Note Title 3/24/2017

Gas-Well-Deliverability-Fetkovich.pdf

MULTIPOINT TESTING OF GAS WELLS

by

M. J. Fetkovich

Phillips Petroleum Company

Reading assignment for all lecture material up to next-to-last week of lectures – start now!

Topics: Reservoir Gas Flow
Tubing Gas Flow
(Pipeline Gas Flow)

Combined R + T Gas Flow

Reservoir Flow in Porous Media

Darcy Equation (d'Arcy)

$$v = \underbrace{\left(\frac{k}{\mu}\right)}_{\text{Bo tret (205-305)}} \cdot \frac{dp}{dx}$$

Head

$P_1 = p_{sc} + H_1 \rho_w g$

$P_2 = p_{sc} + H_2 \rho_w g$

$t_{1\to 2} = \frac{L}{v}$

$$v = K \frac{dH}{dx}$$ Groundwater Flow Eq.

v = Darcy Velocity $\neq$ Actual Flow Velocity

What's the difference?

How are they related?

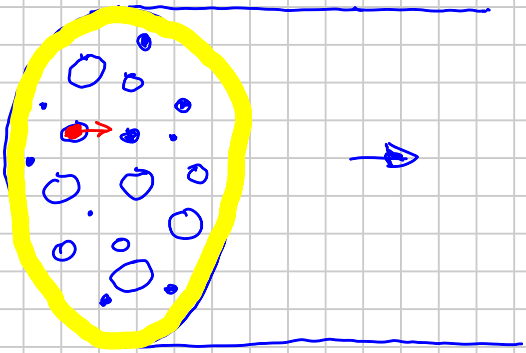
Darcy Velocity "v_D" $(v) \equiv \dfrac{q}{A_b} = \dfrac{k}{\mu}\dfrac{dp}{dx}$

q_R = (local) flowing volumetric rate, m^3/s

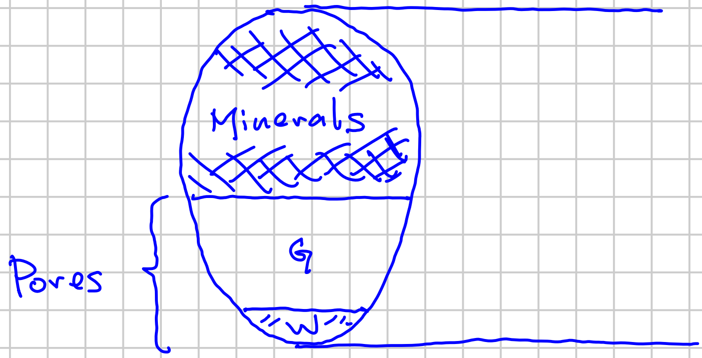
└ @(p,T) @ (x,y,z) spatial point

A_b = bulk area ⊥ to the flow direction

Simplified Pore Level



Simplified Pore-Average



Actual Flow

$$v_f = v_D = \frac{q}{A_g} = \frac{q}{A_b \cdot \phi \cdot S_g}$$

$(\phi S_g) \cong 0.05$

Darcy x-y plane

$$v_x = \frac{k_x}{\mu} \cdot \frac{dp}{dx} \qquad v_y = \frac{k_y}{\mu}\frac{dp_y}{dy}$$

$k_x \neq k_y$ Anisotropy x-y

$$\frac{dp_x}{dx} \neq \frac{dp_y}{dy}$$

$$v_x \neq v_y$$

$(k_z/k_{x,y} \sim 0.1)$

$(k_x \sim k_y)$

Darcy z direction

$$v_z = \frac{k_z}{\mu} \cdot \frac{d\Phi}{dz}$$

$k_z \neq k_x \neq k_y$

$k_z / k_{x,y} \sim (0.5 - 0.01)$

$$\phi \equiv \{ p + \rho g (z - z_{ref}) \}$$ potential

Static Column Water

ϕ = constant $\quad \left(\frac{d\phi}{dz}\right) = 0$

$v_z = 0$

Anisotropic = Not $\underbrace{\text{Isotropic}}_{k_x = k_y = k_z}$

When Darcy's Law does NOT apply:

- "High" velocities

$v_G = \frac{\mu_o}{\mu_g} v_o$ $\quad \frac{\mu_o}{\mu_g}$: 0.2–20 $\quad \mu_g$: 0.02

$v_G >> v_o$

$v \sim \frac{k}{\mu} \frac{dp}{dx}$

G vs O

$\left(\frac{dp}{dx}\right)_G \sim \left(\frac{dp}{dx}\right)_G$

$k_a \sim k_o$

Re = 1–8 (Muskat ...)

$Re \equiv \left[\frac{\rho v d}{\mu} \right]$ — Darcy or ~~Actual~~ ? ; $\bar{d}_g$

start of deviation from Darcy

Forcheimmer (sp?) Eq.

$$\left[\frac{dp}{dx} = \frac{\mu}{k} v + \rho \beta v^2 \right]$$

n (modified Forch. ?)

ρ: Fluid $\quad \beta$: Rock

$\frac{v_G}{v_o} \sim 10-1000$

We will more READILY reach $Re \sim 1-8$ for Gas than for Oil

Seldom $(Re)_{oil} > 1 \Rightarrow$ Dacy OK

often $(Re)_{Gas} > 10 \Rightarrow$ Forch. Needed

Gas Flow: Need multiple flow rates to establish (k, β)

Oil Flow: Need (in theory) <u>one</u> flow rate to get (k)

Gas Rate Equation

Steady State: Time-independent

Core Flow Experiment:

$\dot{m}_{in} = \dot{m}_{out}$ * $\underset{\text{Mass Rate}}{\underline{\text{What}}}$ Flows In = $\underset{\text{Mass Rate}}{\underline{\text{What}}}$ Flows Out

$\Rightarrow$ Inlet Pressure p_1 = const

Outlet -"- p_2 = const

$\{ q_{in} = q_{out}$ = const $\}$ Be careful

$p_1 = 2$ atm $\quad q_1(p_1)$

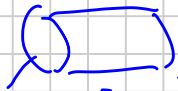
$\quad\quad\quad\quad\quad\quad\quad =$

$p_2 = 1$ atm $\quad q_2(p_2)$

$q_{in}(x=0) \neq q_{out}(x=L)$ Volumetric

Gas Linear Flow:

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



$$A_b = \pi r^2 = \frac{\pi}{4} d^2$$

$$0 \le x \le L$$

$$SS: \quad \dot{m}_{in} = \dot{m}_{out}$$

$$= \dot{m}\,(0 \le x \le L)$$

$$\underset{[kg/s]}{\dot{m}} = \underbrace{v \cdot A_b}_{q} \cdot \rho_g = \text{constant}$$

$$\dot{m} = \underbrace{\left(\frac{k}{\mu_g}\frac{dp}{dx}\right)}_{v_D}\underbrace{\left(\frac{\pi}{4}\right)d^2}_{A_b} \cdot \left(\frac{M_g}{\cancel{R}T}\right)\left(\frac{p}{Z}\right)$$

$$? \quad \rho_g = \underbrace{\frac{M_g}{RT}}_{const.}\left(\frac{p}{Z_g}\right)$$

$$= \underbrace{q_{\bar{g}}}\cdot\frac{p_{sc}\cancel{M_g}}{\cancel{R}T_{sc}}$$

Don't measure gas rate,

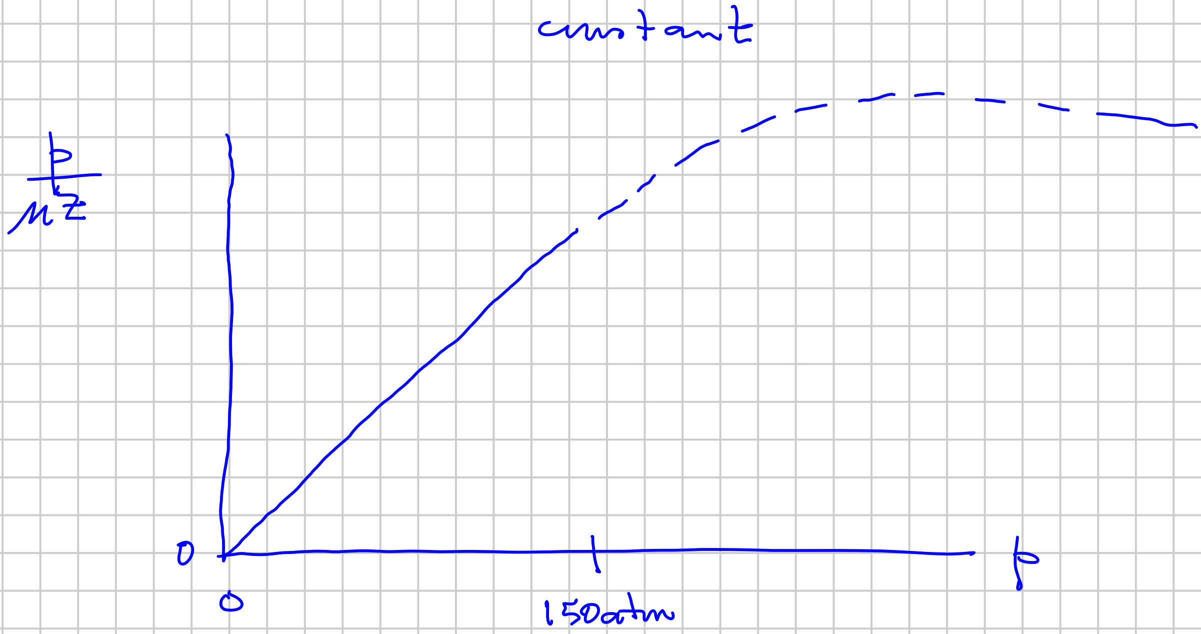
Measure standard condition gas volumetric rate $q_{\bar{g}}$ $[Sm^3/s]$

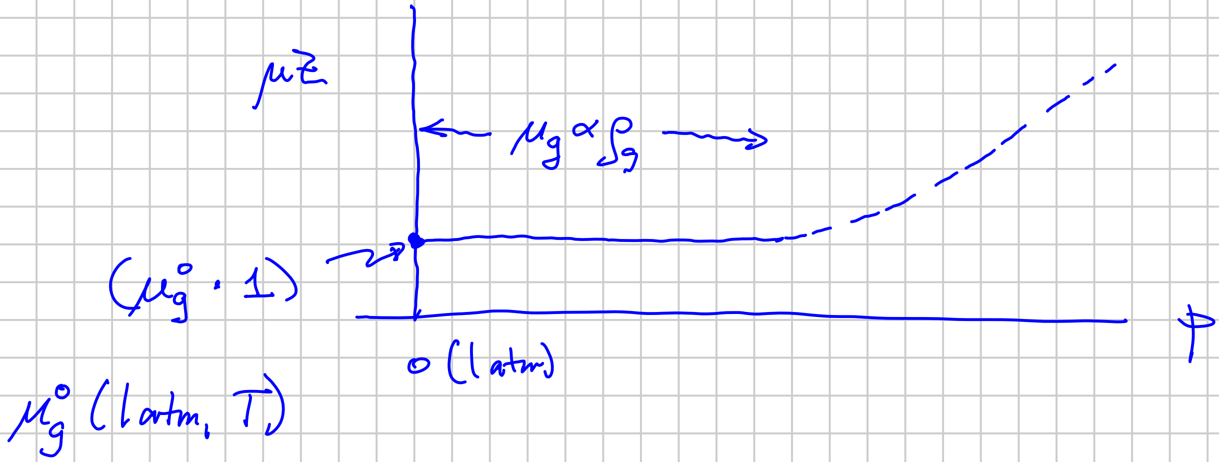
$$\underset{\frac{kg}{s}}{\dot{m}} \sim \underset{S\frac{m^3}{s}}{q_{\bar{g}}} \cdot \rho_{\bar{g}} = q_{\bar{g}} \cdot \frac{p_{sc}M_g}{RT_{sc}}$$

$$q_{\bar{g}} = \left(\frac{\pi d^2}{4}\right)\left(\frac{T_{sc}}{p_{sc}}\right)\left(\frac{1}{T}\right)k \cdot \underbrace{\frac{p}{\mu_g Z_g}}_{f(p)} \cdot \frac{dp}{dx}$$

$$\underset{const}{q_{\bar{g}}}\int_{x=0}^{L} dx = \underbrace{\left(\frac{T_{sc}}{p_{sc}} \times \frac{\pi d^2}{4}\right)\left(\frac{1}{T}\right)k}\int_{\underset{(x=0)}{p_1}}^{p_2(x=L)} \frac{p}{\mu Z}\,dp$$

$$q_{\bar{g}} = \underbrace{\left(\frac{T_{sc}}{p_{sc}}\right)\left(\frac{\pi d^2}{4L}\right)\left(\frac{1}{T}\right)k}\int_{p_1}^{p_2}\frac{p}{\mu Z}\,dp$$

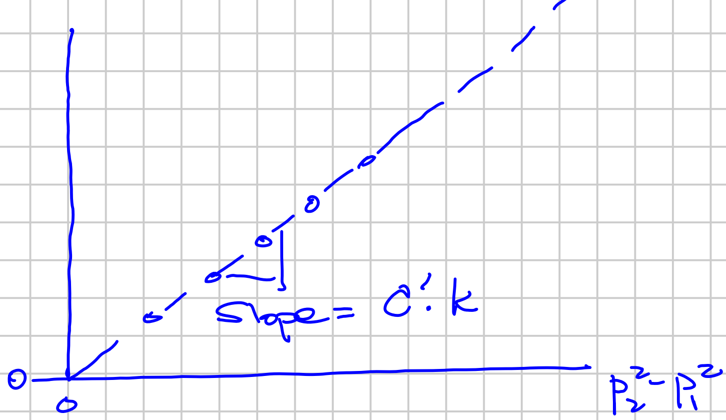




$p \lesssim 150$ atm

$$\int_{p_1}^{p_2} \frac{p}{\mu Z}\, dp = \frac{1}{2\mu_g^o(1)} \cdot (p_2^2 - p_1^2)$$

$$q_g = \underbrace{\left(\frac{T_{sc}}{p_{sc}}\right)\left(\frac{\pi d^2}{4L}\right)\left(\frac{1}{2}\right)\left(\frac{1}{\mu_g^o}\right)\left(\frac{1}{T}\right)}_{\text{constant, } C'} k \,(p_2^2 - p_1^2)$$



DARCY

Steady State Gas Flow @

$p_{out} < p_{in} < 150$ atm

ANY FLOW GEOMETRY

$$q_{\bar{g}} = C\,\underbrace{(p_{in}^2 - p_{out}^2)}$$

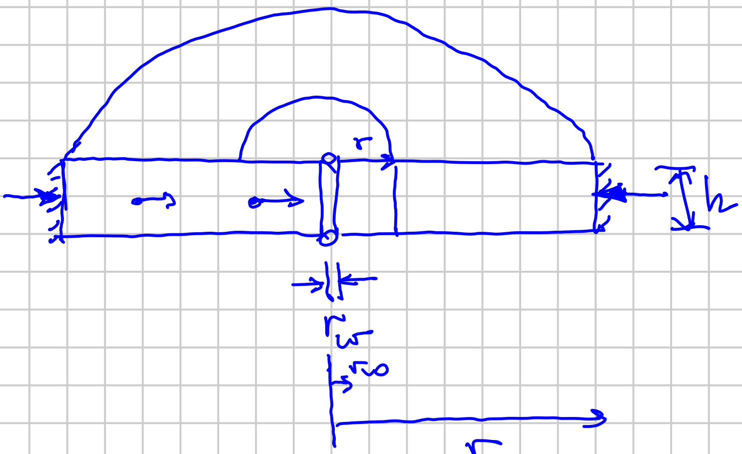
C_{Linear} ✓

$C_{Radial\ Cylindrical}$

SS: $\dot{m}(r_w < r < r_e) =$ constant

Inflowing Gas @ r_e

Steady State System



Side View

external

$p(r=r_e) = p_e$

$p(r=r_w) = p_{wf}$

$$v_r = \frac{k}{\mu}\cdot\frac{dp}{dr}$$

$A_b = 2\pi r h$

$$q_{\bar{g}} = \underbrace{C'}_{\text{units}}\cdot kh \int_{p_{wf}}^{p_e} \frac{p}{\mu Z}\,dp$$

Geometry

Sm^3/d

Find C'

for Norwegian Units

q_g [Sm^3/d]

k [md]

h [m]

r [m]

T [K]

p [bara]

μ_g [cp]