Ahead of Front

Rel. Perm. Ratio

Viscosity Ratio

Fractional Flow (Ratio) $f_w(S_w) \equiv \frac{v_{wD}}{v_{wD} + v_{oD}}$

$$= \frac{1}{1 + \frac{k_{ro}}{k_{rw}}(S_w)\frac{\mu_w}{\mu_o}}$$



$h_1 = h_2$

Breakthrough occurs at the Same Time in both layers. $\phi_{L1} = 0.2$ $\phi_{L2} = 0.10$

Transport $v \neq v_D$

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Quiz

1 page only (front/back), Name written

① Write the Pot Aquifer Material Balance Eq.

$$\frac{p_R}{z}\underbrace{\left[1 - c_e(p_{Ri}-p_R)\right]}=\left(1-\frac{G_p}{G}\right)\left(\frac{p_{Ri}}{z_i}\right)$$

② Define the parameters needed to calculate

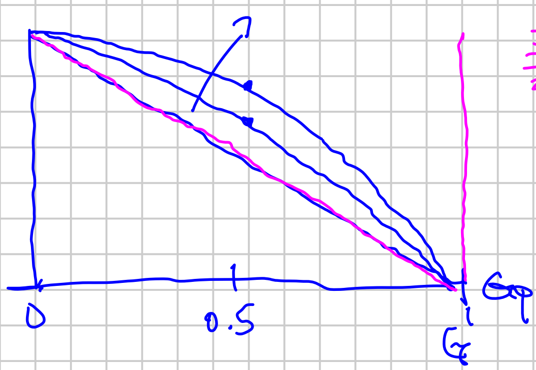
c_e (?) M (?) c_e: M, c_w, c_f | M: V_w

③ What are the basic assumptions (list 2-3) of the Pot Aquifer model? [$p_w \simeq p_g$] ⟸

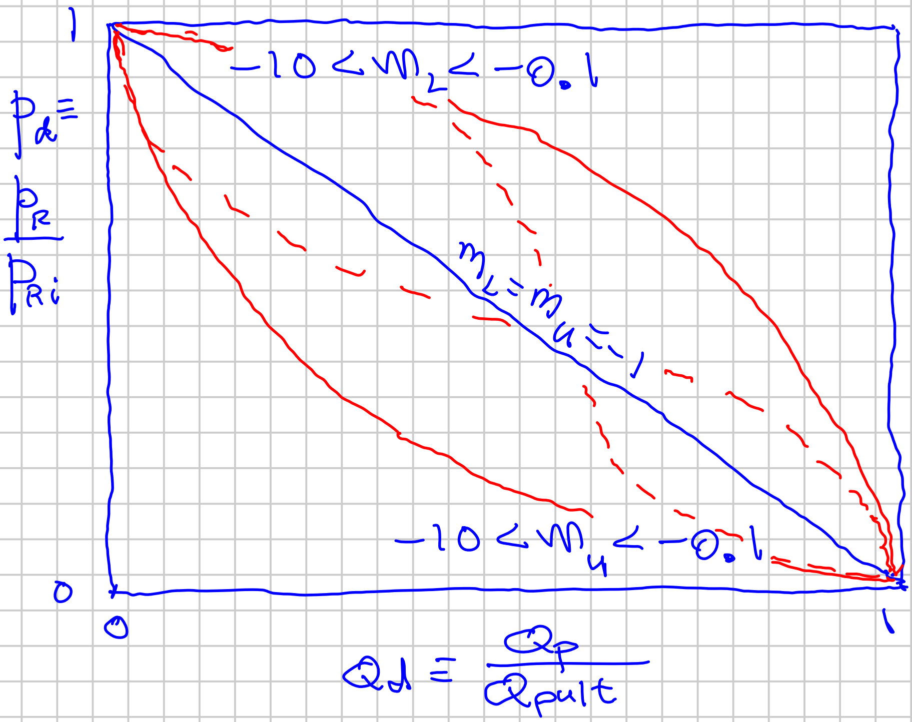
④ Draw p/Z vs Gp for straight-line material balance & for MB w/ Pot Aq.
(a) small water volume (b) large water volume

⑤ When is the $c_{t_w}(p)$ important? lower p's

④ $\frac{p}{z}$



$\frac{p}{z}\left[1 - c_e(p_{Ri}-p_R)\right]$



Find a general relation $p_d(Q_d)$ with following constraints:

$p_d(0) = 1$, $p_d(1) = 0$

$$\left.\frac{dp_d}{dQ_d}\right|_{Q_d=0} = m_L$$

$$\left.\frac{dp_d}{dQ_d}\right|_{Q_d=1} = m_u$$

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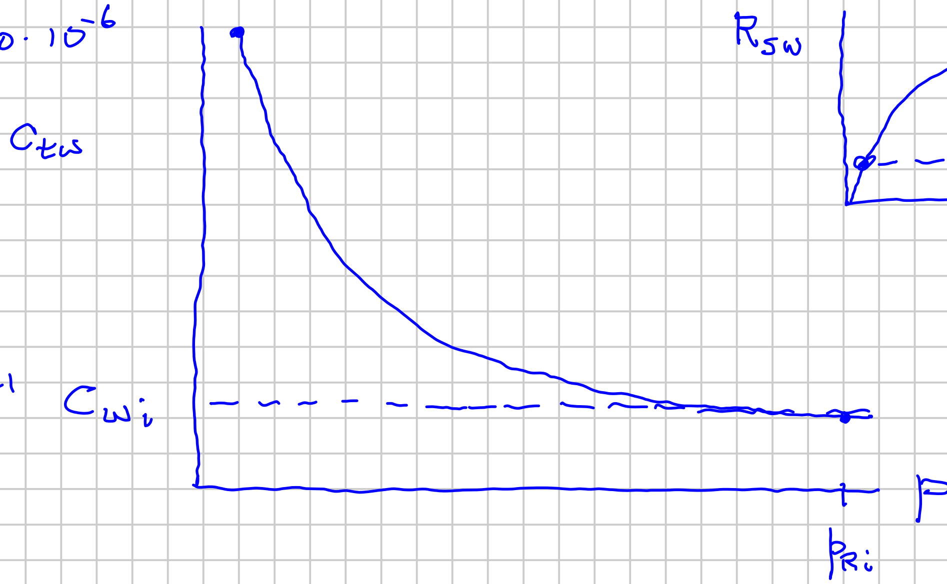
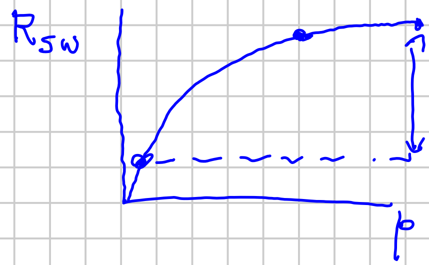
$c_{tw}(p)$: Biggest impact at lower pressures

$\times \bigcirc = 10-50 \cdot 10^{-6}$





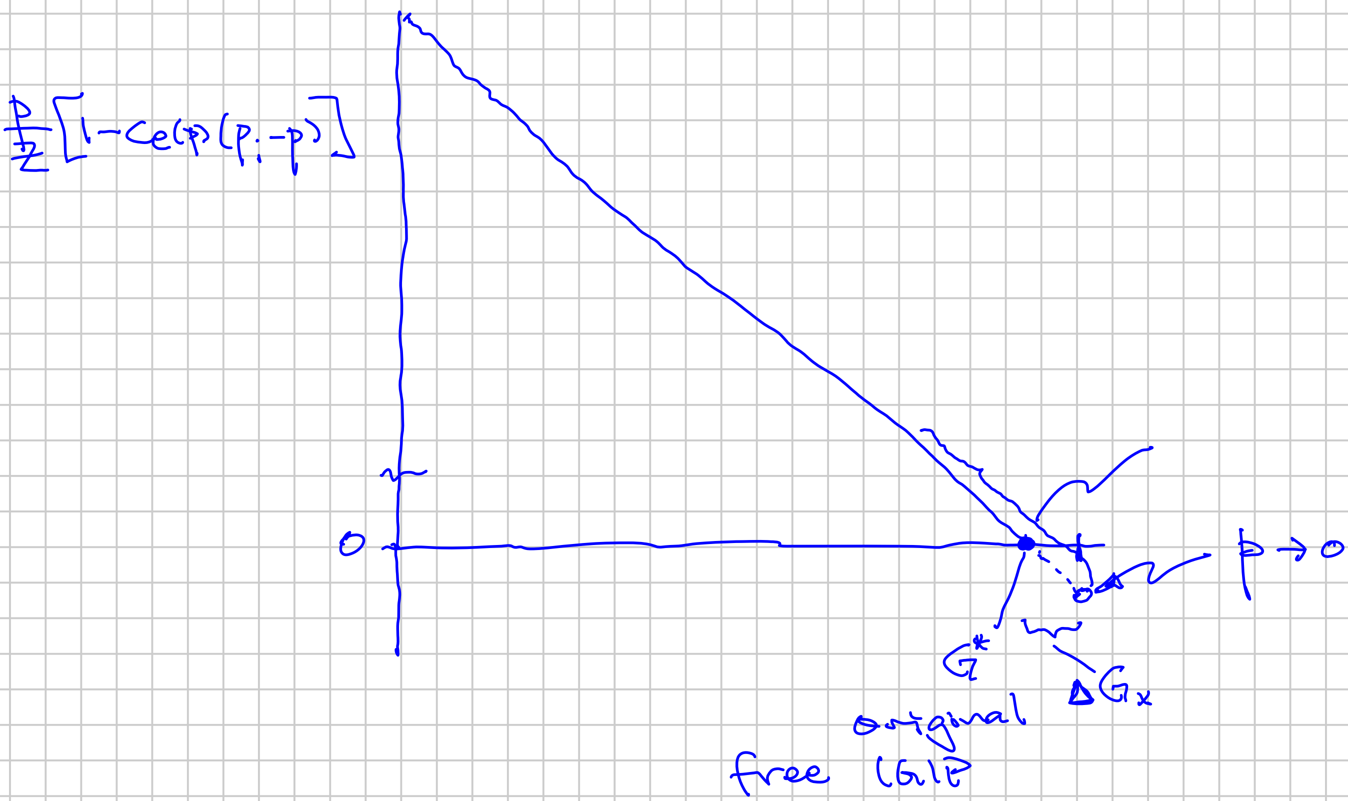
$$c = -\frac{1}{V_t}\left(\frac{\partial V_t}{\partial p}\right)_{T,\underline{\underline{m}}}$$

$p < p_{Ri}$ split into g+w

$$V_t = \underset{\sim \text{const}}{V_w} + V_g(p)$$

$$V_g(p) = \underbrace{(R_{swi} - R_{sw}(p))\, B_g(p)}$$

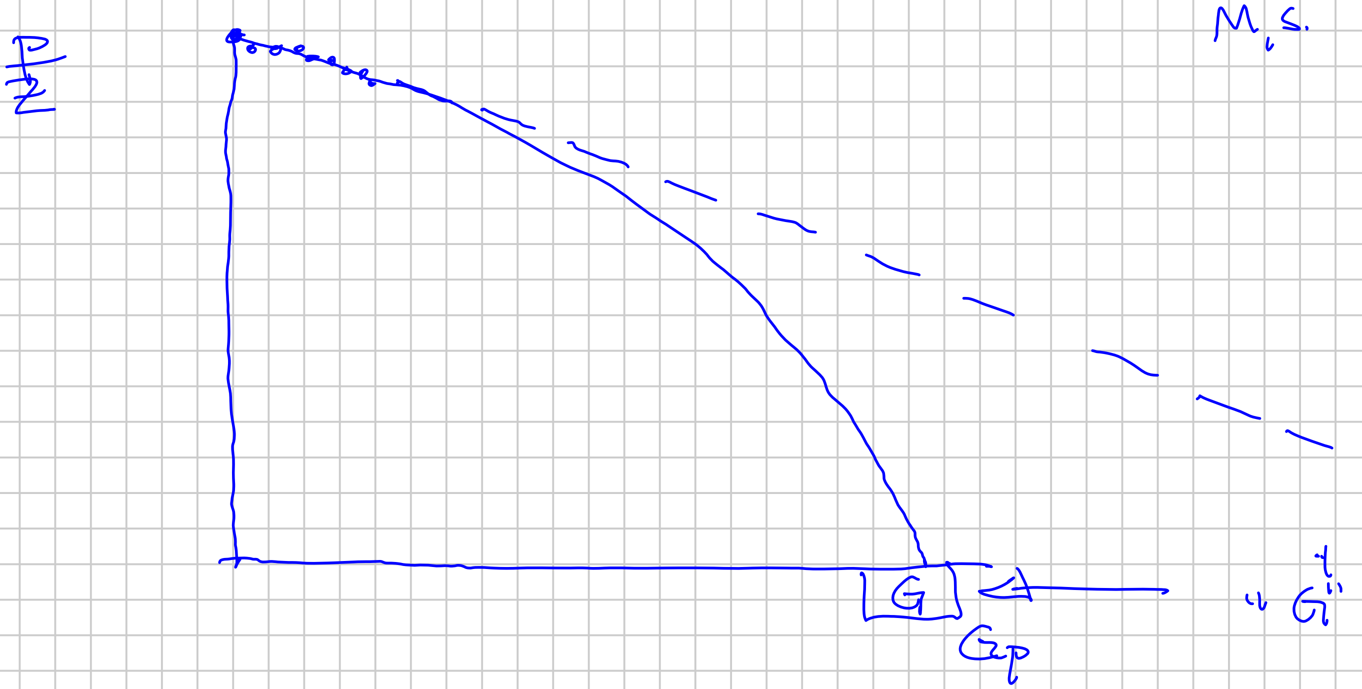
$$\boxed{(R_{si} - R_s(p))\, B_g(p)}$$ Oil M.B.



$$\text{True } G = G^* + \Delta G_x$$

$$\Delta G_x = R_{swi} \cdot IWIP$$

M.S.



"EOR"

v_D v_p

$v_D = 1 \; m/d$

$t_f \neq \dfrac{L_f}{v_D}$

$t_f = \dfrac{L_f}{v_p}$

Prove:

$$v_p = \frac{v_D}{\phi \, \underbrace{\Delta S}_{\text{of the injected phase}}}$$

$S_{wc} = S_{wi} = 0.2$

S_w (Behind Front) $= 1 - S_{orw} = 0.75$ $\Big\} \; \Delta S_w = 0.55$

In Swept Volume 0.25

Modeling Methods

1. Mat. Bal.

2. Approx. Flow Eqs
   - Pseudosteady State "Rate" Eqs $\left.\begin{matrix} q_{\bar{g}} \\ q_{\bar{o}} \\ q_{\bar{w}} \end{matrix}\right\} (p_{\underline{R}} - p_{\underline{wf}})$

     Oil: IPR (Inflow Performance Relationship)

     Gas: BPE ("Reservoir" Backpressure Eq.)

Steady State: doesn't change with time

Pseudo SS: (a) Something does change with time — But very slowly

$p_R(t)$ slowly

(b) Now (at some time) the system behaves SS

③ Numerical Reservoir Simulation (>1980-90s)

<1980 ⇒ 60s BOAST (2) COMP1 (2) (4) "INTERCOMP" (Coats et al) THERM : NOLEN

>1980 ECL100 ECL300 SENSOR VIP NEXUS INTERSECT ... -MORE

Review: See paper (optional) SPE Chapter 17 by Coats et al. (2009): optional reading.

- Finite Difference
  - Conventional IMPES | Implicit | Adaptive Implicit
  - Streamline (key: EOR Volumetric Sweep) "Conformance"

- Grid Refinement
  - Each RFU!
  - Numerical dispersion (fake mixing)
    ⇒ Very problem/process dependent
    ⇒ Requires attention, always
  - Wells: PSS Rate Eqs. = $N_w \cdot N_c$
    ⇒ Needs fully implicit treatment
    - Connects Wells to Grid Cells
  - May include Reservoir-to-Surface connection
    - VL Tables (Vertical Lift)
    - VL Eqs (VIP)

$p_{wf} \to p_t$

$\Delta p(q_g, q_o, q_w, p_{wf})$

-

DEPLETION RECOVERY

① Volumetric Material Balance

Theoretical $p_R \to 0$

$$(\bar{p}_R)_{RFU} = f\left(Q_p\ ;\ p_{Ri}\ ,\ Q_{pu}\right)$$

$p_R(Q_p)$ ~ Est. Ultimate Recovery ("EUR") @ $p_R \to$ Abandonment ≈ 0

② PSS Rate Eq.

$\bar{q}$ $\bar{o}$

$$q = f\left(p_R\ ,\ p_{wf}\ ;\ \underbrace{\frac{PI}{J}\ ,\ C\ \&\ n\ ;\ A\ ,\ B}_{\text{constants}}\right)$$

$$q(p_{wf}, p_R) = \frac{dQ_p}{dt}$$

③ Couple MB & Rate Eq.

Time dependence of $q(t)$ and $Q_p(t)$ for a given, specified $p_{wf}(t)$

- Analytically for special MB / IPR Eqs
- Iterative (Explicit) ~ Solution Excel

$$\left\{ q_o = J(p_R - p_{wf}) \qquad p_R = p_{Ri}\left(1 - \frac{N_p}{N_{pu}}\right) \right\}$$

④ Compare with Empirical (Arp's) DCA Eq.

Decline Curve Analysis

for $p_{wf} = \text{const.}$

$$\underbrace{q \simeq \frac{q_i}{\left[1 + bDt\right]^{1/b}}} = \underbrace{q_i e^{-Dt}}$$

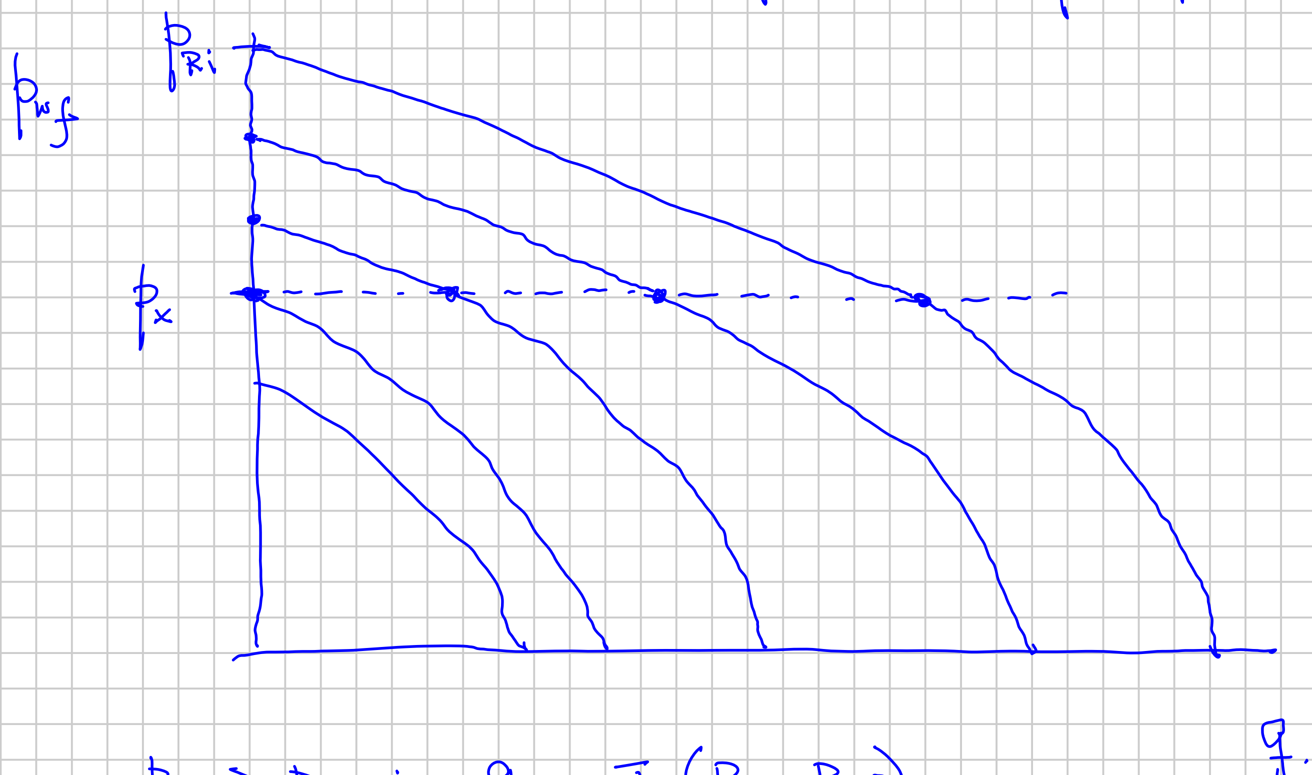
$$\boxed{b = 0}$$

$$\frac{dN_p}{dt} = q_o$$

Low $p_R < 200$ bar High p $p_R > 200$ bar

Generalized Rate Eq. Gas & Oil

Undersat. $p_R > p_b$ Sat. (SGD) $p_R < p_b$



$p_{wf} > p_x$: $q = \underbrace{J}(p_R - p_{wf})$

$p_{wf} < p_x$: $q = J'(p_R^2 - p_{wf}^2)$

OILS : q_o $p_x = \underline{p_b}$

GASES : q_g $p_x \simeq 200 \pm$ bar