Well Test Interpretation

SKM4323

PRINCIPLE OF WELL TESTING

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WEEK 02

Introduction

The pressure can be measured:

- in the well where the flow rate has been changed: this is the method used in most tests.
- or in another well: this is the aim of interference test.

Darcy’s Law

- The flow rate of a fluid flowing through a rock sample is proportional to:
  - the pressure gradient applied to the rock sample.
  - the sample’s cross-section, A.
  - the mobility of the fluids, k/μ.
- Valid within a time interval when the flow rate and other parameters are constant.
- Does not depend on the porosity of the medium, or on the compressibility of either the fluids or the rock.

Darcy's Law…/2

- The vectorial expression of Darcy's law

$$\vec{q} = -\frac{k}{\mu} A \, \overrightarrow{\text{grad}}\, p \qquad (1.1)$$

- Darcy's law can also be expressed as a function of the fluid's filtration rate

$$\vec{V} = \frac{\vec{q}}{A} \qquad (1.2)$$

$$\vec{V} = -\frac{k}{\mu} \, \overrightarrow{\text{grad}}\, p \qquad (1.3)$$

Darcy's Law…/3

- Darcy's law in radial flow is expressed by:

$$q = -\frac{k}{\mu} 2\pi rh \frac{\partial p}{\partial r} \quad \textbf{(1.4)}$$

- It can be integrated between two values of distance from the well, r_w and r_e

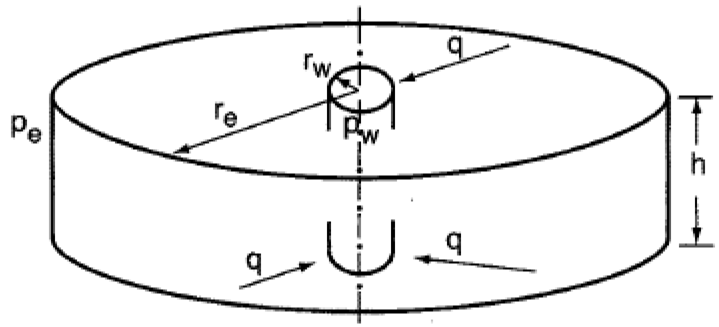


Fig. 1.1

$$q = -\frac{2\pi kh}{\mu} \frac{p_w - p_e}{\ln \frac{r_w}{r_e}} \quad \textbf{(1.5)}$$

Compressibility

- The compressibility of any material is defined by the relative change in the material's volume per unit of pressure variation at constant temperature

$$c = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T \qquad \textbf{(1.6)}$$

- It can be expressed in terms of density

$$c_e = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_T \qquad \textbf{(1.7)}$$

Compressibility…/2

For an oil reservoir, when decompression occurs, the fluid is produced:

- By expansion of the fluids

Oil: $$\Delta V_o = -c_o S_o V_p \Delta p \qquad (1.8)$$

Water: $$\Delta V_w = -c_w S_w V_p \Delta p \qquad (1.9)$$

- By a decrease in the pore volume V_p

Compressibility…/3

When decompression occurs, the fluid pressure decreases while the lithostatic pressure remains constant. The pore volume decreases, thereby causing general fluid production:

$$\Delta V_p = -c_p V_p \Delta p \qquad \textbf{(1.10)}$$

The overall compressibility of a pore volume unit is due to the sum of all its compressible components:

$$c_t = c_o S_o + c_w S_w + c_p$$

Compressibility…/4

The reservoir is modeled by:

- an incompressible porous rock with a porosity of ϕS_o
- an a fluid of equivalent compressibility

$$c_e = \frac{c_o S_o + c_w S_w + c_p}{S_o} \quad \textbf{(1.11)}$$

Compressibility…/5

Order of magnitude:

Oil:	3 to 10 x 10^{-6} psi^{-1}
Water:	3 x 10^{-6} psi^{-1}
Pore Spaces:	3 to 100 x 10^{-6} psi^{-1}

Diffusion Equation

The diffusivity equation governs the variations in a pressure in the reservoir versus time. It is based on two laws and one equation of state:

- Fluid flow equation (Darcy's)
- Material balance
- Equation of states

Diffusion Equation…/2

Fluid flow equation (Darcy's) :

– applied microscopically during the time interval when the various parameters and the flow rate can be considered constant.

– gravitational forces are disregarded.

$$\vec{V} = -\frac{k}{\mu}\,\overrightarrow{\text{grad}}\,p \qquad \textbf{(1.3)}$$

Diffusion Equation…/3

Material balance

– the variation in mass fluid contained in the reservoir volume unit is equal to the difference between the amount of the fluid input and output during the time interval:

$$\operatorname{div} \rho \vec{V} + \frac{\partial(\rho \phi S_o)}{\partial t} = 0 \qquad \textbf{(1.12)}$$

Diffusion Equation…/4

Equation of states

– the gravity of the fluid varies with pressure and the variation is shown by the equivalent compressibility of the flowing fluid:

$$C_e = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_T \qquad \textbf{(1.7)}$$

Diffusion Equation…/5

Considering the material balance equation and express filtrate rate and density versus pressure using Darcy’s law and the equation of state, we will get the following pressure equation:

$$\Delta p = c_e \left(\overrightarrow{\text{grad}}\ p \right)^2 - \frac{\phi \mu c_t}{k} \frac{\partial p}{\partial t} = 0 \qquad \textbf{(1.13)}$$

Diffusion Equation…/6

- Providing two assumptions:
  - fluid flow is low and constant: this is the case for a liquid not for a gas;
  - pressure gradient are low: this is the case in reservoirs where flow rates are small;
  - $c_e \left(\overrightarrow{\text{grad}}\, p\right)^2$ is small compared the two other terms of equation;

The equation is reduced to

$$\Delta p = -\frac{1}{K}\frac{\partial p}{\partial t} = 0 \quad \textbf{(1.14)}$$

Diffusion Equation.../7

$K = \frac{k}{\phi \mu c_t}$ is call the **hydraulic diffusivity of the porous medium**

The diffusivity equation is written as follows in radial flow:

$$\frac{\partial^2 p}{\partial r^2} = \frac{1}{r}\frac{\partial p}{\partial r} - \frac{1}{K}\frac{\partial p}{\partial t} = 0 \qquad \textbf{(1.15)}$$

Solving the Diffusivity Equation

- The assumption that is usually made is to suppose that
  - the reservoir is homogeneous, isotropic, with constant thickness and limited by impermeable boundaries.
  - the well penetrates the total reservoir thickness.
  - the fluid compressibility and viscosity are constant and uniform using the following boundary condition:
    - uniform initial pressure, p_i
    - infinite reservoir
    - constant flow rate in the well that is considered to have an infinitesimal radius.

Solving the Diffusivity Equation…/2

- The variation in pressure versus time and the distance from the well verify the equation:

$$p_i - p(r,t) = -\frac{qB\mu}{4\pi kh}\,Ei\left(\frac{-r^2}{4Kt}\right) \qquad \textbf{(1.16)}$$

where Ei (x) is the exponential integral function define by

$$-Ei(-x) = \int_x^{\infty} \frac{\exp(-u)}{u}\,du$$

Solving the Diffusivity Equation…/3

- The way to solve the diffusivity equation is indicated with various sets of boundary conditions in the book by F. Daviau (1986).

- The equation is written as follows:

$$p_D = -\frac{1}{2}\mathrm{Ei}\left[-\frac{r_D^2}{4t_D}\right]$$

Solving the Diffusivity Equation…/4

…using the following dimensionless factors

Pressure: $$p_D = \frac{2\pi kh}{qB\mu}\Delta p$$ (in SI units)

$$p_D = \frac{kh}{141.2\,qB\mu}\Delta p$$ (in practical US units)

$$p_D = \frac{kh}{18.66\,qB\mu}\Delta p$$ (in practical metric units)

Solving the Diffusivity Equation…/5

Length: $$r_D = \frac{r}{r_w}$$

Time: $$t_D = \frac{k\,\Delta t}{\phi \mu c_t r_w^2}$$ (in SI units)

$$t_D = \frac{0.000264\ k\,\Delta t}{\phi \mu c_t r_w^2}$$ (in practical US units)

$$t_D = \frac{0.00036\ k\,\Delta t}{\phi \mu c_t r_w^2}$$ (in practical metric units)

Compressible Zone

- The flow at a distance r from the well at time t can be determined based on the microscopic Darcy's law expressed in radial flow (1.4) and based on equation (1.16) which describes the pressure variation:

$$q(r,t) = qB \exp\left(-\frac{r^2}{4Kt}\right) \quad \textbf{(1.17)}$$

where

q	is the wellhead flow rate
qB	is the bottomhole flow rate

Compressible Zone…/2

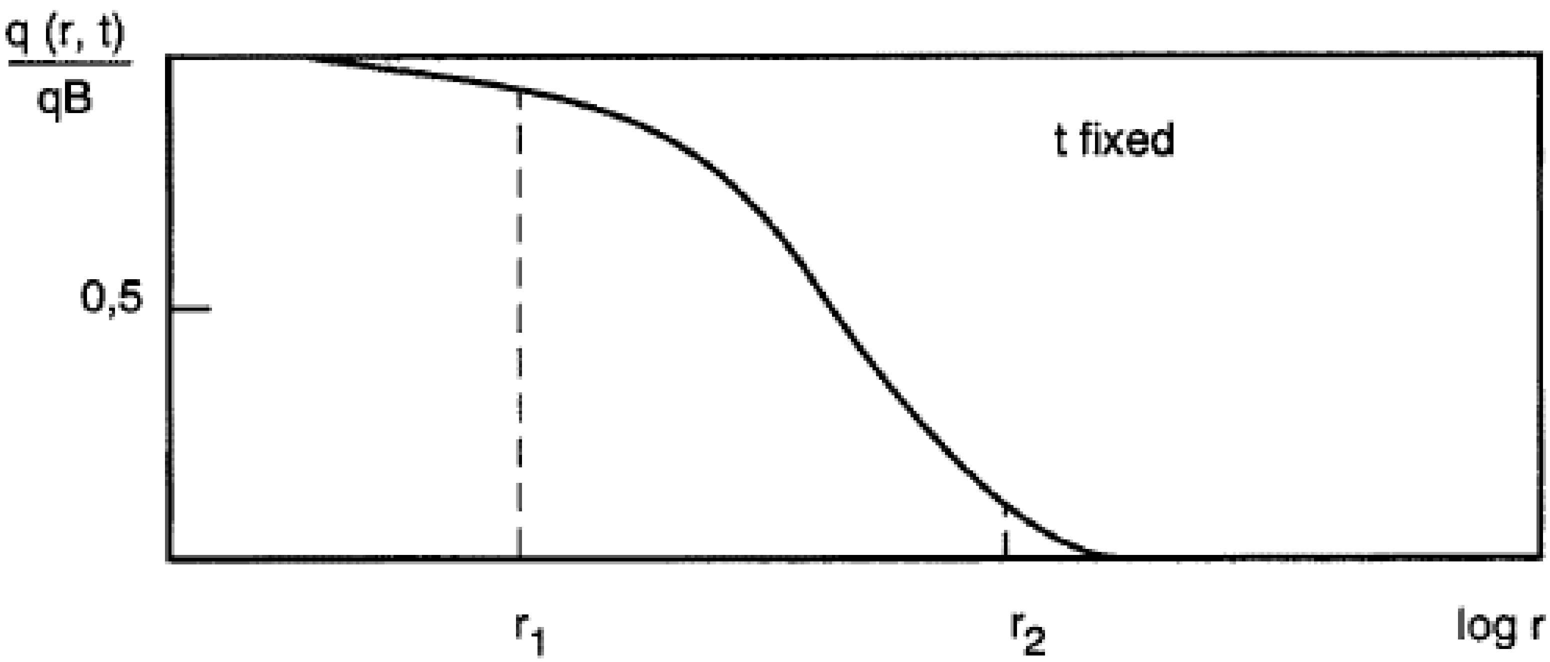


Fig. 1.2 Flow profile

Compressible Zone…/3

- On the flow profile it can be seen that between the wellbore and r_1 the flow rate almost the same value as near the wellbore. Darcy's law is applicable macroscopically in these areas.

- There is a negligible flow through the areas located beyond r_2. The pressure drop between r_2 and an infinite distance is negligible.

Compressible Zone…/4

- Let us look at the variations in the flow profile between two times t and t’

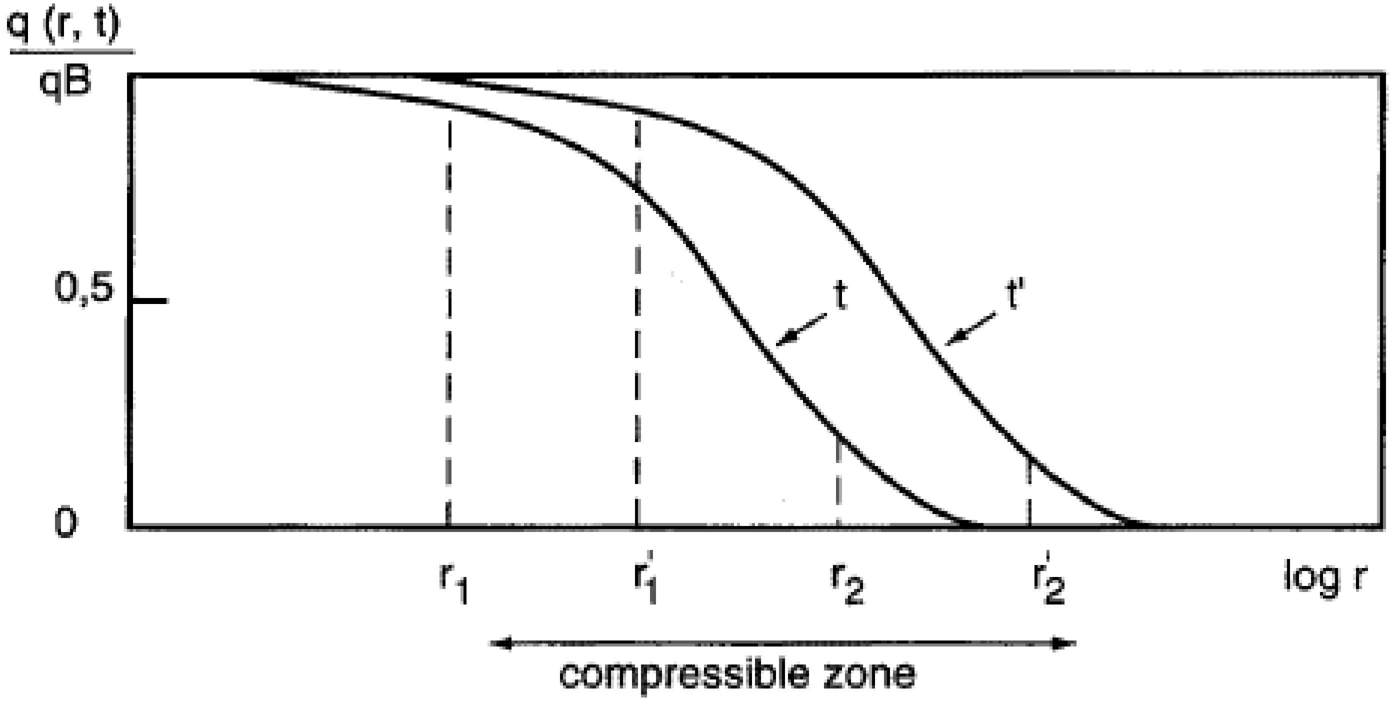


Fig. 1.3

Compressible Zone…/5

- Between t and t' the pressure drop between and infinite distance and the well is therefore mainly due to what is occurring between r_1 and r_2'
- It is in these area that the reservoir compressibility, allowing the flow to go from 0 to qB, comes into play. This area is call **the compressible zone**.
- The pressure drop at the well since the initial pressure is equal to the pressure drop between an infinite distance and the well.
- **The pressure drop in the well mainly reflects the reservoir properties in the compressible zone**.

Compressible Zone…/6

- At the beginning of the test the pressure drop reflects the reservoir properties in the vicinity of the well. Later on the test reaches areas that are farther away.

- This is what enables a well test to:
  - Characterize the average properties far away from the well, permeability for example;
  - Detect facies heterogeneities;
  - Identify permeability barriers.

Radius of Investigation

- Jones's definition:
  - The radius of investigation is the point in the reservoir where the pressure variations represent 1% of the variations observed at the well:

$$r_i = 4\sqrt{\frac{kt}{\phi \mu c_t}} \qquad \text{(in SI units)} \qquad \textbf{(1.18)}$$

Radius of Investigation…/2

- Poettmann's definition:
  - The radius of investigation is the point in the reservoir where the flow is to 1% of the well flow rates:

$$r_i = 4.29\sqrt{\frac{kt}{\phi \mu c_t}} \qquad \text{(in SI units)} \qquad \textbf{(1.19)}$$

Radius of Investigation…/3

- J. Lee and Muskat's definition:
  - The radius of investigation is the point where the pressure variations are the fastest:

The variations are given by the equation below (1.16)

$$p_i - p(r,t) = -\frac{qB\mu}{4\pi kh} Ei\left(\frac{-r^2}{4Kt}\right)$$

Radius of Investigation…/4

The pressure variations are equal to:

$$\frac{dp}{dt} = \frac{qB\mu}{4\pi kh} \frac{\exp\left(-r^2\right)}{4Kt} \qquad \textbf{(1.20)}$$

The variations is at a maximum for

$$\frac{d^2p}{dt^2} = 0, \text{ i.e. for } \frac{r^2}{4Kt} = 1$$

Radius of Investigation…/5

In other terms

$$r_i = 2\sqrt{\frac{kt}{\phi \mu c_t}} \qquad \text{(in SI units)} \qquad \textbf{(1.21)}$$

Simulations performed with a grid-type well simulator show that an event is perceived in the well pressure variations at a time close to that computed with his formula.

Radius of Investigation…/6

In practical units it is expressed as follows:

$$r_i = 0.032\sqrt{\frac{kt}{\phi \mu c_t}}$$ (in practical US units) **(1.22)**

$$r_i = 0.038\sqrt{\frac{kt}{\phi \mu c_t}}$$ (in practical metric units) **(1.23)**

Flow Regimes

- **Transient flow:**
  - Until the compressible zone reaches the boundaries of the reservoir or comes under the influence of another well, the reservoir behaves as if it was infinite for testing purposes.
  - During this period the flow regime is called **transient**.

Flow Regimes…/2

- **Pseudosteady-state flow:**
  - When the compressible zone reaches a series of no-flow boundaries, the flow regimes **pseudosteady-state**.
  - This is the type of flow in producing reservoir with no flow boundaries.

Flow Regimes…/3

- **Steady-state flow:**
  - When the compressible zone is affected by some constant pressure outer boundaries, the flow becomes steady-state.
  - This is the type of flow in a reservoir producing under gas-cap or water drive conditions when the mobility of the water is high compared to that of the oil

A well test is almost always performed in a transient flow regimes even though some boundaries are reached.

Principle of Superposition

- How can the pressure be described in the reservoir when several flow rate variations occur?
- The pressure variations due to several flow rates are equal to the some of the pressure drops due to each of the different flow rates. This property is called superposition.

Principle of Superposition…/2

- **Two flow rates:**

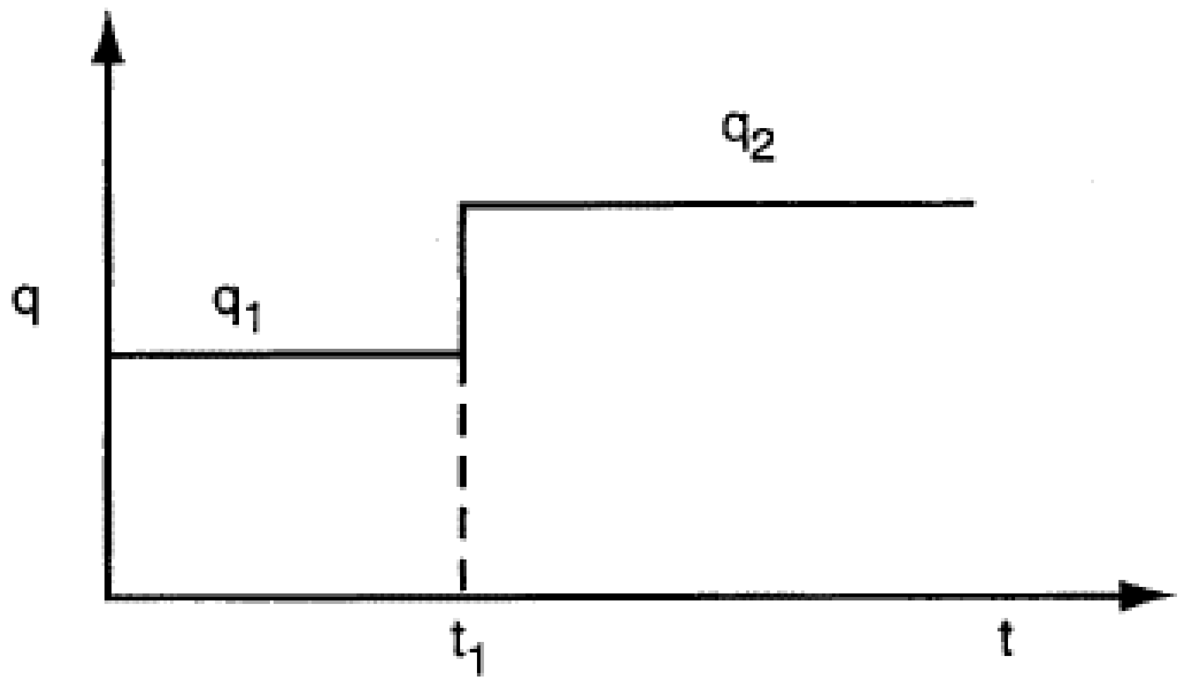


Fig. 1.4 Diagram for two flow rates

Principle of Superposition…/3

- If $p_i - p(t) = \frac{qB\mu}{2\pi kh} p_D(t)$ is the pressure drop due to a flow rate, q, beginning at time, t = 0.
  - The diagram shown in Figure 1.4 can be considered as the sum of:
    - a production of a flow rate q_1 since t = 0, and;
    - a production at flow rate $(q_2 - q_1)$ since $t = t_1$.
- A pressure variation due to the flow rates is equal to

$$p_i - p(t) = \frac{q_1 B\mu}{2\pi kh} p_D(t) + \frac{(q_2 - q_1)B\mu}{2\pi kh} p_D(t - t_1) \qquad \textbf{(1.24)}$$

Principle of Superposition…/4

- **Pressure buildup**
  - One case is of particular interest: when q_2 is zero. This is case for the great majority of tests

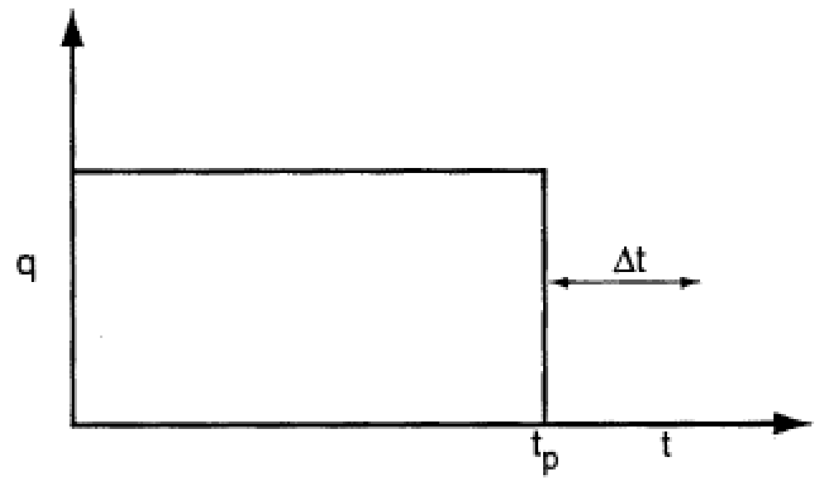


Fig. 1.5 Shut-in test

Equation (1.4) becomes:

$$p_i - p(t) = \frac{qB\mu}{2\pi kh}\left[p_D(t_p + \Delta t) - p_D(\Delta t)\right] \qquad \textbf{(1.25)}$$

Principle of Superposition…/5

- **Multirate testing**

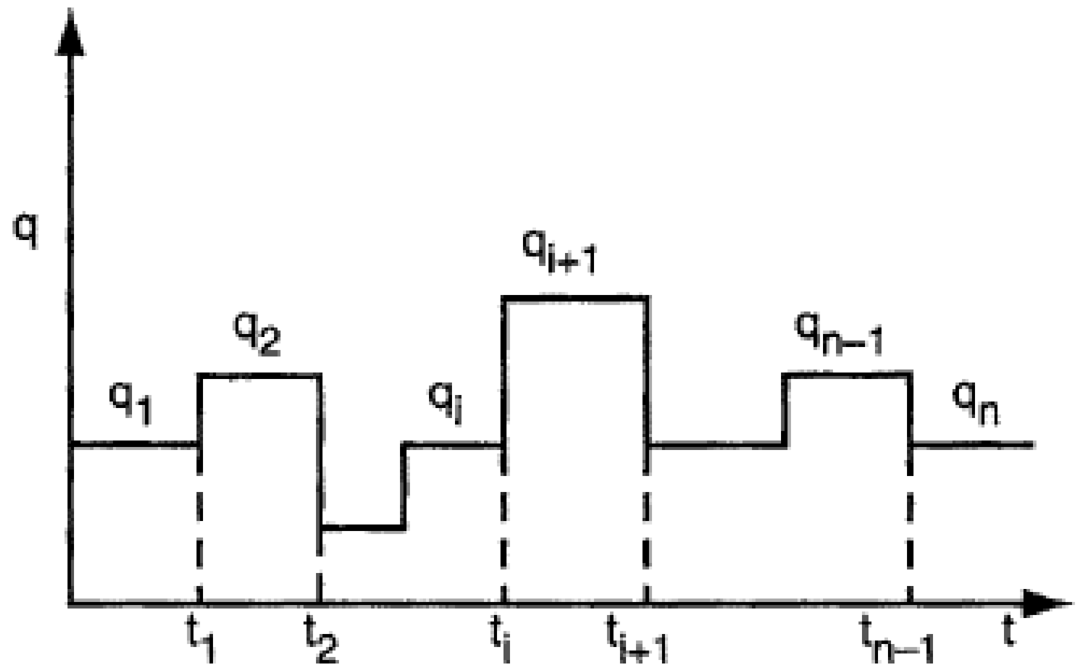


Fig. 1.6 Multirate testing

Principle of Superposition…/6

For multirate testing (Fig. 1.6)

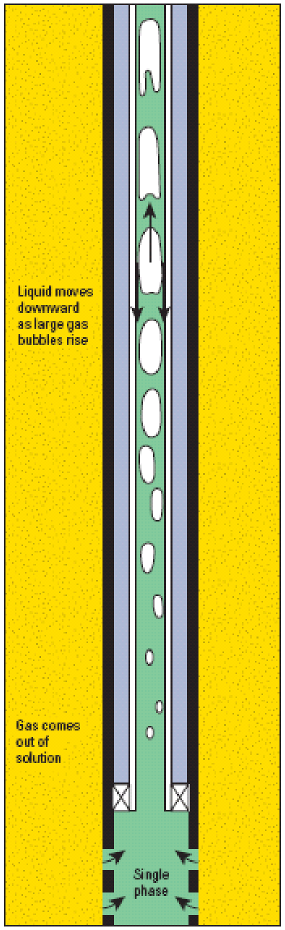
$$p_i - p(t) = \frac{B\mu}{2\pi kh} \sum_{i=1}^{n} (q_i - q_{i-1})\, p_D\,(t - t_{i-1}) \qquad \textbf{(1.26)}$$

with q_0 = 0 and t_0 = 0.

Wellbore Storage Definition

- A well test begins with a sudden variations in the well flow rate. The variation occurs in the well, at the wellhead usually, or closer to the formation in a DST or with a bottomhole shut-in.
- The flow out of the formation undergoes a gradual variation because of the compressibility of the fluid column in the tubing between the bottom of the hole and the shut-in point.

Wellbore Storage Definition…/2



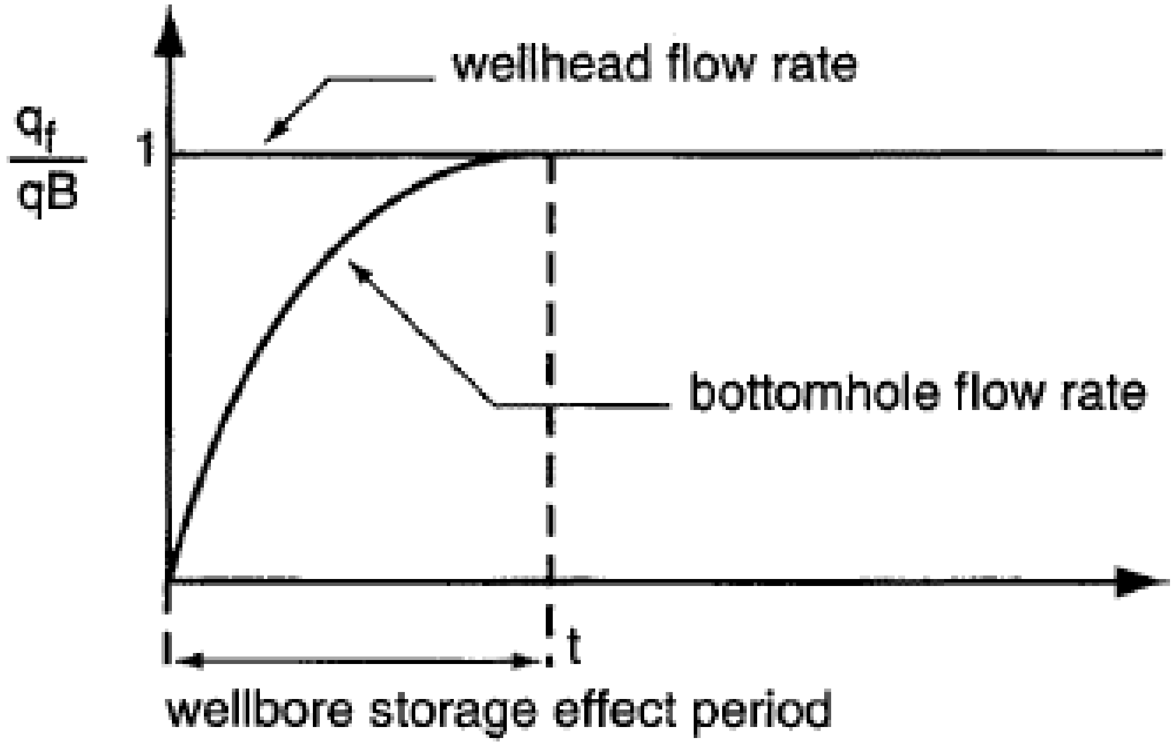


Fig. 2.1

Wellbore Storage Definition…/3

- The surface flow rate when the well is opened is assumed to go at once from 0 to q, but the bottomhole flow rate does not increase instantly from 0 to qB.
- The bottom of the well begins producing gradually (Fig. 2.1).

Wellbore Storage Definition…/4

- The period when the bottomhole flow rates is called the wellbore storage effect period.
- Wellbore storage is defined by

$$C = -\frac{\Delta V}{\Delta p} \qquad \textbf{(2.1)}$$

where

ΔV = the volume variation of fluid in the well under well condition

Δp = the variation in pressure applied to the well

Wellbore Storage Definition…/5

- Wellbore storage is homogeneous with the product of a volume by a compressibility.
- A dimensionless factor is related to wellbore storage defined by:

$$C_D = \frac{C}{2\pi \phi c_t h r_w^2}$$ (in SI and practical metric units) **(2.2)**

$$C_D = \frac{0.89\,C}{\phi c_t h r_w^2}$$ (in practical US units) **(2.3)**

End of the Wellbore Storage Effect

- **Ramey's criterion**

$$t_D = (60 + 3.5S)C_D \qquad \textbf{(2.11)}$$

i.e. approximately:

$$t = \frac{(200\,000 + 12\,000S)C}{kh/\mu} \qquad \text{(in practical US units)} \qquad \textbf{(2.12)}$$

where S is the skin of the well

End of the Wellbore Storage Effect.../2

- **Chen and Brigham's criterion:**

$$t_D = 50\, C_D \exp(0.14\, S) \qquad \textbf{(2.13)}$$

i.e. approximately:

$$t = \frac{170\,000\, C \, \exp(0.14\, S)}{kh/\mu} \quad \text{(in practical US units)} \qquad \textbf{(2.14)}$$

where S is the skin of the well.

End of the Wellbore Storage Effect…/3

- **Rule of thumb:**
  - This criterion can be applied to the representation used for type curves. This representation shows pressure variations versus time on log-log graph.
  - The period when the well storage effect prevails is represented by a straight lime with a slope of 1.
  - The rule of thumbs locates the end of the wellbore storage effect at the intersection of the measurement point curve and the line parallel to the slope 1 line translated by 1.5 cycles (Fig. 2.3).

End of the Wellbore Storage Effect…/4

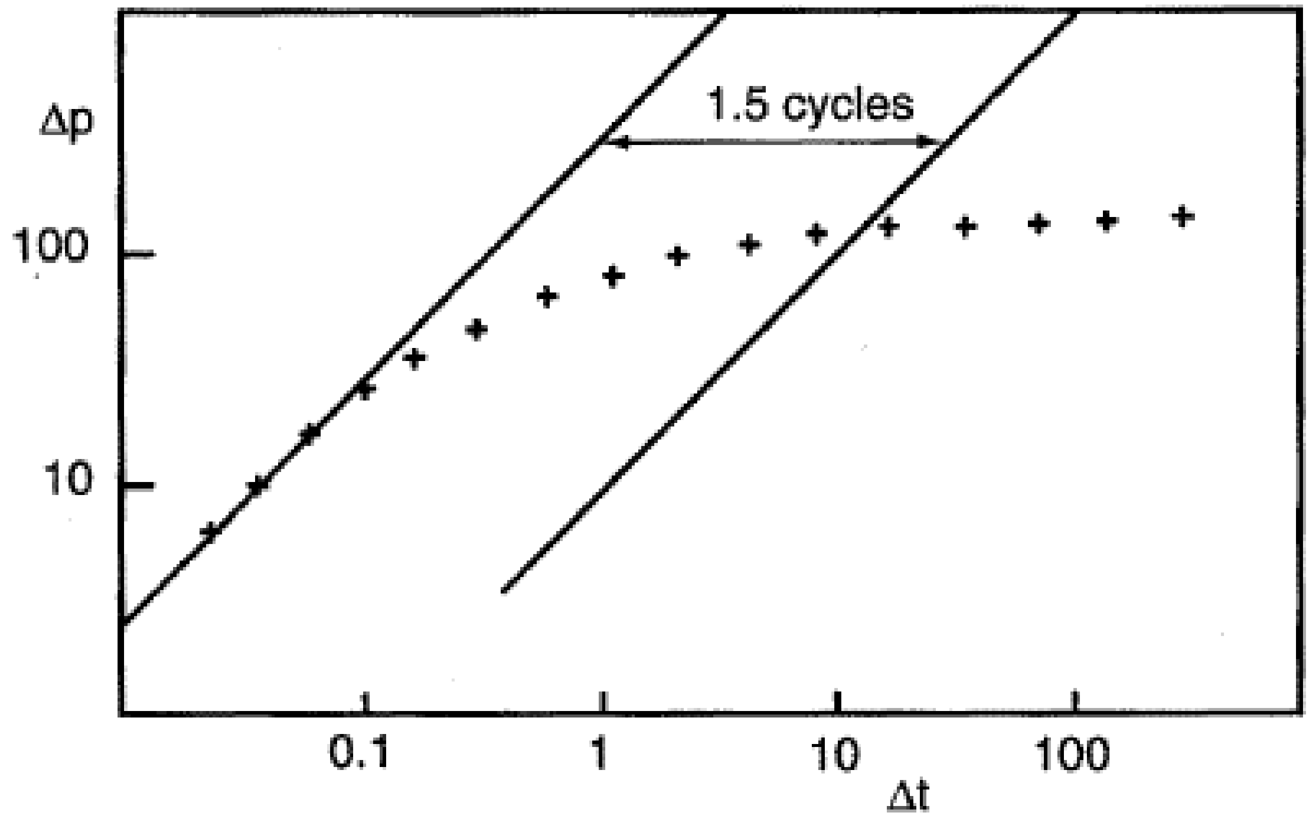


Fig. 2.3

Skin Definition

- The vicinity of the wellbore has characteristics that are different from those in the reservoir as a result of drilling and well treatment operations.
- The skin effect reflects the difference in pressure drop that exists in the vicinity of the well between:
  - the reservoir as it is, and
  - as it would be if its characteristics (especially permeability) were uniform right up to the wellbore.

Skin Definition…/2

- The skin effects reflects the connection between the reservoir and the well. The difference in pressure drop in the vicinity of the wellbore can be interpreted in several ways:
  – by using infinitesimal skin;
  – skin of a finite thickness;
  – or the effective radius method.

Infinitesimal Skin

- The additional pressure drop due to the skin effect is defined by:

$$\Delta p_s = \frac{\alpha\, qB\mu}{kh} S \qquad \textbf{(3.1)}$$

with

α	=	$1/2\pi$	(in SI units)
α	=	141.2	(in practical US units)
α	=	18.66	(in practical metric units)

Infinitesimal Skin…/2

- In Hurst and Van Everdingen's approach, the pressure drop due to the skin effect is located in an infinitely thin film around the wellbore.

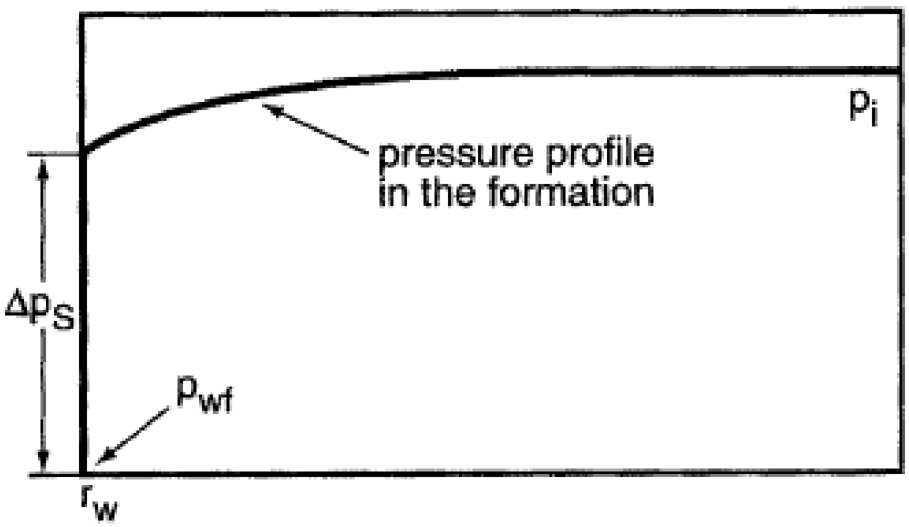


Fig. 3.1

The skin effect, S, is homogeneous with a dimensionless pressure drop.

Finite Thickness Skin

- Another representation consists in assuming the pressure drop is located in an area with a radius r_s and permeability k_s around the well.

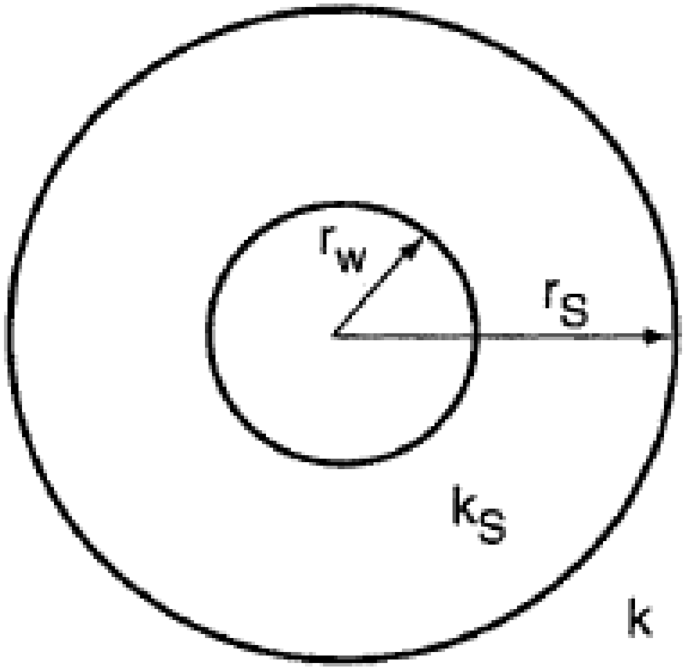


Fig. 3.2

Finite Thickness Skin…/2

- The difference in pressure drop between the real reservoir and a reservoir uniform right up to the wellbore is expressed as follows with Darcy's law:

$$\Delta p_s = \frac{qB\mu}{2\pi k_s h} \ln \frac{r_s}{r_w} - \frac{qB\mu}{2\pi kh} \ln \frac{r_s}{r_w}$$

- By expressing Δp_s with equation (3.1) we get:

$$S = \left(\frac{k}{k_s} - 1 \right) \ln \frac{r_s}{r_w} \qquad \textbf{(3.2)}$$

Effective Radius

- The effective radius method consists in replacing the real well with a radius r_w and skin S by a fictitious well with a radius r_w' and zero skin.

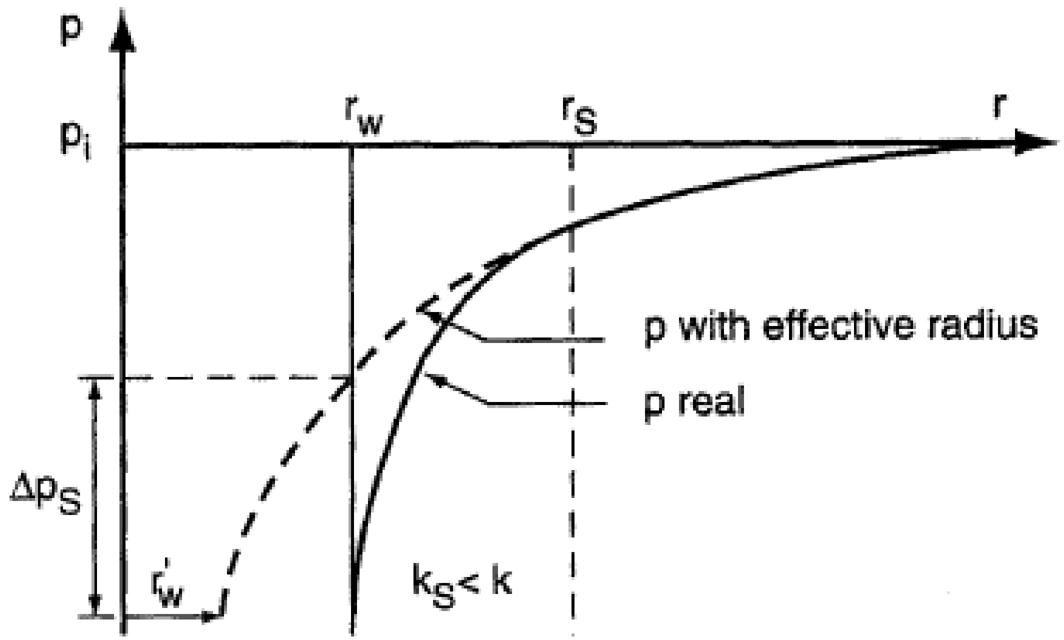


Fig. 3.3

Effective Radius.../2

- Radius r_w' is determined to have a pressure drop between r_s and r_w' in the fictitious well equal to the pressure drop between r_s and r_w in the real well:

$$\Delta p\,(r'_w\,, S=0)=\Delta p\,(r_w\,, S)$$

- Expressing the pressure drop with Darcy's law:

$$\frac{qB\mu}{2\pi kh}\ln\frac{r_s}{r'_w}=\frac{qB\mu}{2\pi kh}\left(\ln\frac{r_s}{r_w}+S\right)$$

We get:

$$r'_w=r_w\exp(-S) \qquad \textbf{(3.3)}$$

Generalization of the Skin Concept

The skin can be used to account for:

- **Perforations:**
  - The flow restriction due to the perforation hole: a positive skin;
  - The punctured reservoir due to the perforating operation itself: a negative skin (minifracture);
  - The fact that only some of the perforations are active: a positive skin.

Generalization of the Skin Concept…/2

- **Inclined wells:**
  - The inclination of a well improves flow in the vicinity of the wellbore and contributes to negative skin.
- **Partially perforating the reservoir**
  - Perforating only part of the thickness of the reservoir causes a restriction in the stream lines near the wellbore and contributes to positive skin.

Generalization of the Skin Concept…/3

- **Hydraulic fracturing:**
  - Hydraulic fracturing considerably improves the flow around the wellbore. It produces a negative skin.
- **A horizontal well:**
  - A horizontal well can under certain conditions be treated as a vertical well with negative skin due to the improvement to flow brought about by the well.

Generalization of the Skin Concept…/4

- **Gas well: deviation from Darcy's law**
  - The fluid velocity in the vicinity of a gas well is often high. Flow does not follow Darcy's law near the well.
  - Positive skin, depending on the flow rate, show the additional pressure drop due to the deviation from Darcy's law.

Generalization of the Skin Concept…/5

- **Injection skin:**
  - Injection of fluid (water, polymers, etc) into the reservoir creates a zone of different mobility in the vicinity of the wellbore.
  - It causes additional pressure drop that can also be considered as a skin when the compressible zone is beyond the fluid injection radius.

Generalization of the Skin Concept…/6

- **Geological skin:**
  - A well in a low-input lens can be reflected by a skin.
    - The reservoir has the characteristics of the distant regions that supply the lens;
    - The skin reflects the characteristics of the lens

References

1. Bourdarot, Gilles : Well Testing: Interpretation Methods, Éditions Technip, 1998.
2. Internet.