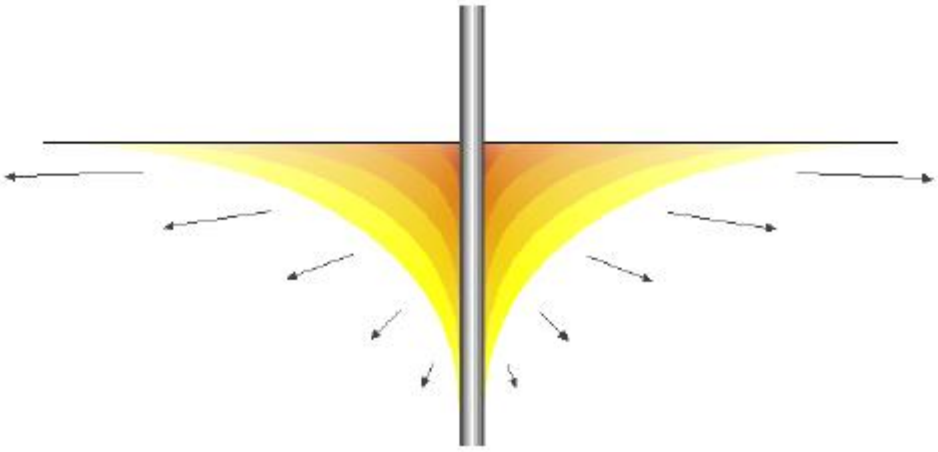
Advanced Pressure Transient Analysis



Well Test Analysis of Horizontal Well

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Outline

- Introduction
- Horizontal well test model
- Characteristic flow regimes
- Permeability anisotropy
- Horizontal well test analysis

Introduction

- Advances in drilling and completion technologies have placed horizontal wells among the techniques used to improve production performance.

- For example in the case of gas cap or bottom water drive, horizontal wells prevent coning without introducing the flow restriction seen in partial penetration wells.

- Horizontal drilling is also efficient to increase the well surface area for fluid withdrawal, thus improving the productivity.

Horizontal Well Test Analysis

❑It is much more difficult to interpret well test data from a horizontal well than from a vertical well.

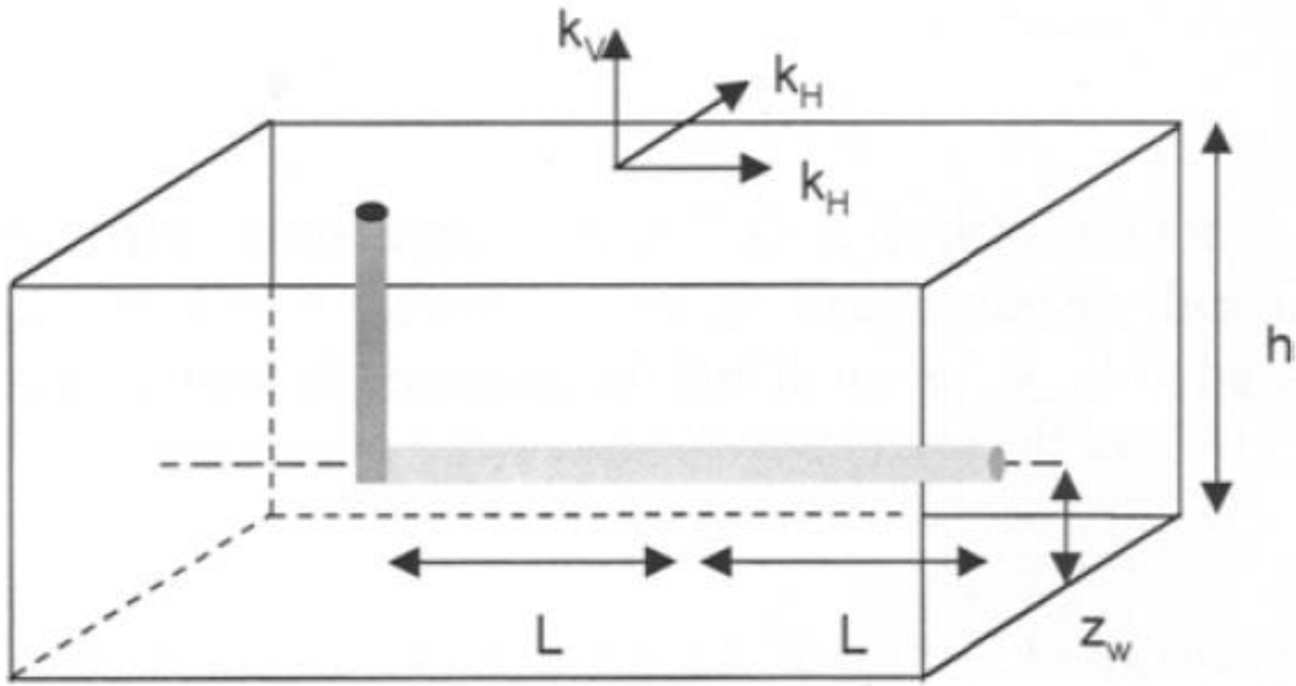
❑The flow geometry is three-dimensional and radial symmetry no longer exists.

❑Several flow regimes must be considered to analyze the data.

❑Wellbore storage effects are much more significant, and horizontal wells will commonly exhibit partial penetration and end effects that make interpretation very difficult.

❑In vertical wells, we are accustomed to dealing with variables such as average permeability, net vertical thickness, and skin. In horizontal wells, we need more detail. Not only is vertical thickness important, but the horizontal dimensions of the reservoir, relative to the horizontal wellbore, need to be known.

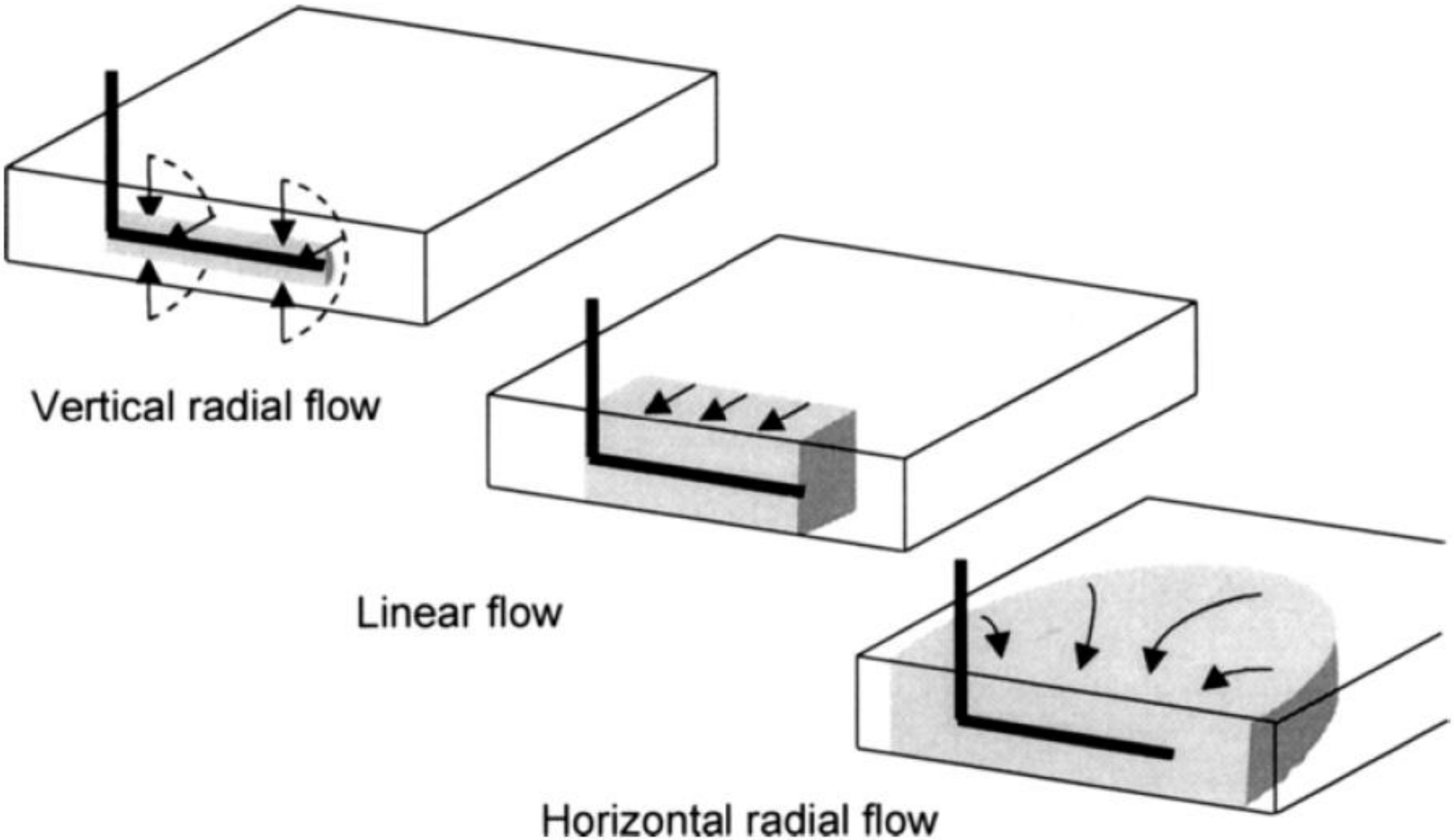
Model Description



The well is strictly horizontal, the penetration half-length is L and z_w defines the distance between the drain hole and the bottom-sealing boundary. The vertical part of the well is not perforated, there is no flow towards the end of the well and the well conductivity is infinite, k_H and k_V- are the horizontal and the vertical permeability.

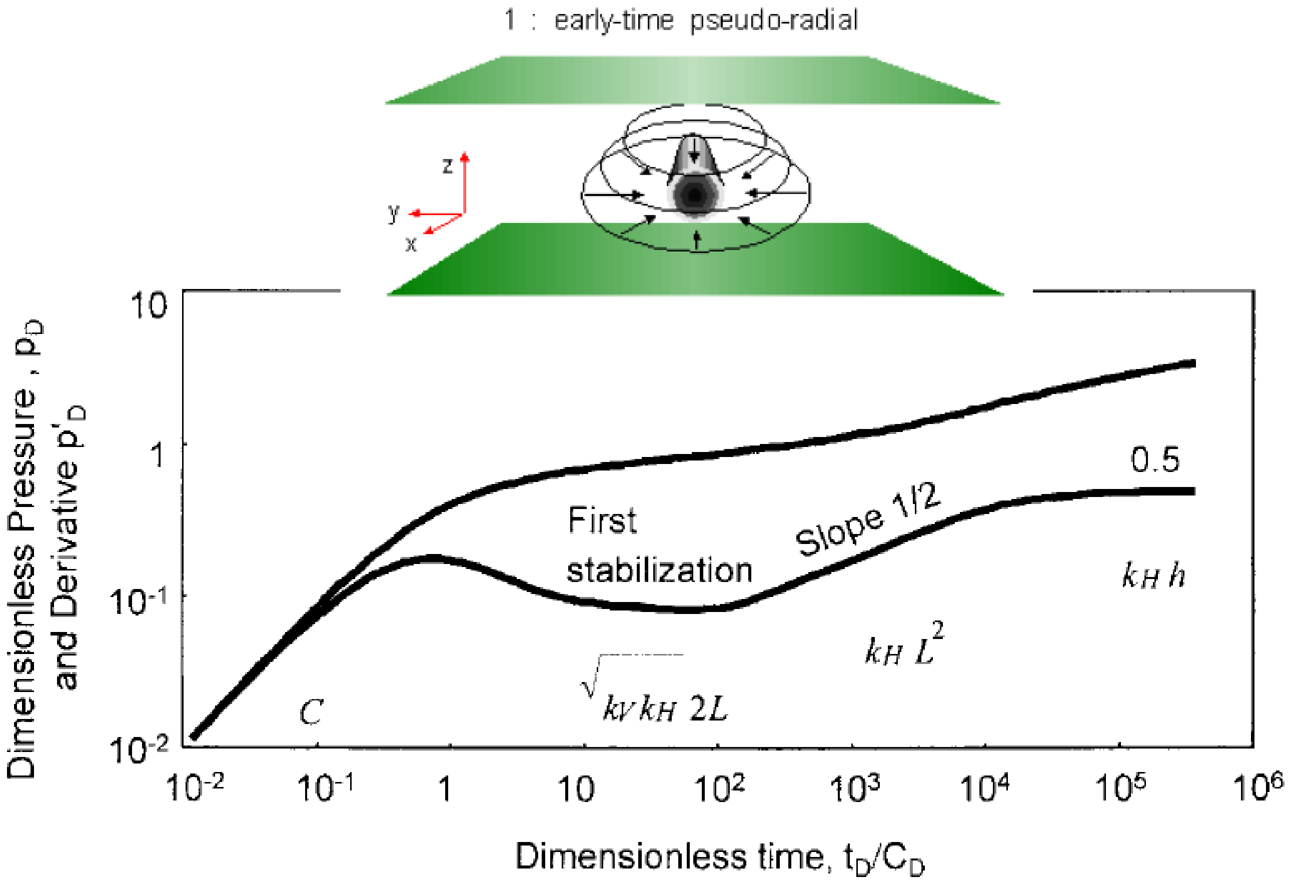
Characteristic Flow Regimes

In an infinite system, the geometry of the flow lines towards a horizontal well produces a sequence of three typical regimes, as depicted in the below figure.



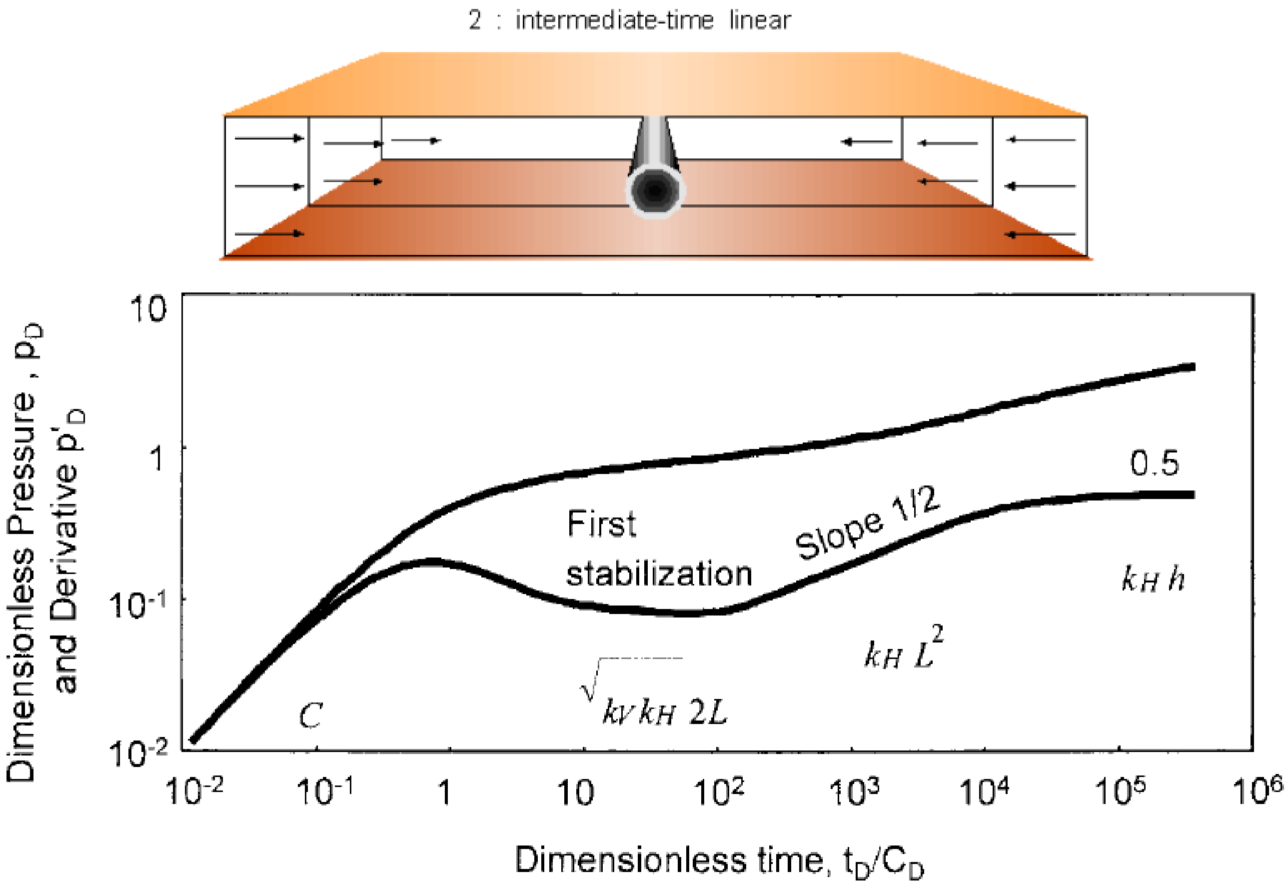
Characteristic Flow Regimes

1. The first regime is radial flow in the vertical plane. On a log-log derivative plot, the wellbore storage hump is followed by a first stabilization. During this radial flow regime, the permeability-thickness product $2(K_V*K_H)^{0.5}*L$ is defined with the average permeability in the vertical plane, and the well effective length 2L.



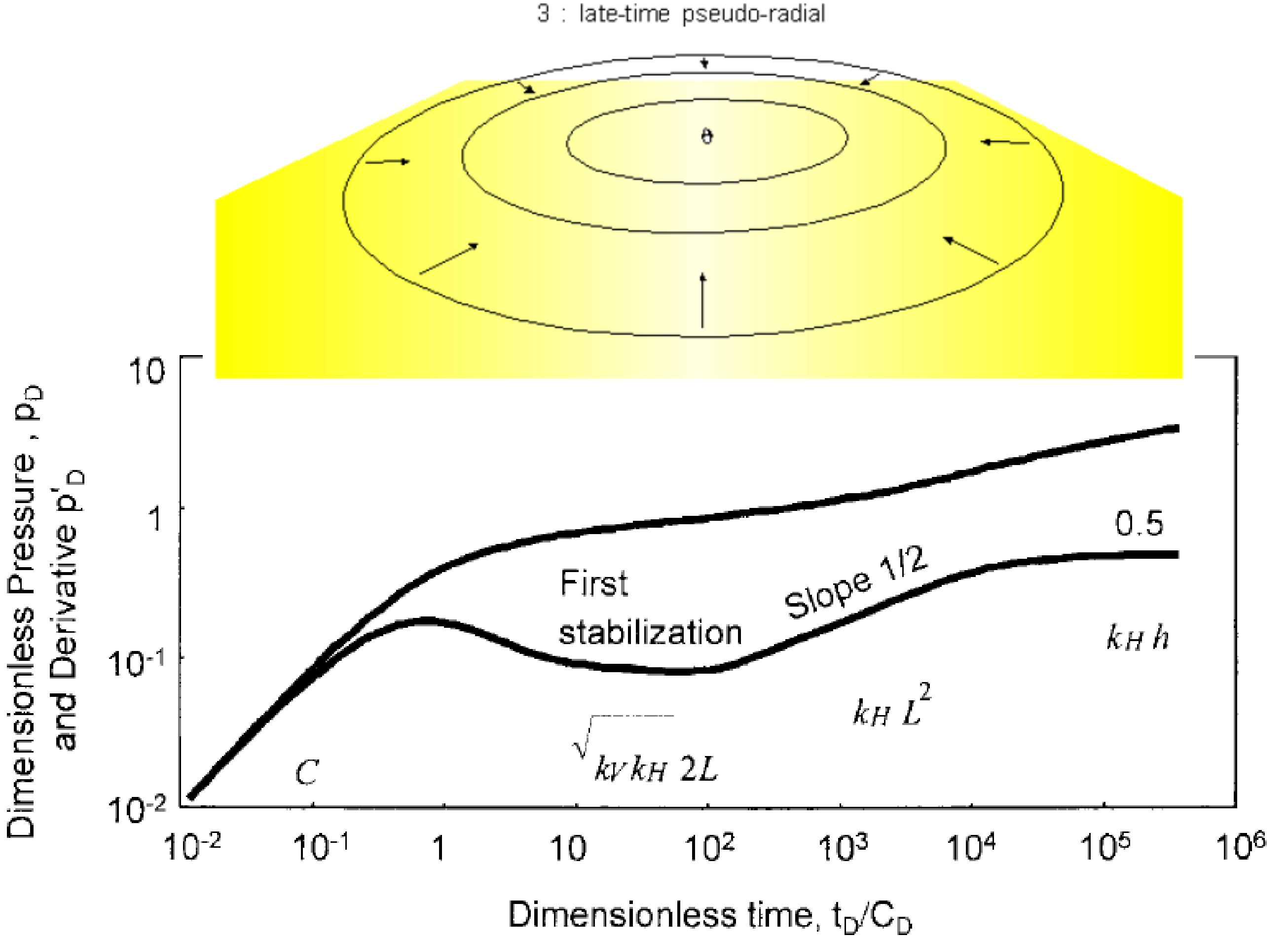
Characteristic Flow Regimes

2. When the sealing upper and lower limits are reached, a linear flow behavior is established. The derivative follows a half-unit slope log-log straight line.



Characteristic Flow Regimes

3. Later, the flow lines converge from all reservoir directions towards the well, producing a horizontal radial flow regime. The derivative stabilization corresponds to the infinite acting radial flow in the reservoir, the permeability-thickness product is k_H h.



Characteristic Flow Regimes

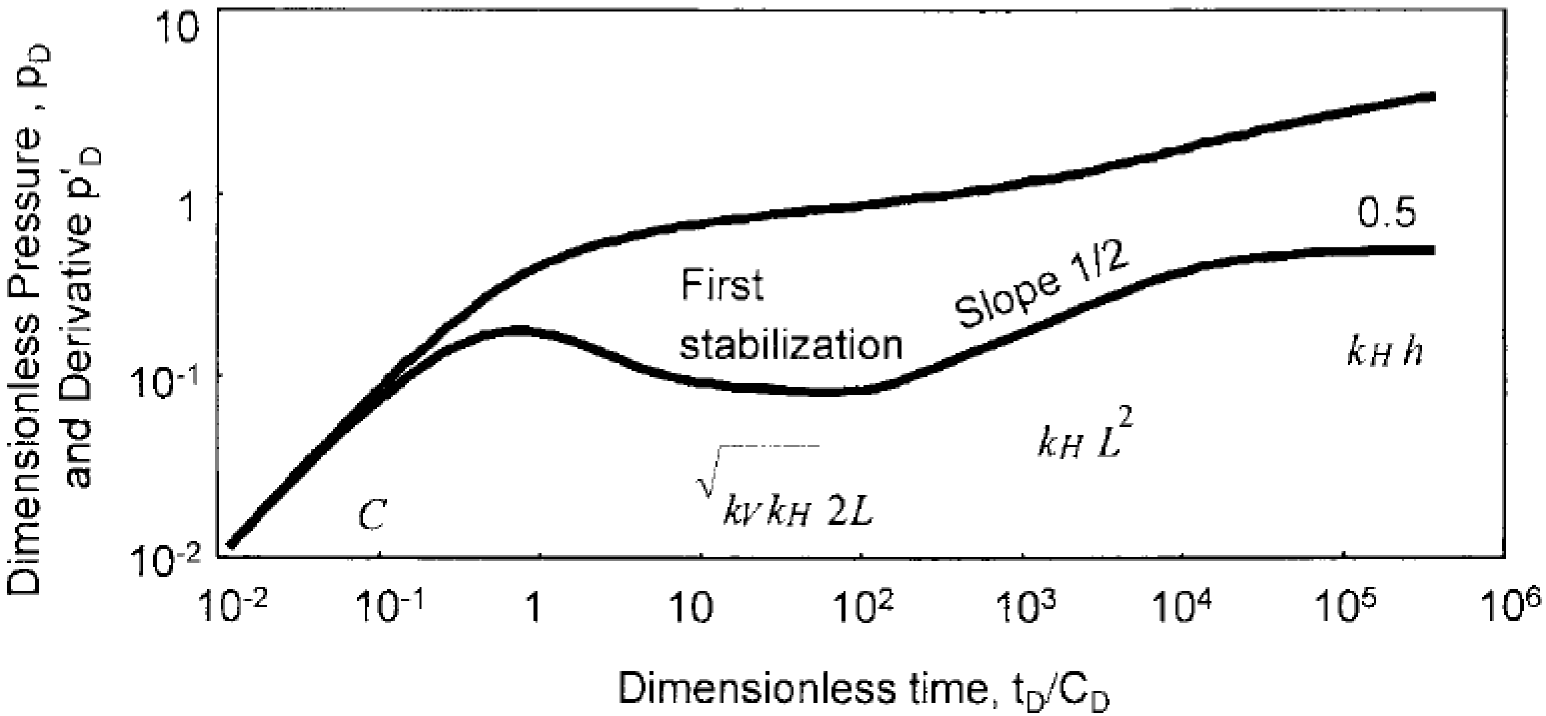


Figure 3.26. Horizontal well with wellbore storage and skin, homogeneous reservoir. Log-log scales, p_D versus t_D/C_D. C_D=1000, S_w =0, L =1000ft, h =100ft, r_w =0.25ft, z_w/h =0.5, k_V/k_H =0.1.

Extensions of the model

- In practice, the well geometry is not as simple as in the ideal configuration (exactly horizontal). Most horizontal drain holes are not straight and parallel to the upper and lower boundaries, but show several oscillations over the formation thickness.

- Frequently, the skin is not uniform along the drain hole

- In many cases the well does not produce on the complete length but in one or several segments.

- When the pressure gradient in the wellbore become large, the infinite conductivity hypothesis is not applicable and the horizontal well shows a finite conductivity behavior.

Analytical Solutions

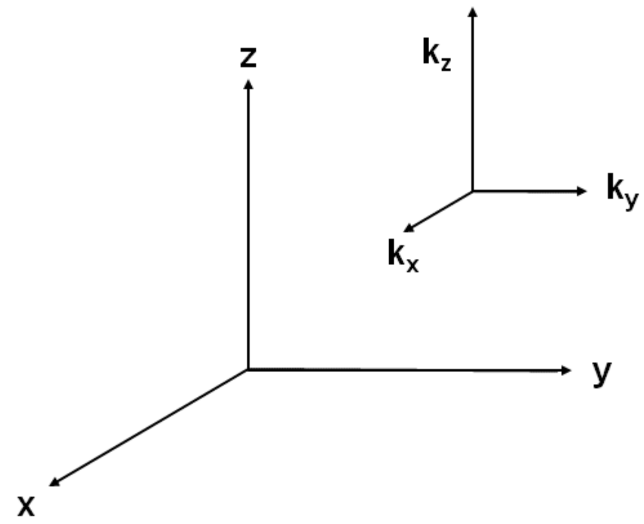
It is shown that when the basic horizontal well model is used to describe complex well or reservoir configurations, **the effective well length** and **the average vertical permeability** k_z-resulting from analysis can be significantly in error. With complex wellbore conditions, k_V, is frequently underestimated whereas it can be over-estimated in layered systems with semi-permeable interbeds.

The first analytical solutions for uniform flux and infinite conductivity horizontal well responses have been derived in the mid 80's: Daviau et al. (1985), Clonts and Ramey (1986) and Rosa and Carvalho (1989) have used source and Green's functions whereas Goode and Thambynayagam (1987) and Kuchuk et al. (1991 a) obtained a solution by application of Laplace and Fourier transforms. With the infinite conductivity horizontal well model, the pressure is assumed constant along the wellbore. This is obtained by measuring the pressure of a uniform flux horizontal drain at an equivalent point in the well (Daviau, Clonts, Rosa), or by averaging the pressure along the length of the well (Goode, Kuchuk).

Permeability Anisotropy

- Finding The Equivalent Isotropic System For An Anisotropic Reservoir
- Vertical Well In Anisotropic Reservoir
- Horizontal Well In Anisotropic Reservoir

Anisotropic Reservoir



The diffusivity equation shown here describes the single-phase flow of a slightly compressible liquid through a homogeneous, anisotropic reservoir, neglecting gravity.

$$k_x \frac{\partial^2 p}{\partial x^2} + k_y \frac{\partial^2 p}{\partial y^2} + k_z \frac{\partial^2 p}{\partial z^2} = \frac{\phi \mu c_t}{0.0002637} \frac{\partial p}{\partial t}$$

Coordinate Transformation

$$x' = a_x x$$

$$y' = a_y y$$

$$z' = a_z z$$

$$k_x' = a_x^2 k_x$$

$$k_y' = a_y^2 k_y$$

$$k_z' = a_z^2 k_z$$

$$a_x a_y a_z = 1$$

$$x' = a_x x \qquad\qquad k_x' = a_x^2 k_x$$

$$y' = a_y y \qquad a_x a_y a_z = 1 \qquad k_y' = a_y^2 k_y$$

$$z' = a_z z \qquad\qquad k_z' = a_z^2 k_z$$

❑We may transform any anisotropic system that has the coordinate axes aligned with the principal axes of permeability with this coordinate transformation.

❑Note that we must transform both the coordinates x, y, and z and the principal permeabilities k_x, k_y, and k_z.

❑The condition that $a_x a_y a_z = 1$ is not absolutely necessary. However, it is convenient for several reasons:

1) Volume remains unchanged in the transformation. This allows us to use the same porosity in both systems.

2) Volumetric flow rates across any surface are the same in the original and transformed systems. This allows us to transform boundary conditions corresponding to constant rate production by simply transforming the boundary itself

Diffusivity Equation In Transformed System

$$k_x'\frac{\partial^2 p}{\partial x'^2} + k_y'\frac{\partial^2 p}{\partial y'^2} + k_z'\frac{\partial^2 p}{\partial z'^2} = \frac{\phi\mu c_t}{0.0002637}\frac{\partial p}{\partial t}$$

- What have we gained? This equation still allows k_x, k_y, and k_z to be different - we have simply transformed one anisotropic system into another.

- The advantage is that we can still choose the a_x, a_y, and a_z for our convenience. In particular, we choose a_x, a_y, and a_z so that $k_x = k_y = k_z$ for the region of interest.

- Placing this requirement on a_x, a_y, and a_z , we have the transformation given on the next slide.

Transformation To Equivalent Isotropic System

$$\bar{k} = \sqrt[3]{k_x k_y k_z}$$

$$x' = \sqrt{\frac{\bar{k}}{k_x}}\,x \qquad k_x' = \frac{\bar{k}}{k_x}\,k_x$$

$$y' = \sqrt{\frac{\bar{k}}{k_y}}\,y \qquad k_y' = \frac{\bar{k}}{k_y}\,k_y$$

$$z' = \sqrt{\frac{\bar{k}}{k_z}}\,z \qquad k_z' = \frac{\bar{k}}{k_z}\,k_z$$

- This transformation applies for anisotropic reservoirs that are homogeneous, that is, the principal permeabilities are the same throughout the reservoir.
- For a homogeneous isotropic reservoir, the transformed k_x, k_y, and k_z are all equal to the geometric mean permeability kbar.

Equivalent Isotropic System
Two Dimensional Case

$$\bar{k} = \sqrt{k_x k_y}$$

$$x' = \sqrt{\frac{\bar{k}}{k_x}}\, x \qquad k_x' = \frac{\bar{k}}{k_x} k_x$$

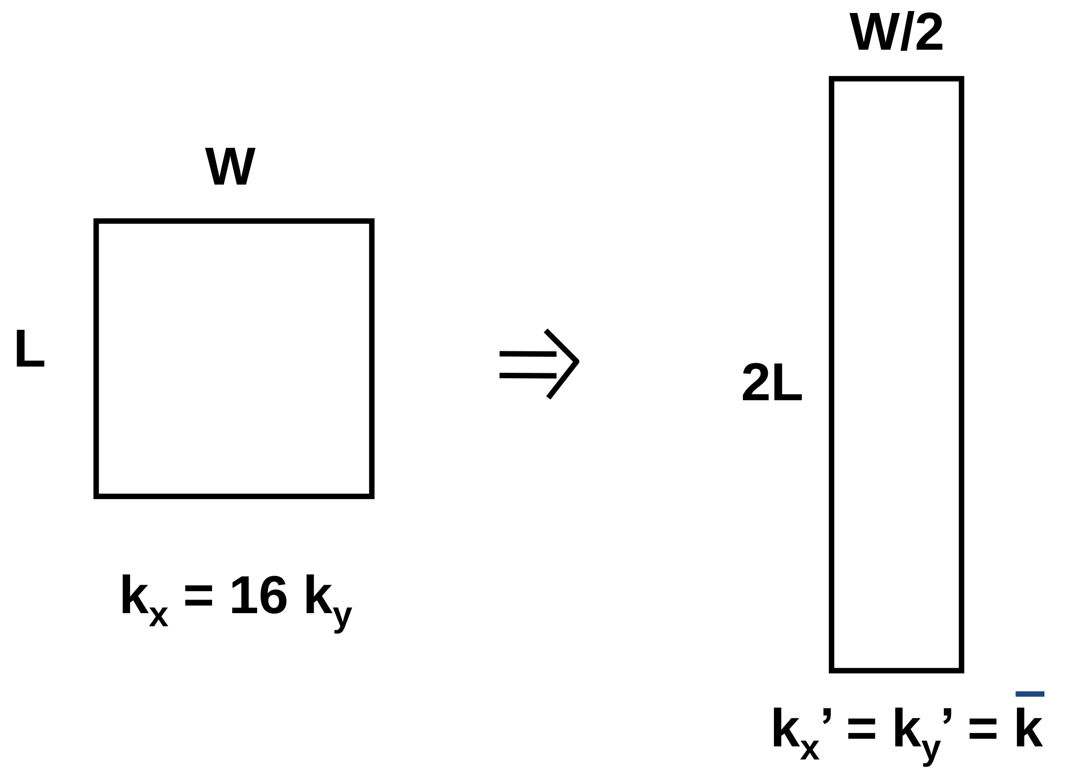
$$y' = \sqrt{\frac{\bar{k}}{k_y}}\, y \qquad k_y' = \frac{\bar{k}}{k_y} k_y$$

- In a two-dimensional system, it is not necessary to transform the z-dimension, since there is no flow in the z-direction, the z-component of permeability does not affect the pressure response.

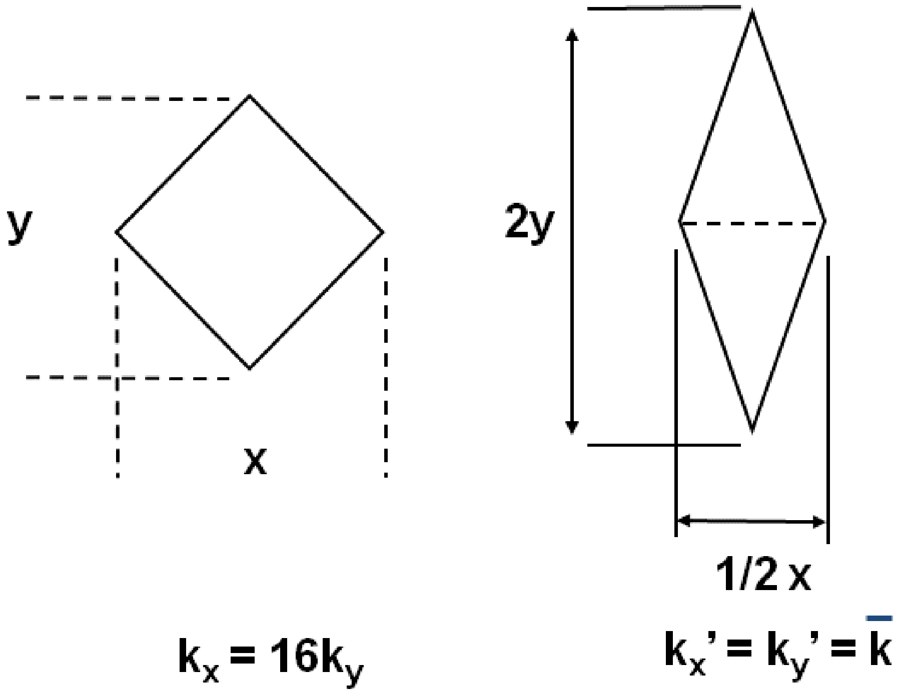
- In this case, we can simplify the necessary transformation to the form shown here.

Equivalent Isotropic System Case I

As an example, consider a anisotropic square reservoir having $k_x = 16\ k_y$. The equivalent isotropic reservoir is a 4x1 rectangle, with w'=w/2 and l'=2l.



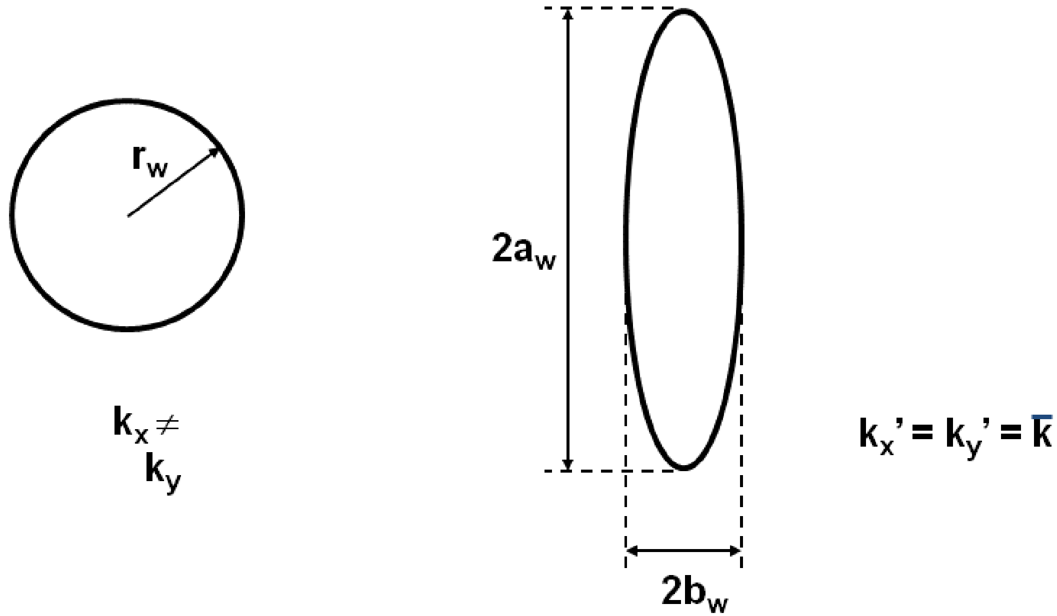
Equivalent Isotropic System Case II



❑What if the original reservoir lay with its diagonals along the directions of the principal permeabilities?

❑Consider now a anisotropic square reservoir having $k_x = 16\ k_y$ with the principal permeabilities parallel to the diagonals. In this case, the equivalent isotropic reservoir is a rhombus, with one diagonal twice as long as the corresponding diagonal in the original system, and the other diagonal only 1/2 as long as the diagonal in the original system.

Equivalent Isotropic System Vertical Wellbore



❑A circular wellbore in an anisotropic system transforms to an elliptical wellbore in the equivalent isotropic system.

❑The elliptical wellbore could be represented as either a geometric skin factor, or by an equivalent wellbore radius.

Transformation for Vertical Wellbore

- The transformed permeability is given by the geometric mean of the permeabilities in the x- and y-directions. Since this is a two-dimensional system, it is not necessary to transform the z-direction. In a partially penetrating vertical wellbore, it will be necessary to transform the z-direction as well.

- The semiaxes of the elliptical cross-section of the transformed wellbore are given by a_w and b_w.

- The radius of the equivalent circular wellbore is obtained from a relationship developed by Kucuk.

$$\bar{k} = \sqrt{k_x k_y}$$

$$a_w = \sqrt{\frac{\bar{k}}{k_y}}\, r_w$$

$$b_w = \sqrt{\frac{\bar{k}}{k_x}}\, r_w$$

$$r_w' = \frac{a_w + b_w}{2}$$

Permeability Anisotropy

In the case of a reservoir with horizontal permeability anisotropy, the pressure response of a producing well can be described by an equivalent isotropic reservoir model of average radial permeability (Earlougher, 1977). With the maximum k_{max} and the minimum k_{min} permeability oriented 90 degree apart, the average permeability is:

$$\bar{k} = \sqrt{k_{max} k_{min}}$$

Permeability Anisotropy

An equivalent transformed isotropic system can be used to describe the pressure behavior of the reservoir by changing the dimensions in the two main directions of permeability. The transformation of variables is, respectively for the maximum and the minimum permeability directions:

$$x' = x\sqrt{\frac{\bar{k}}{k_{max}}} = x\sqrt[4]{\frac{k_{min}}{k_{max}}} \tag{3.4}$$

$$y' = y\sqrt{\frac{\bar{k}}{k_{min}}} = y\sqrt[4]{\frac{k_{max}}{k_{min}}} \tag{3.5}$$

In the equivalent isotropic system, the wellbore is changed into an ellipse

Major axis, in the low permeability direction $r_w \sqrt[4]{k_{max}/k_{min}}$

Minor axis, in the high permeability direction $r_w \sqrt[4]{k_{min}/k_{max}}$

Permeability Anisotropy

The **area of the well** is the same in the original and transformed systems, but the **perimeter** is increased. The elliptical well behaves like a cylindrical hole whose equivalent radius is the average of the major and minor axes (Brigham, 1990):

$$r_{we} = \frac{1}{2} r_w \left[\sqrt[4]{k_{min} / k_{max}} + \sqrt[4]{k_{max} / k_{min}} \right] \quad (3.6)$$

Since the analysis results are calculated with reference to the actual wellbore radius $\mathbf{r_w}$ the reservoir anisotropy produces an **apparent negative skin component**:

$$\begin{aligned} S_{ani} &= -\ln \frac{\sqrt[4]{k_{min} / k_{max}} + \sqrt[4]{k_{max} / k_{min}}}{2} \\ &= -\ln \frac{\sqrt{k_{min}} + \sqrt{k_{max}}}{2\sqrt{\bar{k}}} \end{aligned} \quad (3.7)$$

Permeability Anisotropy

With typical permeability anisotropy values in the horizontal plane, the negative geometrical skin effect is low. For horizontal wells, the effect of permeability anisotropy between the vertical and horizontal directions can be much larger, and apparent negative skins of S_{ani} =-1 may be observed.

Table 3.1. Anisotropy skin S_{ani}

k_{max} / k_{min}	10	100	1000
S_{ani}	-0.157	-0.55	-1.06

Dimensionless Variables

❑The circular section of the horizontal well is changed into an ellipse and the horizontal well behaves like a cylinder with the apparent larger equivalent radius **r_{we}** of Equation 3.6.

❑With large anisotropy k_V/k_H, r_{we} can be 2 or 3 times larger than the actual wellbore radius and the resulting anisotropy skin **S_{ani}** clearly negative

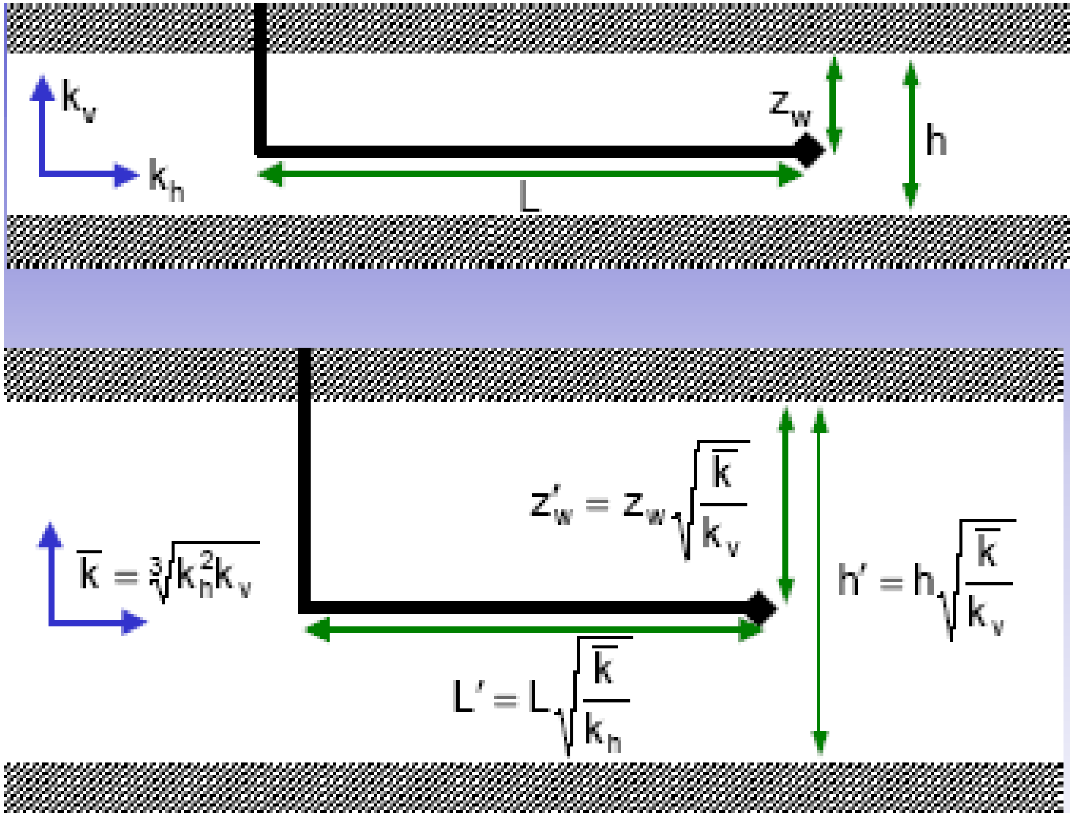
$$p_D = \frac{kh}{141.2qB\mu}\Delta p \qquad t_{DL} = \frac{0.000264k}{\phi\mu c_t L^2}\Delta t \qquad h_D = \frac{h_a}{L} = \frac{h}{L}\sqrt{\frac{k_H}{k_V}}$$

$$h_a = h\sqrt{\frac{k_H}{k_V}}$$

$$z_{wa} = z_w\sqrt{\frac{k_H}{k_V}}$$

Permeability Anisotropy

This anisotropic System…



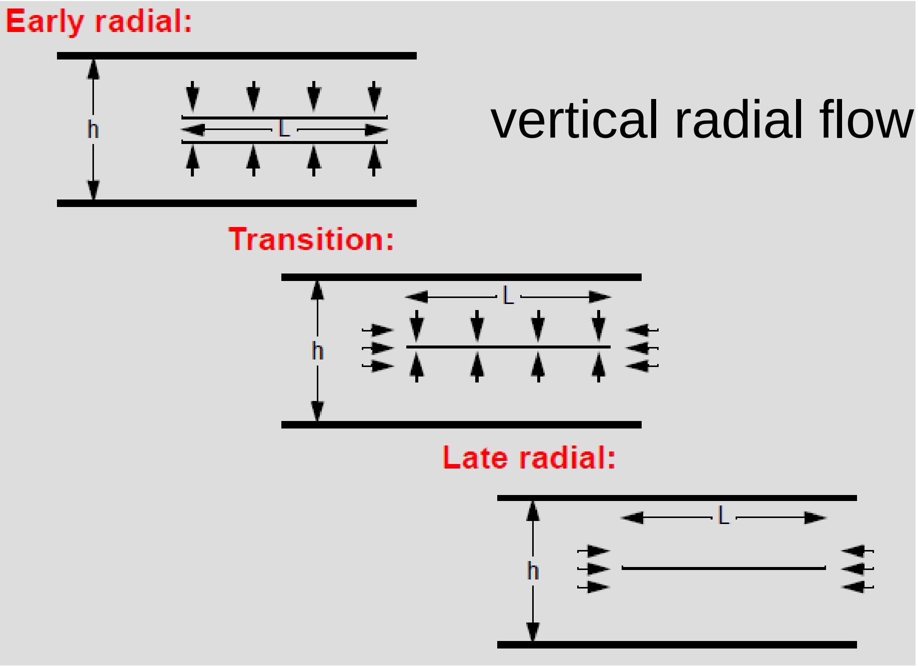
Is equivalent to this Isotropic system which is easy to deal with

Using these scaled dimension

$$r_{we} = \frac{1}{2} r_w \left[\sqrt[4]{k_{min} / k_{max}} + \sqrt[4]{k_{max} / k_{min}} \right]$$

Horizontal Well - Skin Coefficients

S_W : the mechanical infinitesimal skin
S_{ani}: the anisotropy skin
S_{Tv}: the apparent skin during the vertical radial flow regime
S_G: the geometrical skin
S_{TH}: the total skin during the horizontal radial flow

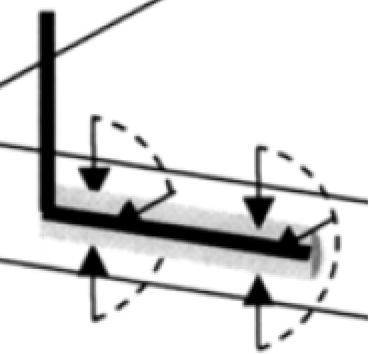


vertical radial flow regime

horizontal radial flow

Equations for the Characteristic Regimes

In the following sections, the different limiting forms of the Kuchuk et al. (1991) solution are presented, and the different skin coefficients defined from horizontal well responses are described.



Radial Flow in the Vertical Plane

During the vertical radial flow regime, the equation of the semi-log straight line is expressed (Kuchuk, 1995)

$$\Delta p = \frac{162.6 q B \mu}{2\sqrt{k_V \cdot k_H}\, L}\left[\log \frac{\sqrt{k_V \cdot k_H}\,\Delta t}{\phi \mu c_t r_w^2} - 3.23 + 0.87 S_w - 2\log \frac{1}{2}\left(\sqrt[4]{\frac{k_V}{k_H}} + \sqrt[4]{\frac{k_H}{k_V}}\right)\right] \quad (3.31)$$

The second logarithm of Equation 3.31 corresponds to the negative anisotropy skin S_{ani} resulting flom the equivalent wellbore radius r_{we}, of Equation 3.6. The total skin factor S_{TV} measured from the early time radial flow analysis combines the wellbore mechanical skin factor S_W, and S_{ani}.

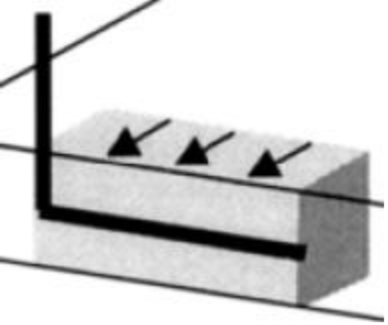
$$S_{TV} = S_w + S_{ani} = S_w - \ln \frac{\sqrt[4]{k_V / k_H} + \sqrt[4]{k_H / k_V}}{2} \quad (3.32)$$

Semi-log Plot

$$m_{r1} = \frac{162.6 q \mu B}{2\sqrt{k_v k_H} L_w}$$

$$S_{TV} = S_w + S_{ani} = S_w - \ln \frac{\sqrt[4]{k_V / k_H} + \sqrt[4]{k_H / k_V}}{2}$$

$$s = 1.151 \left[\frac{\Delta p_{1hr}}{m_{r1}} + 3.2275 + 2 \log \frac{1}{2} \left(\sqrt[4]{\frac{k_v}{k_H}} + \sqrt[4]{\frac{k_H}{k_v}} \right) - \log \left(\frac{\sqrt{k_H k_v}}{\phi \mu c_t r_w^2} \right) \right]$$



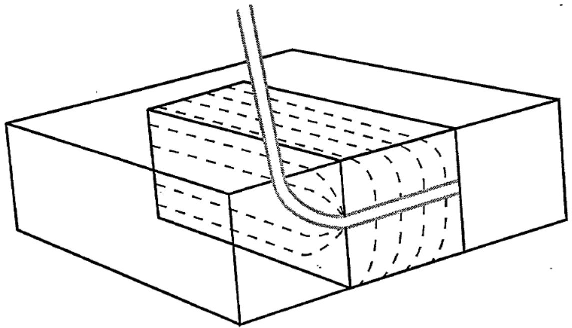
Linear Flow Regime

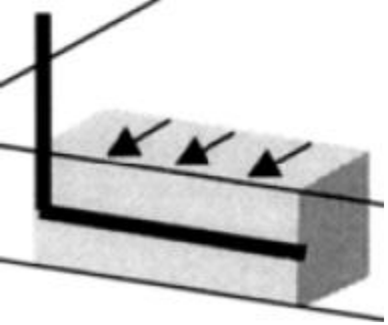
During the linear flow regime, the pressure changes as the square root of the elapsed time:

$$\Delta p = \frac{8.128qB}{2Lh}\sqrt{\frac{\mu\Delta t}{\phi c_t k_H}} + \frac{141.2qB\mu}{2\sqrt{k_V \cdot k_H}\,L} S_w + \frac{141.2qB\mu}{k_H h} S_z \quad (3.33)$$

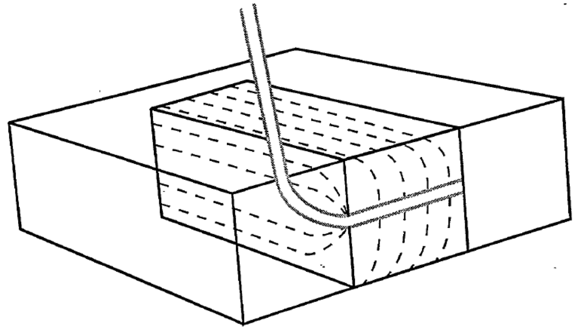
$$\Delta p = 4.06\frac{qB}{hx_f}\sqrt{\frac{\mu}{\phi c_t k}}\sqrt{\Delta t} \quad (1.25)$$

The first term of Equation 3.33 is similar to Equation 1.25 for a well intercepting a fully penetrating vertical fracture. With a horizontal well, the flow lines have to converge towards the well located at z_W in the formation thickness. This partial penetration effect produces a pressure drop, expressed with the skin $\mathbf{S_Z}$. During the linear flow regime, the two skin effects $\mathbf{S_W}$, and **Sz** are additive.





Linear Flow Regime



$$S_z = -1.151\sqrt{\frac{k_H}{k_V}}\,\frac{h}{L}\log\left[\frac{\pi r_w}{h}\left(1+\sqrt{\frac{k_V}{k_H}}\right)\sin\left(\frac{\pi z_w}{h}\right)\right] \quad (3.34)$$

Equation 3.34 is approximate and only valid when the length of the well is long compared to the apparent thickness (Equation 3.30, $h_D < 2.5$).

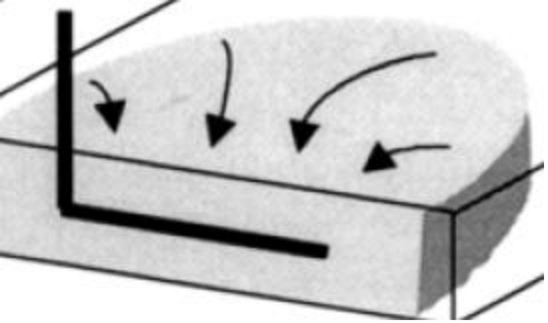
Linear flow analysis

$$\Delta p = \frac{8.128\,qB}{2Lh}\sqrt{\frac{\mu\,\Delta t}{\phi c_t k_H}} + \frac{141.2\,qB\mu}{2\sqrt{k_V k_H}\,L} S_w + \frac{141.2\,qB\mu}{k_H\,h} S_z$$

$$S_z = -1.151\sqrt{\frac{k_H}{k_V}}\frac{h}{L}\log\left[\frac{\pi r_w}{h}\left(1+\sqrt{\frac{k_V}{k_H}}\right)\sin\left(\frac{\pi z_w}{h}\right)\right]$$

Pressure vs. the square root of time $m_{l1} = \frac{8.128q}{2Lh}\sqrt{\frac{\mu}{k_H \phi c_t}}$

$$s = \left(2L\sqrt{k_H k_V}\,/141.2q\mu\right)\Delta p_{0hr} + 2.303\log\left[\frac{\pi r_w}{h}\left(1+\sqrt{\frac{k_V}{k_H}}\right)\sin\left(\frac{\pi z_w}{h}\right)\right]$$



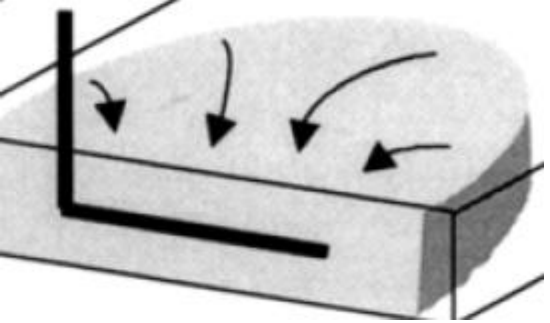
Pseudo-radial Flow from the Reservoir

Using the well half-length L as the reference for semi-log analysis of horizontal radial flow, Kuchuk et al. define:

$$\Delta p = 162.6\frac{qB\mu}{k_H h}\left[\log\frac{k_H \Delta t}{\phi\mu c_t L^2} - 2.53\right] + \frac{141.2qB\mu}{2\sqrt{k_V k_H}\,L}S_w + \frac{141.2qB\mu}{k_H h}S_{zT} \qquad (3.35)$$

where S_{zT} is :

$$S_{zT} = S_z - 0.5\frac{k_H}{k_V}\frac{h^2}{L^2}\left(\frac{1}{3} - \frac{z_w}{h} + \frac{z_w^2}{h^2}\right) \qquad (3.36)$$



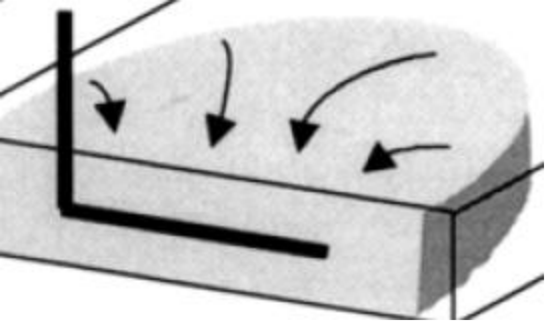
Pseudo-radial Flow from the Reservoir

In practice, the efficiency of horizontal wells is frequently described by the total skin S_{TH} defined with reference to a fully penetrating vertical well of radius r_w. With the usual radial flow relationship,

$$\Delta p = 162.6 \frac{qB\mu}{k_H h}\left[\log \frac{k_H \Delta t}{\phi \mu c_t r_w^2} - 3.23 + 0.87 S_{\mathrm{TH}}\right] \qquad (3.37)$$

the total skin factor S_{TH} combines the wellbore mechanical skin factor S_W, and the geometrical skin S_G.

$$\begin{aligned} S_{\mathrm{TH}} &= \frac{h}{2L}\sqrt{\frac{k_H}{k_V}} S_w + S_G \\ &= \frac{h}{2L}\sqrt{\frac{k_H}{k_V}} S_w + S_{zT} + 1.151\left(0.70 + 2\log\frac{r_w}{L}\right) \end{aligned} \qquad (3.38)$$



Pseudo-radial Flow from the Reservoir

$$S_G = 0.81 - \ln \frac{L}{r_w} + S_{zV}$$

$$= 0.81 - 1.151\left\{ 2\log \frac{L}{r_w} + \sqrt{\frac{k_H}{k_V}}\,\frac{h}{L}\log\left[\frac{\pi r_w}{h}\left(1+\sqrt{\frac{k_V}{k_H}}\right)\sin\left(\frac{\pi z_w}{h}\right)\right]\right\} - 0.5\,\frac{k_H}{k_V}\,\frac{h^2}{L^2}\left(\frac{1}{3} - \frac{z_w}{h} + \frac{z_w^2}{h^2}\right) \quad (3.39)$$

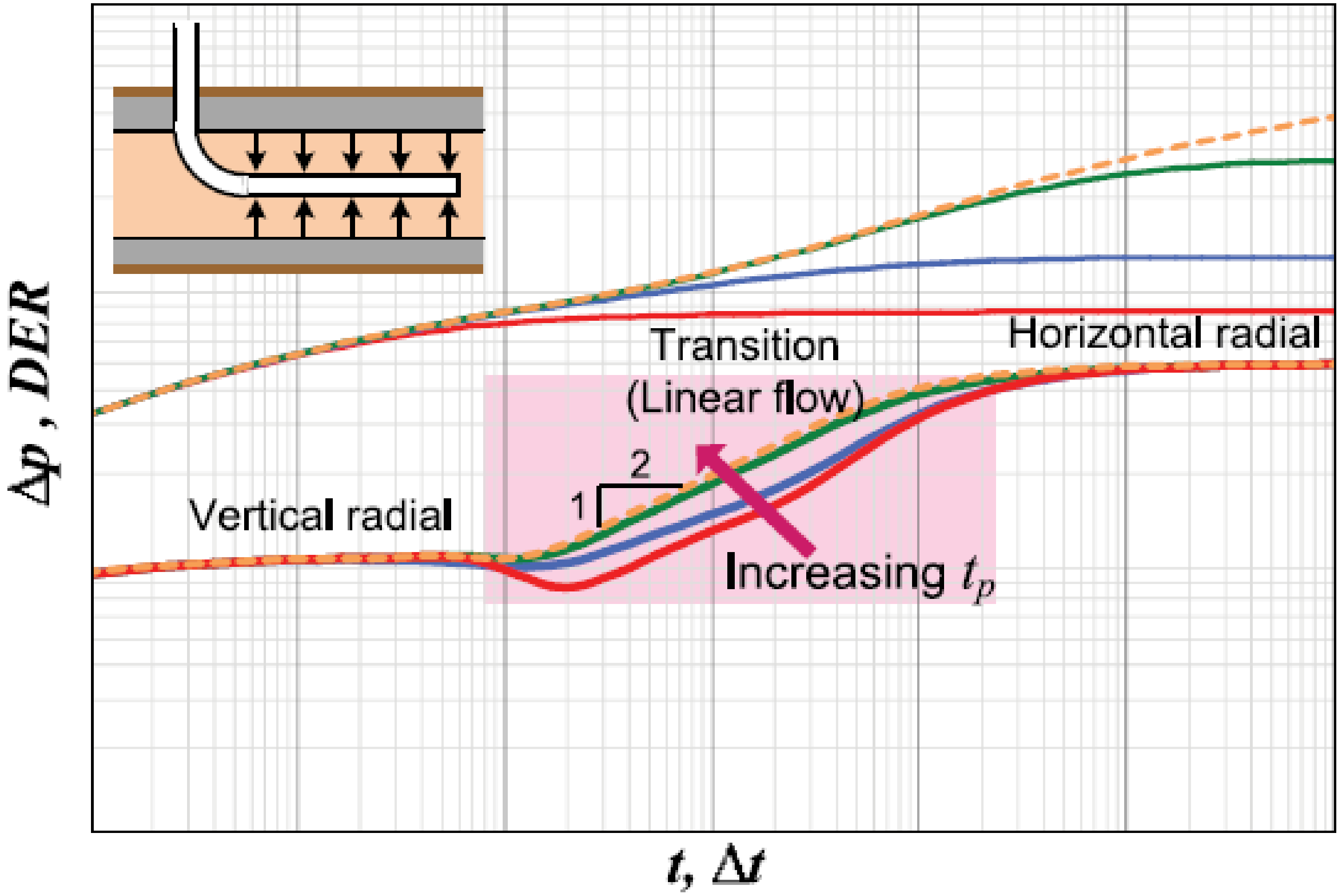
Horizontal pseudo-radial flow semi-log analysis

Semi log straight-line slope $m_{r1} = \frac{162.6 q \mu B}{k_H L_w}$

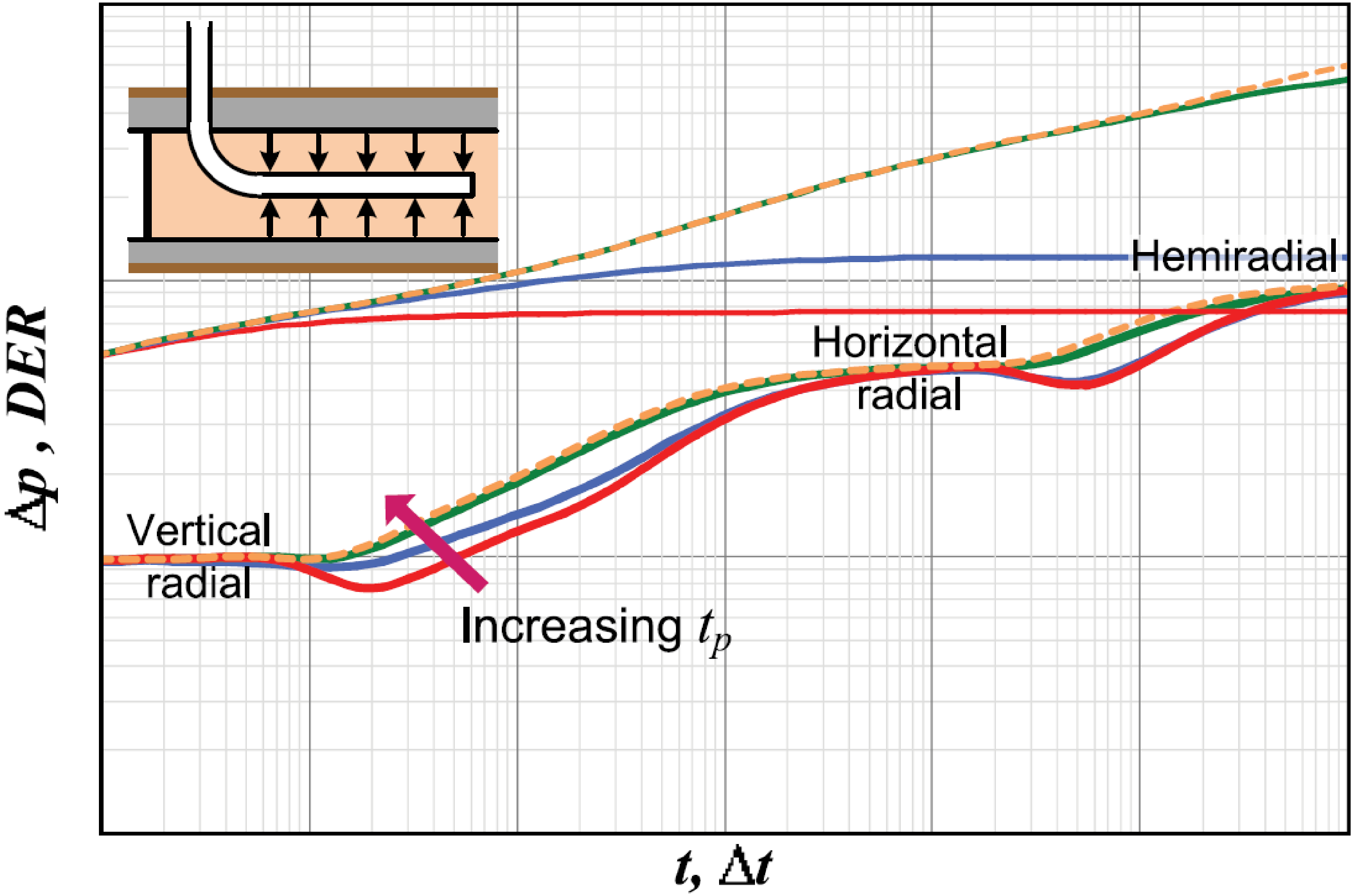
$$s = 2.303 \sqrt{\frac{k_V}{k_H}} \frac{L}{h} \left[\frac{\Delta p_{1hr}}{m_{r3}} - \log\left(\frac{k_H}{\phi \mu c_t r_w^2} \right) + 2.5267 \right] - s_z$$

$$s_z = -2.303 \log\left[\frac{\pi r_w}{h} \left(1 + \sqrt{\frac{k_V}{k_H}} \right) \sin\left(\frac{\pi z_w}{h} \right) \right] - \sqrt{\frac{k_H}{k_V}} \frac{h}{L_w} \left(\frac{1}{3} - \frac{z_w}{h} + \frac{z_w^2}{h^2} \right)$$

Horizontal Well



Horizontal Well- One No-Flow Boundary



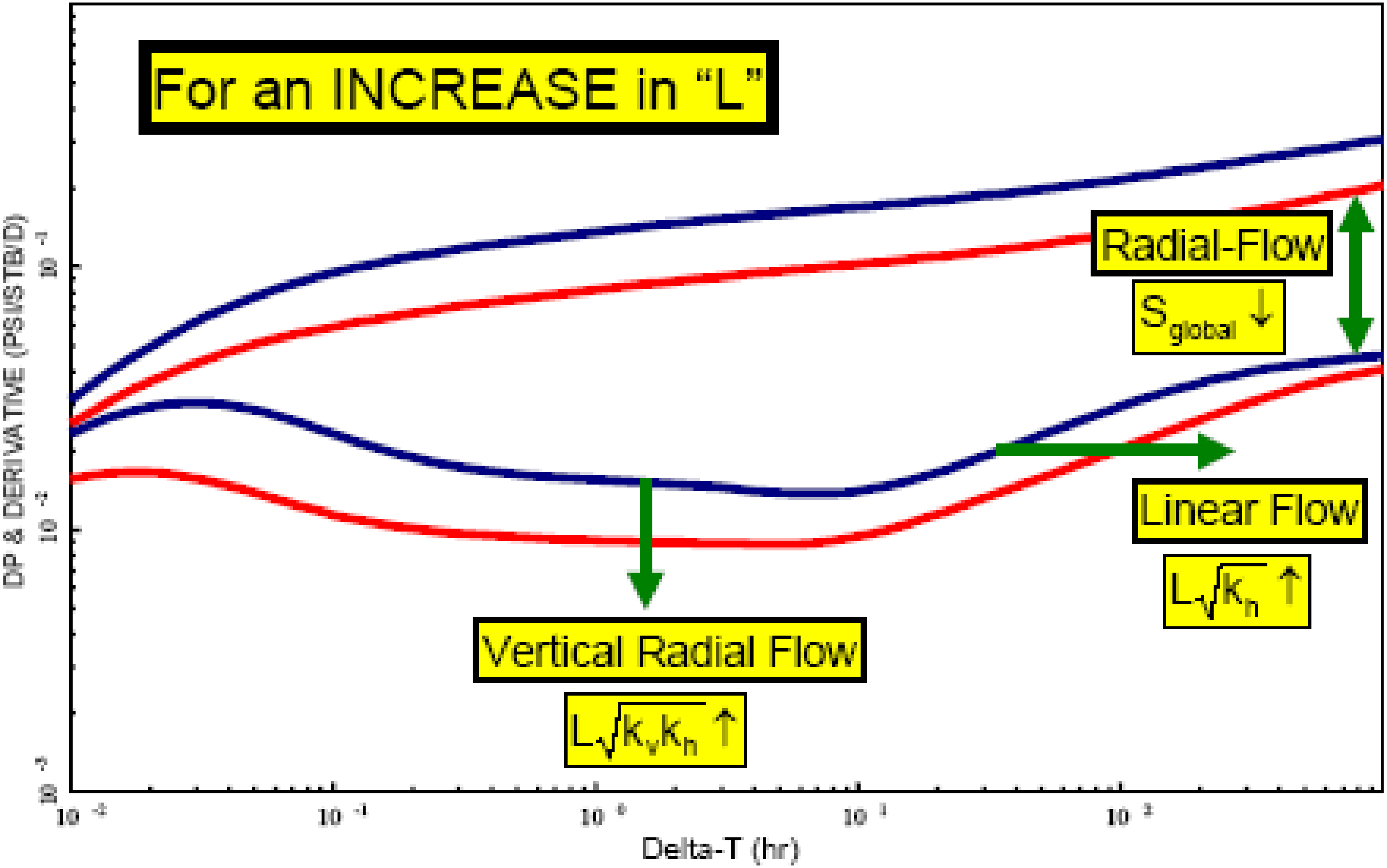
Horizontal Well

- If all flow regimes are evident, k_x, k_y and k_z can be determined individually
- Effective length L_e can be determined if k_y is assumed (often equal to k_x)
- After end of vertical radial flow, horizontal well behavior is very similar to infinite-conductivity fracture
  - ➡ Replace L_e by $2x_f$, and add a geometric skin due to flow convergence into horizontal well
- Horizontal well with multiple transverse infinite-conductivity fractures
  - ➡ Initially behaves like a single large fracture, equal in area to the sum of the individual fractures
  - ➡ After interference between the fractures, behaves like a large stimulated area
- Finite conductivity vertical fracture intersected by horizontal well does NOT result in bilinear flow

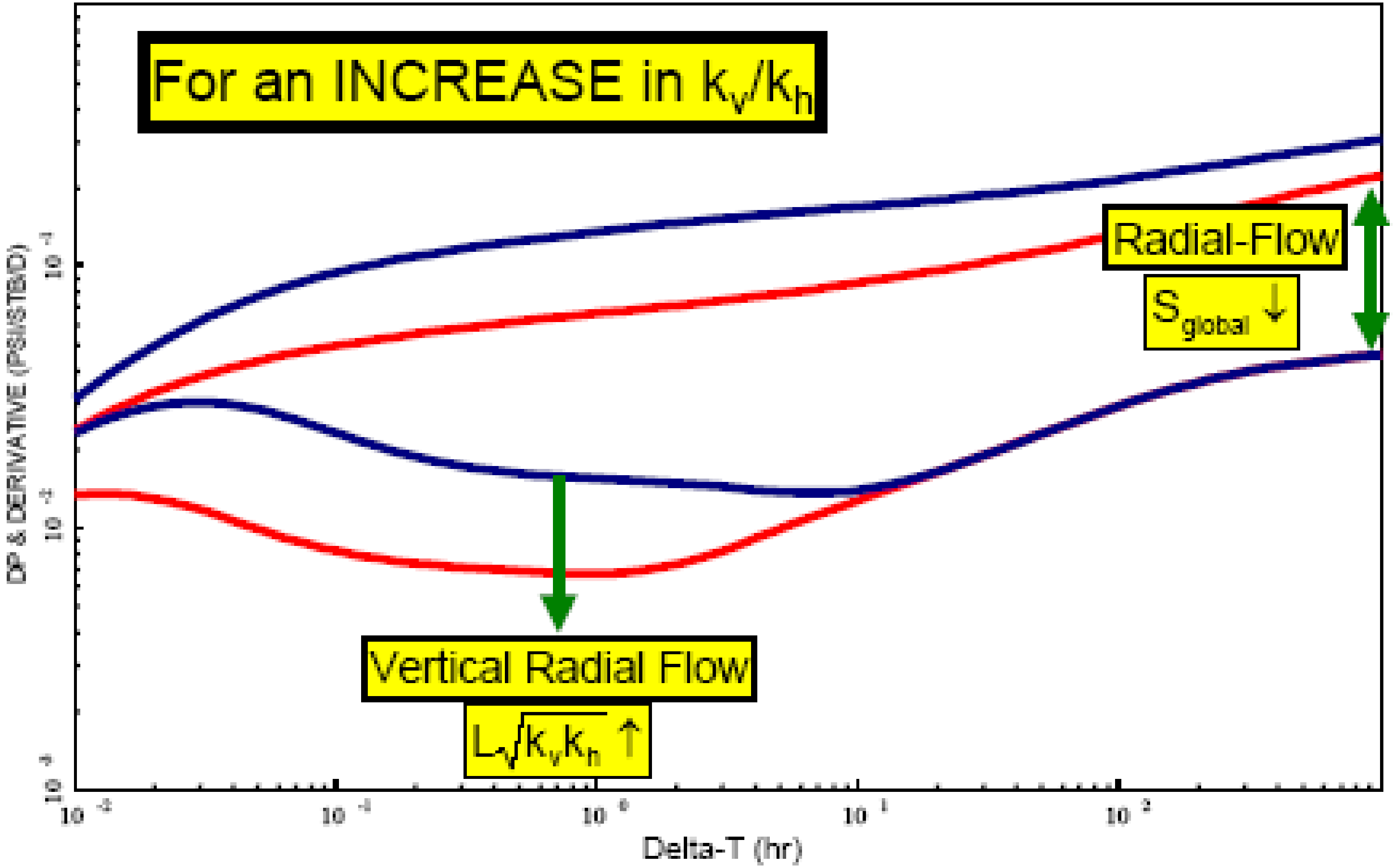
Three Steps to Evaluate Pressure Transient Data from Horizontal Well

- Identify the specific flow regimes in the test data.
- Apply the proper analytical and graphical procedures to the data.
- Evaluate the uniqueness and sensitivity of the results to assumed properties.

Horizontal well Sensitivity



Horizontal well Sensitivity



Horizontal well Sensitivity