Al-Ayen University
College of Petroleum Engineering

Reservoir Engineering II

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2020/2021

Lecture 17: Water Influx (Part 1)

Ref.: Reservoir Engineering Handbook by Tarek Ahmed

Outline

- Introduction
- Classification of Aquifers
  - Degree of Pressure Maintenance
  - Outer Boundary Conditions
  - Flow Regimes
  - Flow Geometries
- Water Influx Models
- The Pot Aquifer Model

Introduction

- Nearly all hydrocarbon reservoirs are surrounded by water-bearing rocks called *aquifers.*
- These aquifers may be substantially larger than the oil or gas reservoirs they adjoin as to appear infinite in size, or they may be so small in size as to be negligible in their effect on reservoir performance.
- Many gas and oil reservoirs produced by a mechanism termed *water drive.* Often this is called *natural water drive* to distinguish it from *artificial water drive* that involves the injection of water into the formation.
- Hydrocarbon production from the reservoir and the subsequent pressure drop prompt a response from the aquifer to offset the pressure decline.
- This response comes in a form of *water influx,* commonly called *water encroachment.*
- *Water encroachment* is attributed to:
  1. Expansion of the water in the aquifer
  2. Compressibility of the aquifer rock
  3. Artesian flow where the water-bearing formation outcrop is located structurally higher than the pay zone

Classification of Aquifers

Reservoir-aquifer systems are commonly classified on the basis of:

- Degree of pressure maintenance
- Flow regimes
- Outer boundary conditions
- Flow geometries

Degree of Pressure Maintenance

Based on the degree of the reservoir pressure maintenance provided by the aquifer, the natural water drive is often qualitatively described as:

- Active water drive
- Partial water drive
- Limited water drive

- The term *active* water drive refers to the water encroachment mechanism in which the rate of water influx equals the reservoir *total* production rate.

$$\begin{bmatrix}\text{water influx}\\ \text{rate}\end{bmatrix}=\begin{bmatrix}\text{oil flow}\\ \text{rate}\end{bmatrix}+\begin{bmatrix}\text{free gas}\\ \text{flow rate}\end{bmatrix}+\begin{bmatrix}\text{water production}\\ \text{rate}\end{bmatrix}$$

$$\begin{bmatrix}\text{water influx}\\ \text{rate}\end{bmatrix} = \begin{bmatrix}\text{oil flow}\\ \text{rate}\end{bmatrix} + \begin{bmatrix}\text{free gas}\\ \text{flowrate}\end{bmatrix} + \begin{bmatrix}\text{water production}\\ \text{rate}\end{bmatrix}$$

or

$$e_w = Q_o\ B_o + Q_g\ B_g + Q_w\ B_w$$

$$e_w = \frac{dW_e}{dt} = B_o \frac{dN_p}{dt} + (GOR - R_s)\frac{dN_p}{dt} B_g + \frac{dW_p}{dt} B_w$$

where

e_w = water influx rate, bbl/day
Q_o = oil flow rate, STB/day
B_o = oil formation volume factor, bbl/STB
Q_g = **free** gas flow rate, scf/day
B_g = gas formation volume factor, bbl/scf
Q_w = water flow rate, STB/day
B_w = water formation volume factor, bbl/STB
W_e = cumulative water influx, bbl
t = time, days

N_p = cumulative oil production, STB
GOR = current gas-oil ratio, scf/STB
R_s = current gas solubility, scf/STB
B_g = gas formation volume factor, bbl/scf
W_p = cumulative water production, STB
dN_p/dt = daily oil flow rate Q_o, STB/day
dW_p/dt = daily water flow rate Q_w, STB/day
dW_g/dt = daily water influx rate e_w, bbl/day
$(GOR - R_s)\ dN_p/dt$ = daily free gas flow rate, scf/day

Example

Calculate the water influx rate e_w in a reservoir whose pressure is stabilized at 3000 psi.

Given: initial reservoir pressure = 3500 psi
$dN_p/dt = 32{,}000$ STB/day
$B_o = 1.4$ bbl/STB
GOR = 900 scf/STB
$R_s = 700$ scf/STB
$B_g = 0.00082$ bbl/scf
$dW_p/dt = 0$
$B_w = 1.0$ bbl/STB

Solution

$$e_w = \frac{dW_e}{dt} = B_o \frac{dN_p}{dt} + (GOR - R_s) \frac{dN_p}{dt} B_g + \frac{dW_p}{dt} B_w$$

$$e_w = (1.4)\ (32{,}000) + (900 - 700)\ (32{,}000)\ (0.00082) + 0$$
$$= 97{,}280 \text{ bbl/day}$$

Outer Boundary Conditions

The aquifer can be classified as infinite or finite (bounded).

a. Infinite system indicates that the effect of the pressure changes at the oil/aquifer boundary can never be felt at the outer boundary. This boundary is for all intents and purposes at a constant pressure equal to initial reservoir pressure.

b. Finite system indicates that the aquifer outer limit is affected by the influx into the oil zone and that the pressure at this outer limit changes with time.

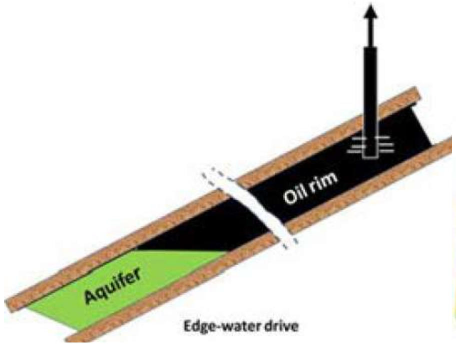
Flow Regimes

There are basically three flow regimes that influence the rate of water influx into the reservoir. As previously described, those flow regimes are:

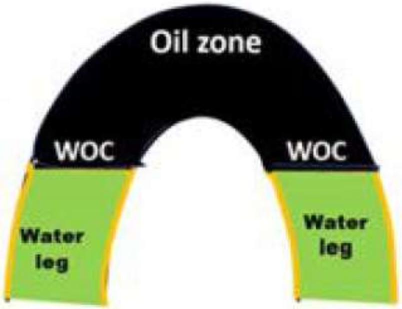
a. Steady-state
b. Semisteady (pseudosteady)-state
c. Unsteady-state

Flow Geometries

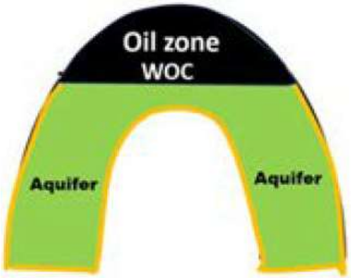
- **Edge-water drive**
  - Water moves into the flanks of the reservoir
  - Water flow is radial and lateral (negligible vertical flow)
- **Bottom-water drive**
  - Reservoir in contact with aquifer throughout its areal extent
  - Water flow is radial and vertical (significant vertical flow)
- **Linear-water drive**
  - Water influx from one flank of the reservoir
  - Strictly linear with constant cross-sectional area



Edge-water drive



Edge-water drive



Bottom-water drive

Linear-water drive

Water Influx Models

The mathematical water influx models that are commonly used in the petroleum industry include:

- Pot aquifer
- Schilthuis' steady-state
- Hurst's modified steady-state
- The Van Everdingen-Hurst unsteady-state
  - Edge-water drive
  - Bottom-water drive
- The Carter-Tracy unsteady-state
- Fetkovich's method
  - Radial aquifer
  - Linear aquifer

The Pot Aquifer Model

- The simplest model that can be used to estimate the water influx into a gas or oil reservoir.
- The model is based on the basic definition of compressibility.
- A drop in the reservoir pressure, due to the production of fluids, causes the aquifer water to expand and flow into the reservoir.

The compressibility is defined mathematically as:

$$\Delta V = c\ V\ \Delta p$$

Applying the above basic compressibility definition to the aquifer gives:

Water influx = (aquifer compressibility) (initial volume of water) (pressure drop)

or $$W_e = (c_w + c_f)\ W_i\ (p_i - p)$$

where W_e = cumulative water influx, bbl

c_w = aquifer water compressibility, psi^{-1}

c_f = aquifer rock compressibility, psi^{-1}

W_i = initial volume of water in the aquifer, bbl

p_i = initial reservoir pressure, psi

p = current reservoir pressure (pressure at oil-water contact), psi

Assuming the aquifer shape is radial, then:

$$W_i = \left[\frac{\pi\left(r_a^2 - r_e^2\right)h\ \phi}{5.615}\right]$$

r_a = radius of the aquifer, ft
r_e = radius of the reservoir, ft
h = thickness of the aquifer, ft
ϕ = porosity of the aquifer

Where the effective radius of the reservoir is expressed in terms of the reservoir pore volume "V_P" as given by:

$$r_e = \sqrt{\frac{360\ V_P}{\pi h \phi \theta}}$$

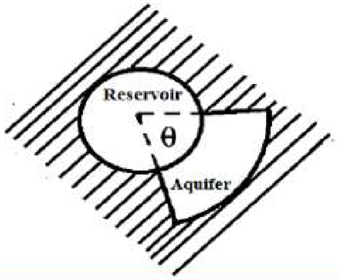
Where reservoir pore volume "V_P" is expressed in ft^3.

- Quite often, water does not encroach on all sides of the reservoir, or the reservoir is not circular in nature. To account for these cases, a modification to the first Equation must be made:

$$W_e = (c_w + c_f)\ W_i\ f\ (p_i - p)$$

where the fractional encroachment angle f is defined by:

$$f = \frac{(\text{encoachment angle})^{\circ}}{360^{\circ}} = \frac{\theta}{360^{\circ}}$$



- The above model is only applicable to a small aquifer, i.e., pot aquifer, whose dimensions are of the same order of magnitude as the reservoir itself.

Example

Calculate the cumulative water influx that results from a pressure drop of 200 psi at the oil-water contact with an encroachment angle of 80°. The reservoir-aquifer system is characterized by the following properties:

	Reservoir	Aquifer
radius, ft	2600	10,000
porosity	0.18	0.12
c_f, psi^{-1}	4×10^{-6}	3×10^{-6}
c_w, psi^{-1}	5×10^{-6}	4×10^{-6}
h, ft	20	25

Solution

$$W_i = \left[\frac{\pi\left(r_a^2 - r_e^2\right) h\ \phi}{5.615}\right] = \left(\frac{\pi\left(10,000^2 - 2600^2\right)(25)(0.12)}{5.615}\right) = 156.5 \text{ MMbbl}$$

$$W_e = (c_w + c_f)\ W_i\ f\,(p_i - p) = (4+3)\ 10^{-6}\ \left(156.5 \times 10^6\right)\left(\frac{80}{360}\right)(200) = 48,689 \text{ bbl}$$

THANK YOU