Note Title 3/17/2016

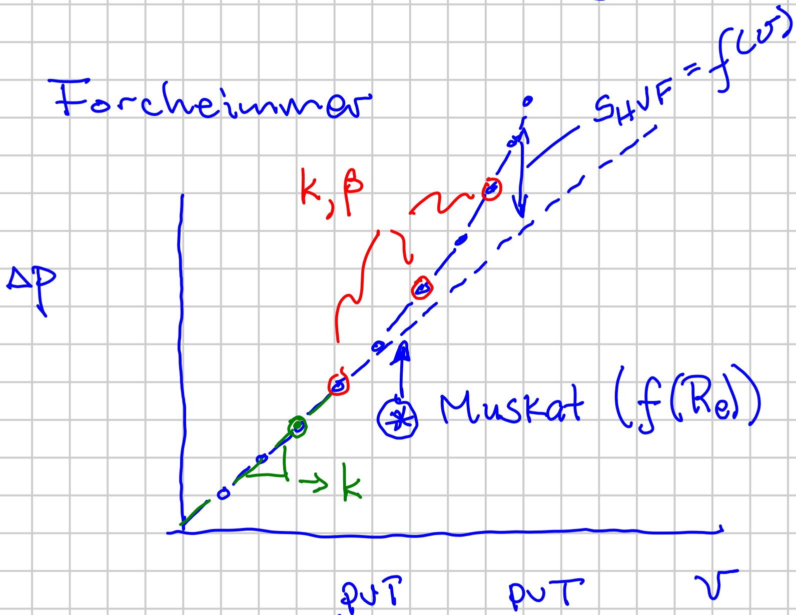
GAS (RESERVOIR) RATE EQS.

$k > 10$ md (100s → 1000s md)

$$v = \frac{q}{2\pi r h} \qquad v(r)$$

v_{max} @ $r \sim r_w$

Forcheimmer



$$\frac{dp}{dx} = \frac{\mu}{k} v + \underbrace{\rho \beta v^2}$$

PVT (μ), PVT (ρ), Rock (k)

High-velocity non-Darcy

Important $Re \gtrsim 1\text{–}10$

$$\boxed{Re = \frac{d v \rho}{\mu}}$$

$$f = \frac{\Delta p}{v^2}$$

$$\beta \sim \frac{1}{k}$$

Ekofisk:

$d_p \sim 0.5\ \mu m$

$\rho_o \sim 400\ kg/m^3$

$\mu_o \sim 0.2$ mPa·s

$q_o = 10{,}000$ STB/D $B_o = 1.6$ bbl/STB, $h = 10$ m

MULTI-RATE TESTING

MULTIPOINT TESTING OF GAS WELLS

by

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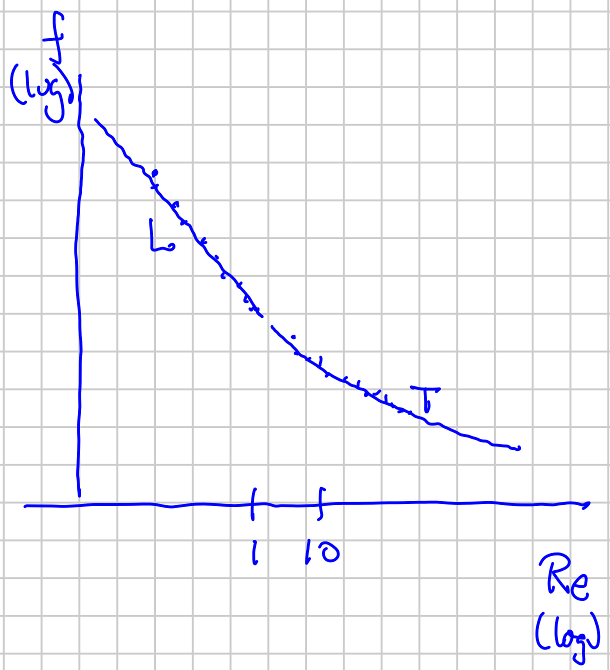
Gas Fields in Norway

- Cod (pre-Ekofisk)
- Albuskjell (Ekofisk Chalk)
- Frigg ~ 7 Tcf
- Sleipner multi-Tcf
- Troll (gas) ~ 40^+ Tcf
- Åsgard (Smørbukk)
- Ormen Lange ~ 7 Tcf

1980 ~ Katz & Firoozabadi



$$q_o = J_o (p_R - p_{wf}) \checkmark \qquad \underline{p_{wf} > p_b}$$

Darcy – often 'got' right

$$q_g = J_g (p_R - p_{wf}) \qquad \underline{p_{wf}} > 250 \text{ bar} \qquad \text{(high-pressure approx.)}$$

$$* \; q_g = C (p_R^2 - p_{wf}^2) \qquad \underline{p_R} \lesssim 150 \text{ bar} \qquad \text{(low-pressure approx.)}$$

$$q_g = C (p_{pR} - p_{pwf}) \qquad \text{Any } (p_R, p_{wf}) \text{ range}$$

Ekofisk:

$d_p \sim 0.5 \, \mu$

$\rho_o \sim 400 \text{ kg/m}^3$

$\mu_o \sim 0.2 \text{ mPa·s}$

$q_o = 1500 \text{ Sm}^3/\text{d}$ $\quad$ $B_o = \underbrace{1.6 \text{ m}^3/\text{Sm}^3}$ @ 0.25 m, $\quad h = 10$ m

v @ 0.25 m

$$Re = \frac{d v \rho}{\mu}$$

$$v_o = 1600 \frac{\cancel{\text{Sm}^3}}{\cancel{\text{d}}} \cdot 1.6 \frac{\text{m}^3}{\cancel{\text{Sm}^3}} \cdot \frac{1}{2\pi (\underset{\text{m}}{0.25})(\underset{\text{m}}{10})} \cdot \frac{\cancel{\text{d}}}{86400 \text{ s}}$$

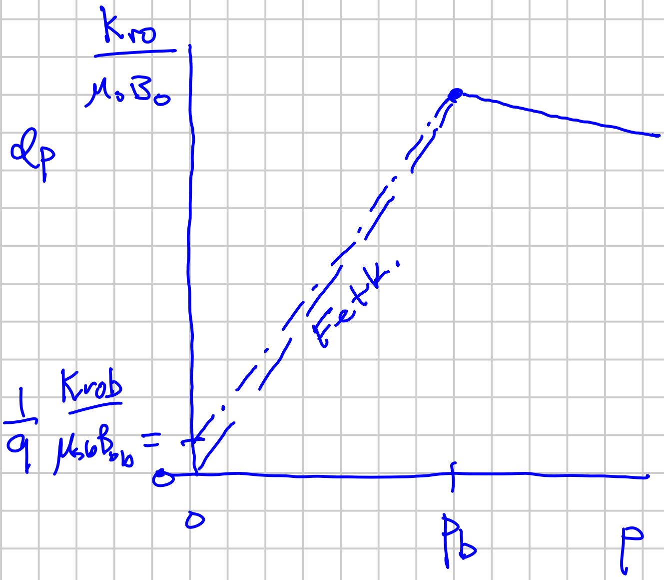
$$= 1.9 \cdot 10^{-3} \quad \text{m/s}$$

$$Re = \frac{(0.5 \cdot 10^{-6} \text{ m})(1.9 \cdot 10^{-3} \; \overset{\text{m/s}}{}\,)(400 \text{ kg/m}^3)}{0.2 \cdot 10^{-3} \quad \text{Pa·s}}$$

$$= 2 \cdot 10^{-3}$$

$$q_o = \underbrace{\frac{kh}{\ln r_e/r_w}}_{C_o} \cdot \underbrace{\int_{p_{wf}}^{p_R} \frac{k_{ro}(p)}{\mu_o B_o}\, dp}$$

$$q_o = C_o \left(p_R^2 - p_{wf}^2\right)$$



Darcy for Gas:

$$B_g = \left(\frac{p_{sc}}{T_{sc}} \cdot T_R\right)\frac{Z}{p}$$

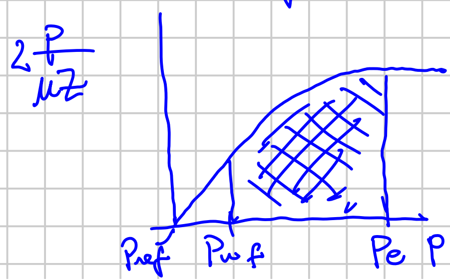
$$v = \frac{k}{\mu}\frac{dp}{dr}$$

$$v = \frac{q_{\bar g} \cdot B_g}{2\pi r h} = \underbrace{q_{\bar g}\left(\frac{p_{sc} T_R}{T_{sc}\, 2\pi h}\right)\frac{Z}{pr}}_{v} = \frac{k}{\mu}\frac{dp}{dr}$$

$$q_{\bar g} \cdot \int_{r_w}^{r_e} \frac{1}{r}\, dr = \underbrace{\frac{2\pi k h T_{sc}}{p_{sc} T_R}} \int_{p_{wf}}^{p_e} \frac{p}{\mu Z}\, dp$$

$$q_{\bar g} \cdot \ln\frac{r_e}{r_w} =$$

$$q_{\bar g} = q_g = \underbrace{\left(\frac{\pi T_{sc}}{p_{sc}}\right)}_{\substack{\text{numerical}\\ \text{constant}\\ +\\ \text{units}\\ \text{stuff}}} \cdot \underbrace{\frac{kh}{T_R \cdot \ln r_e/r_w}} \cdot \underbrace{2\int_{p_{wf}}^{p_e} \frac{p}{\mu Z}\, dp}$$

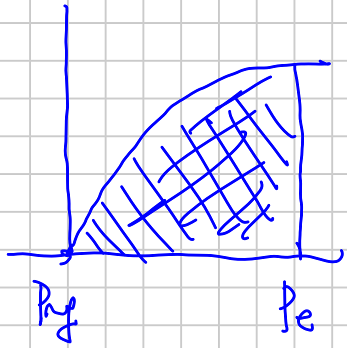


197x Al-Hussainy - Ramey - Crawford

Gas Pseudopressure Function

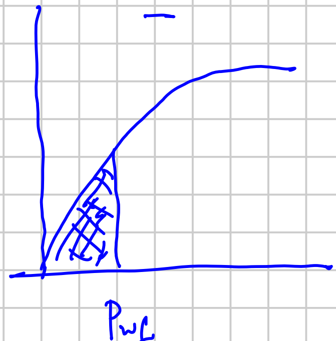
$$m(p) \equiv 2 \cdot \int_{p_{ref}\,(1\,\text{atm})}^{p} \frac{p}{\mu Z}\,dp$$

p_p



$m(p_e)$

$-$



$m(p_{wf})$

$$2\int_{p_{wf}}^{p_e} \frac{p}{\mu Z}\,dp = \underbrace{2\int_{p_{ref}}^{p_e} \frac{p}{\mu Z}\,dp}_{m(p_e)} - \underbrace{2\int_{p_{ref}}^{p_{wf}} \frac{p}{\mu Z}\,dp}_{m(p_{wf})}$$

$$(p_{pe} - p_{pwf})$$

$$q_g = \underbrace{\left(\frac{\pi T_{sc}}{p_{sc}}\right)}_{\text{Number}} \frac{kh}{T_R \ln r_e/r_w} \cdot (p_{pe} - p_{pwf})$$

$\left.\begin{matrix} T_{pc} \\ p_{pc} \end{matrix}\right\} y_i, \gamma_g$

p	μ	Z	$2p/\mu Z$	p_p
p_{Ri}				
⋮				
1 atm				

PVT transformation

$$\boxed{q_g = \frac{\overset{[md]}{0.703}\ \overset{[ft]}{kh}}{\underset{[°R]}{T_R}\ \underset{[-]}{\ln r_e/r_w}} \underset{[psi]}{(p_{pe} - p_{pwf})}}$$

$[scf/D]$

$\boxed{SS}$ ✓

Fetkovich $\underline{[Mscf/D]}$

Different : $m_F(p) \equiv \int_{p_{ref}}^{p} \frac{1}{\mu_g B_g} dp$

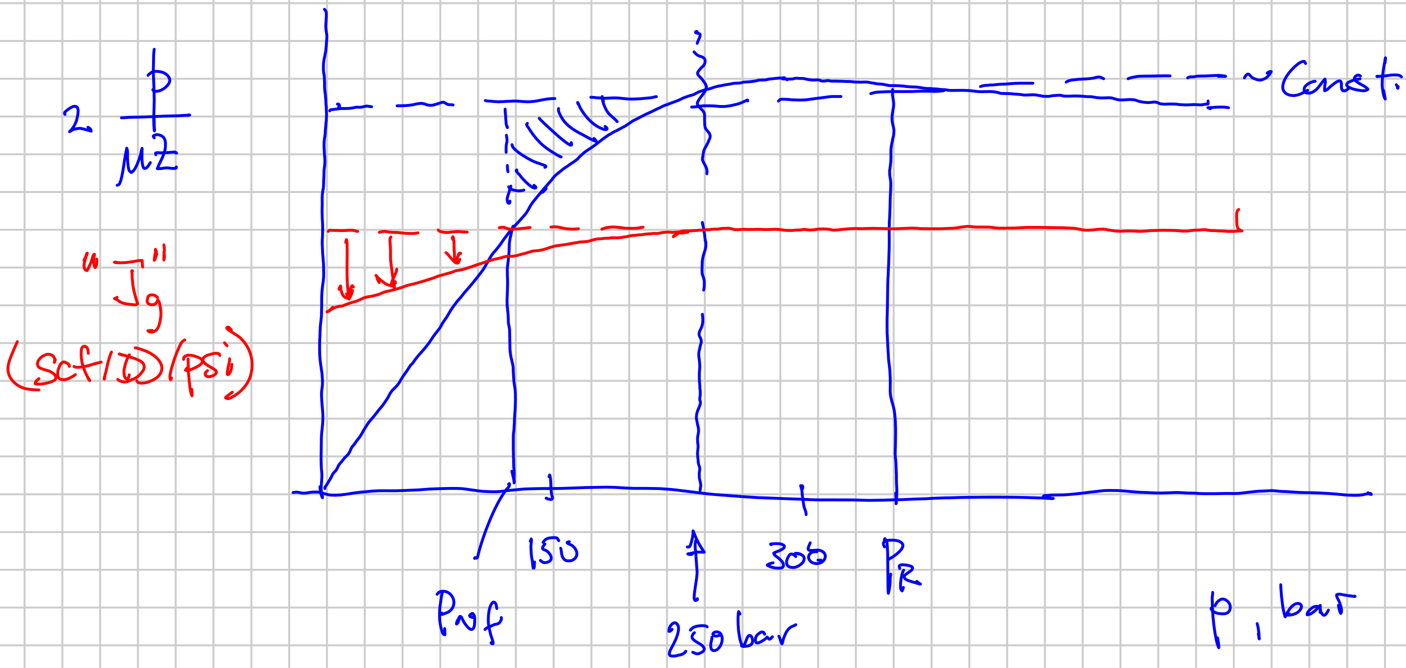
Ignores the "2"

B_g "contains" T_{sc}, p_{sc}

PSS (BD) : $\bar{p}_R$ & Add skin (s)

$$\boxed{q_g = \frac{0.703\ kh\ (p_{pR} - p_{pwf})}{T_R\left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s\right]}}$$

$\underline{\text{DARCY}}$ flow only



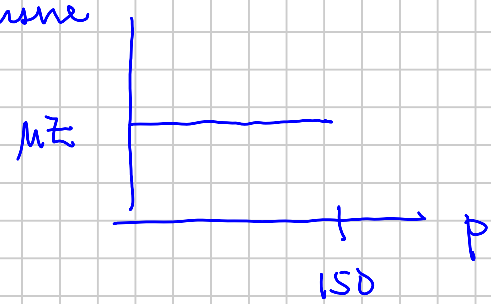
$$q_g = J_g\,(p_R - p_{wf}) = \left(\frac{\pi T_{sc}}{p_s}\right) \frac{kh}{T_R\ \ln \frac{r_e}{r_w}} \underbrace{\left(2\frac{p}{\mu Z}\right)}_{\sim \text{const}} \cdot \int_{p_{wf}}^{p_R} dp$$

Low-Pressure Assumption (Most developed reservoirs < 196x)

$$q_g = \frac{0.703\, kh\,(p_R^2 - p_{wf}^2)}{(\mu Z)\, T_R \left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s\right]}$$

$p_{wf} < p_R < 150$ bar

@ Any pressure



What if derive this equation using Forchheimer Eq.?

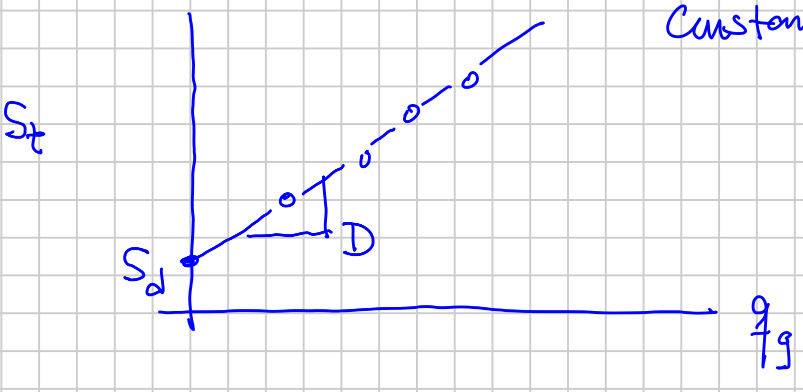
$$\boxed{q_g = \frac{0.703\, kh\,(p_{pR} - p_{pwf})}{T_R \left[\ln\frac{r_e}{r_w} - \frac{3}{4} + s_t\right]}}$$

$S_t = S_d + D\, q_g$

Constant (β)

Darcy : $D = 0$

$\beta = 0$



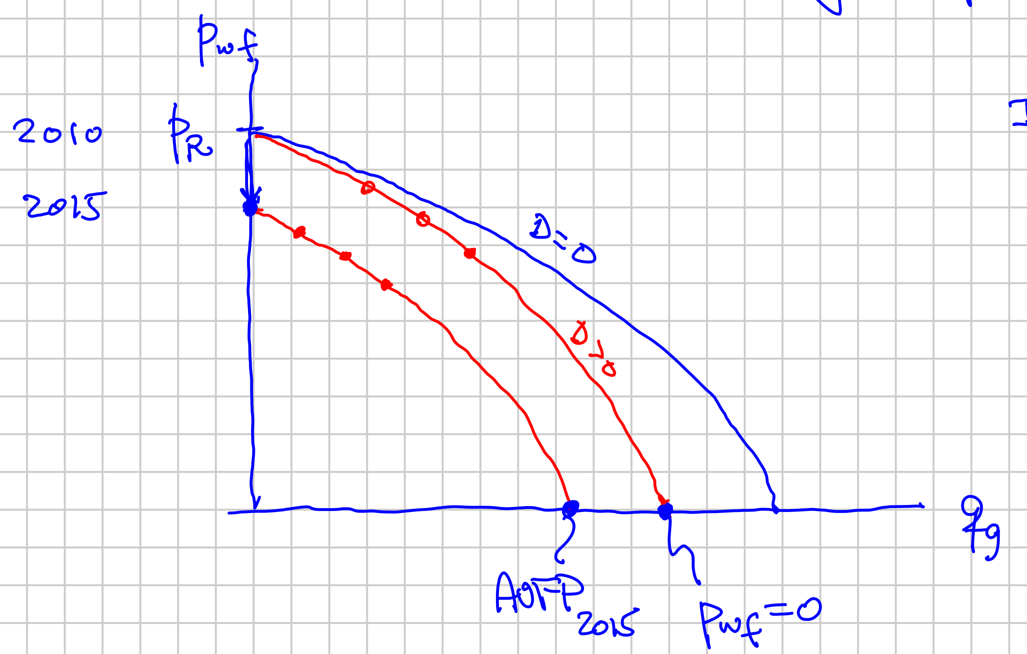
$$B\, q_g^2 + A\, q_g - \underbrace{(p_{pR} - p_{pwf})} = 0$$

$$A = \frac{T_R \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + S_d \right]}{0.703\ Kh} \qquad \underline{\text{Constants}}$$

$$B = \frac{T_R}{0.703\, Kh} \cdot D$$

Two methods of graphically representing

IPR Plot (Today - Prosper)

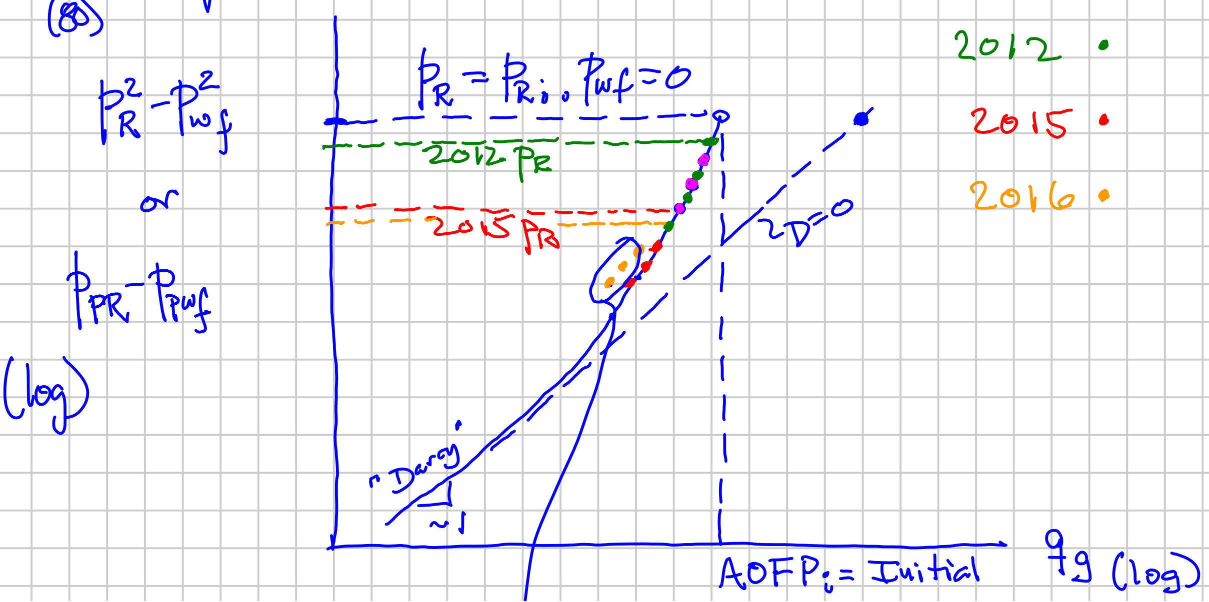


Absolute Open Flow Potential

$AOFP_{2010}$

Reservoir Backpressure Plot

Pre-1970 (80) p^2 Assumption OK



Flagging a Problem (s_d ?)