Al-Ayen University
College of Petroleum Engineering

Reservoir Engineering II

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Lecture 13: Skin Factor and Non-Darcy Flow

Refs.: Reservoir Engineering Handbook by Tarek Ahmed
Fundamentals of Reservoir Engineering by L.P. Dake

Outline

- Skin Factor
  - Steady-State Radial flow
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  - Pseudosteady-State radial Flow
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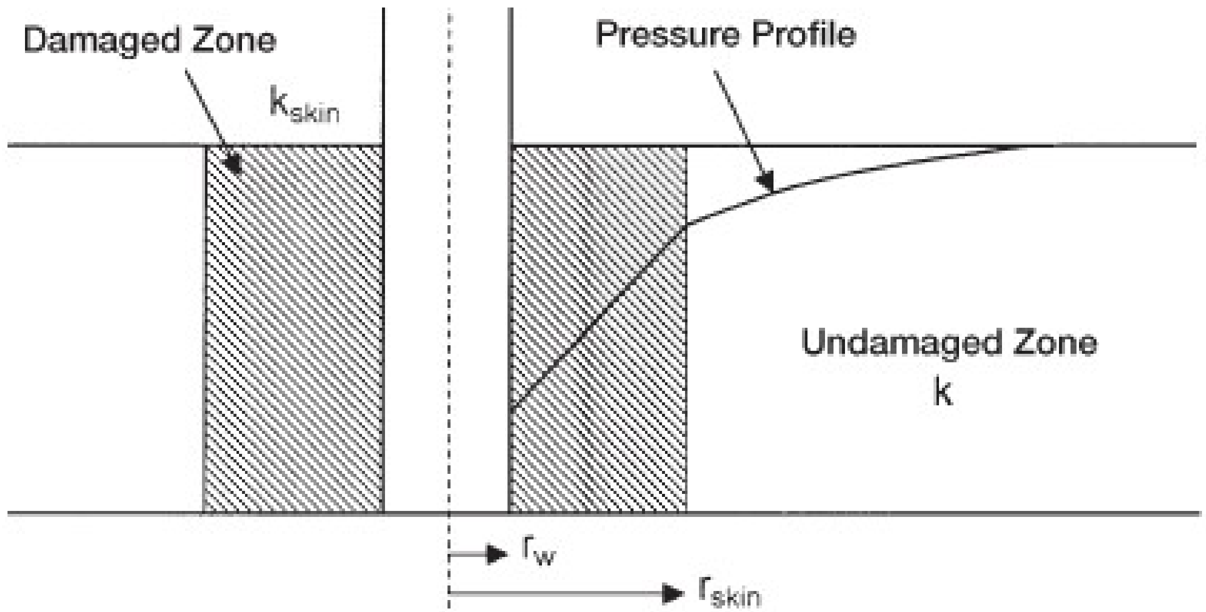
Skin Factor

- The permeability near the wellbore is always different from the permeability away from the well where the formation has not been affected by drilling or stimulation.
- The resulting effect of altering the permeability around the well bore is called the ***skin effect***.



- Hawkins (1956) suggested that the pressure drop across the zone can be approximated by Darcy's equation. Hawkins proposed the following approach:

$$\Delta p_{skin} = \begin{bmatrix} \Delta p \text{ in skin zone} \\ \text{due to } k_{skin} \end{bmatrix} - \begin{bmatrix} \Delta p \text{ in the skin zone} \\ \text{due to } k \end{bmatrix}$$

Applying Darcy's equation gives:

$$\Delta p_{skin} = \left[\frac{Q_o B_o \mu_o}{0.00708\, h\, k_{skin}}\right] \ln\left(\frac{r_{skin}}{r_w}\right) - \left[\frac{Q_o B_o \mu_o}{0.00708\, h\, k}\right] \ln\left(\frac{r_{skin}}{r_w}\right)$$

or

$$\Delta p_{skin} = \left(\frac{Q_o B_o \mu_o}{0.00708\, kh}\right)\left[\frac{k}{k_{skin}} - 1\right] \ln\left(\frac{r_{skin}}{r_w}\right)$$

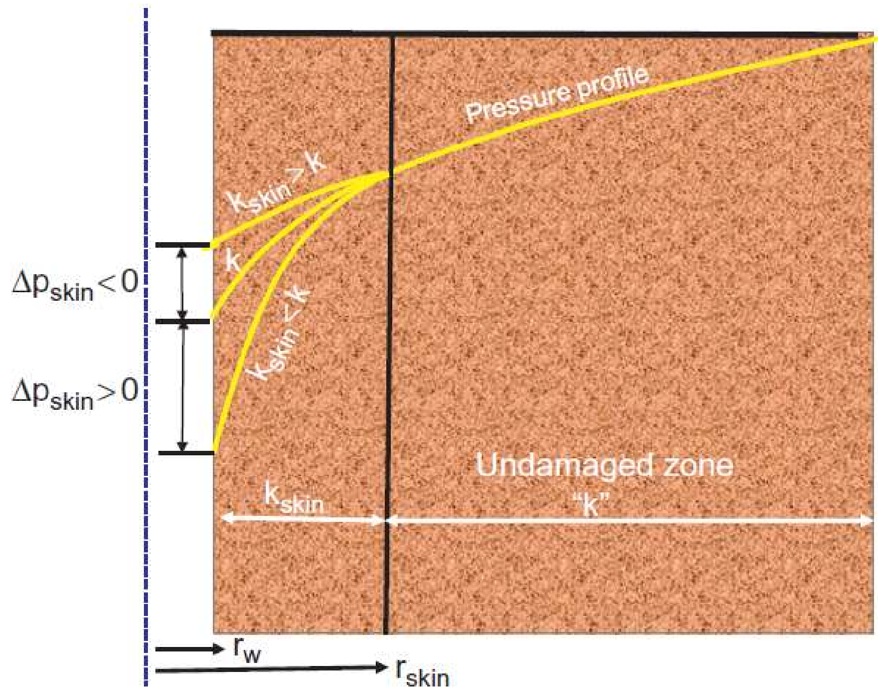
where k = permeability of the formation, md

k_{skin} = permeability of the skin zone, md

$$\Delta p_{skin} = 141.2 \left[\frac{Q_o B_o \mu_o}{kh}\right] s$$

where s is called the skin factor and defined as:

$$s = \left[\frac{k}{k_{skin}} - 1\right] \ln\left(\frac{r_{skin}}{r_w}\right)$$



There are three possible outcomes in evaluating the skin factor s: **s > 0 (d**amaged zone)**, s < 0 (**improved zone) **or s = 0** (no alternation in the permeability)

- Assuming that $(\Delta p)_{ideal}$ represents the pressure drawdown for a drainage area with a uniform permeability k, then:

$$(\Delta p)_{actual} = (\Delta p)_{ideal} + (\Delta p)_{skin}$$

or

$$(p_i - p_{wf})_{actual} = (p_i - p_{wf})_{ideal} + \Delta p_{skin}$$

- The above concept can be applied to all the previous flow regimes to account for the skin zone around the wellbore as follows:

1. Steady-State Radial Flow:

$$(p_i - p_{wf})_{actual} = \left[\frac{Q_o B_o \mu_o}{0.00708\, kh}\right] \ln\left(\frac{r_e}{r_w}\right) + \left[\frac{Q_o B_o \mu_o}{0.00708\, kh}\right] s$$

or

$$Q_o = \frac{0.00708\, kh (p_i - p_{wf})}{\mu_o B_o \left[\ln \frac{r_e}{r_w} + s\right]}$$

where Q_o = oil flow rate, STB/day

k = permeability, md

h = thickness, ft

s = skin factor

B_o = oil formation volume factor, bbl/STB

μ_o = oil viscosity, cp

p_i = initial reservoir pressure, psi

2. Unsteady-State Radial Flow

- **For Slightly Compressible Fluids:**

$$p_i - p_{wf} = 162.6\left(\frac{Q_o B_o \mu_o}{kh}\right)\left[\log\frac{kt}{\phi\mu c_t r_w^2} - 3.23\right] + 141.2\left(\frac{Q_o B_o \mu_o}{kh}\right)s$$

or

$$p_i - p_{wf} = 162.6\left(\frac{Q_o B_o \mu_o}{kh}\right)\left[\log\frac{kt}{\phi\mu c_t r_w^2} - 3.23 + 0.87s\right]$$

- **For Compressible Fluids:**

$$m(p_{wf}) = m(p_i) - \frac{1637\, Q_g\, T}{kh}\left[\log\frac{kt}{\phi\,\mu\, c_{ti}\, r_w^2} - 3.23 + 0.87s\right]$$

and, in terms of the pressure-squared approach, gives:

$$p_{wf}^2 = p_i^2 - \frac{1637\, Q_g\, T\, \bar{z}\, \bar{\mu}}{kh}\left[\log\frac{kt}{\phi\,\mu_i\, c_{ti}\, r_w^2} - 3.23 + 0.87\, s\right]$$

3. Pseudosteady-State Flow

- **For Slightly Compressible Fluids:**

$$Q_o = \frac{0.00708\,kh\,(\overline{p}_r - p_{wf})}{\mu_o\,B_o\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]}$$

- **For Compressible Fluids:**

$$Q_g = \frac{kh\,[m\,(\overline{p}_r) - m(P_{wf})]}{1422\;T\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]}$$

or, in terms of the pressure-squared approximation, gives:

$$Q_g = \frac{kh\,(p_r^2 - p_{wf}^2)}{1422\,T\,\overline{\mu}\,\overline{z}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s\right]}$$

where Q_g = gas flow rate, Mscf/day
k = permeability, md
T = temperature, °R
$(\overline{\mu}_g)$ = gas viscosity at average pressure $\overline{p}$, cp
$\overline{z}_g$ = gas compressibility factor at average pressure $\overline{p}$

Example

Calculate the skin factor resulting from the invasion of the drilling fluid to a radius of 2 feet. The permeability of the skin zone is estimated at 20 mD as compared with the unaffected formation permeability of 60 mD. The wellbore radius is 0.25 ft.

Solution

$$s = \left[\frac{k}{k_{skin}} - 1\right] \ln\left(\frac{r_{skin}}{r_w}\right)$$

$$s = \left[\frac{60}{20} - 1\right] \ln\left(\frac{2}{0.25}\right) = 4.16$$

Effective or A**pparent Wellbore Radius**

Matthews and Russell (1967) proposed an alternative treatment to the skin effect by introducing the ***effective*** *or* ***apparent wellbore radius,*** r_{wa}, that accounts for the pressure drop in the skin. They define r_{wa} by the following equation:

$$r_{wa} = r_w e^{-s}$$

All of the ideal radial flow equations can be also modified for the skin by simply replacing wellbore radius r_w with that of the apparent wellbore radius r_{wa}. For example, Equation of the slightly compressible fluids can be equivalently expressed as:

$$p_i - p_{wf} = 162.6\left(\frac{Q_o B_o \mu_o}{kh}\right)\left[\log\frac{kt}{\phi \mu_o c_t r_{wa}^2} - 3.23\right]$$

Non-Darcy Flow

- For the horizontal flow of fluids through a porous medium at *low and moderate rates*, the pressure drop is represented by Darcy's law: $$\frac{dp}{dr} = \frac{\mu}{k} u$$

  where u is the fluid velocity = $\frac{q}{2 \pi rh}$

- At *higher flow rates*, the appropriate flow equation is that of Forchheimer (1901), which is:

$$\frac{dp}{dr} = \frac{\mu}{k} u + \beta \rho u^2 \quad , \qquad \beta \rho u^2 = \text{The non-Darcy component}$$

Where β is the *coefficient of inertial resistance*, the following dimensional analysis shows, has the dimension $(length)^{-1}$.

$$\frac{dp}{dr} \left[\frac{ML}{T^2L^2}\right] \left[\frac{1}{L}\right] = [\beta] \ \rho \left[\frac{M}{L^3}\right] \ u^2 \left[\frac{L^2}{T^2}\right] \longrightarrow \beta = L^{-1}$$

The non-Darcy component is negligible at low flow velocities and is generally omitted from liquid flow equations. The non-Darcy component is included in equations describing the flow of a real gas through a porous medium. Even for gas, the non-Darcy component is significant only in the restricted region of high pressure drawdown, and flow velocity, close to the wellbore.

- The non-Darcy flow is conventionally included in the flow equations as an additional skin factor, that is, as a time independent perturbation affecting the solutions of the basic differential equation.

- The additional pressure drop due to the non-Darcy flow can be derived by integrating the non-Darcy component, as follows:

$$\beta\rho u^2 = \text{The non-Darcy component}$$

$$\Delta p_{\text{non Darcy}} = \int_{r_w}^{r_e} \beta\rho \left(\frac{q}{2\ \pi\ rh}\right)^2 dr$$

or expressed as a drop in the real gas pseudo pressure:

$$\Delta m(p)_{nD} = \int_{r_w}^{r_e} \frac{2p}{\mu Z}\beta\rho \left(\frac{q}{2\ \pi\ rh}\right)^2 dr$$

Also since $\rho = \gamma_g \times$ density of air at s.c. $\times (1/Bg)$

$$= \text{constant} \times \gamma_g \times \frac{p}{ZT}$$

where γ_g is the gas gravity (air=1), density of air at S.C. = 0.076 Ib/scft , thus:

$$\Delta m(p)_{nD} = \text{constant} \times \int_{r_w}^{r_e} \left(\frac{pq}{ZT}\right)^2 \frac{\beta T \gamma_g}{\mu\ r^2 h^2} dr$$

and since $\frac{pq}{ZT} = \frac{p_{sc} q_{sc}}{T_{sc}} = \text{constant} \times q_{sc}$

$$\Delta m(p)_{nD} = \text{constant} \times \frac{\beta T \gamma_g q_{sc}^2}{h^2} \int_{r_w}^{r_e} \frac{dr}{\mu r^2}$$

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- Since non-Darcy flow is usually confined to a localised region around the wellbore where the flow velocity is greatest, the viscosity term in the equation is usually evaluated at the bottom hole flowing pressure p_{wf} and hence is not a function of position. Integrating the equation gives:

$$\Delta m(p)_{nD} = \text{constant} \times \frac{\beta T \gamma_g q_{sc}^2}{\mu h^2} \left(\frac{1}{r_w} - \frac{1}{r_e} \right)$$

If the equation is expressed in field units (Q - Mscf/d, β - ft^{-1}) and assuming $\frac{1}{r_w} >> \frac{1}{r_e}$, then

$$\Delta m(p)_{nD} = 3.161 \times 10^{-12} \frac{\beta T \gamma_g Q^2}{\mu_w h_p^2 r_w} = FQ^2$$

where F is the non-Darcy flow coefficient psia^2/cp/(Mscf/d)^2.

- The value of the thickness h is conventionally taken as h_p, the perforated interval of the well.

- This non-Darcy term is interpreted as being a rate-dependent skin and can be included in all the compressible gas flow equations in the same way as the skin factor.
- For instance, the gas flow equation of the steady state flow can be modified as follows:

$$m(p_i) - m(p_{wf}) = \left(\frac{1637\,Q_g\,T}{kh}\right)\left[\log\frac{kt}{\phi\mu_i c_{ti} r_w^2} - 3.23 + 0.87s\right] + FQ_g^2$$

or

$$m(p_i) - m(p_{wf}) = \left(\frac{1637\,Q_g\,T}{kh}\right)\left[\log\frac{kt}{\phi\mu_i c_{ti} r_w^2} - 3.23 + 0.87s + 0.87\,DQ_g\right]$$

or

$$m(p_i) - m(p_{wf}) = \left[\frac{1637\,Q_g\,T}{kh}\right]\left[\log\frac{kt}{\phi\mu_i c_{ti} r_w^2} - 3.23 + 0.87s'\right]$$

The coefficient D is called the *inertial or turbulent flow factor* and given by: $D = \frac{Fkh}{1422T}$

The *apparent* or *total skin factor* (s'): $s' = s + DQ_g$

- Two methods are available for the determination of the non-Darcy flow coefficient, which are:
  - ➢ from the analysis of well tests,
  - ➢ by experimentally measuring the values of the coefficient of inertial resistance, β and using it in to calculate F.

Summary

- The resulting effect of altering the permeability around the well bore is called the *skin effect.*

- There are three possible outcomes in evaluating the skin factor s: **s > 0 (d**amaged zone)**,** **s < 0 (**improved zone) **or s = 0** (no alternation in the permeability)**.**

- The non-Darcy component is negligible at low flow velocities and is generally included in equations describing the flow of a real gas through a porous medium close to the wellbore.

- The non-Darcy term is interpreted as being a rate-dependent skin and can be included in all the compressible gas flow equations in the same way as the skin factor.

Discussion

Why is the non-Darcy component omitted from liquid flow equations and included in gas flow equations through porous media?

THANK YOU