Hydrodynamic Transition Zone at OWC in Non-Darcy Flow

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1. Introduction

Worldwide, there are great numbers of oil reservoirs with un-recovered oil and thousands of marginal wells that are idling, not because the resources have been depleted, but because they have become unprofitable due to excessive water production. For most operators, produced water is a single most important factor controlling economics of their business. Excessive water production makes the whole economics of reservoir/well management vulnerable to ever-fluctuating crude oil prices.

There are many ways water finds its way to wells – due to wells' integrity failure, or heterogeneity of the oil bearing formation (natural fractures, high permeability channels, etc.). However, even in relatively homogenous strata, after the water breaks through the oil into a well, it progressively dominates the inflow thus leaving the oil behind (by-passed). This process is known as a progressive transition zone above the oil water contact (OWC) and applies to well-reservoir systems with water coning, water cresting and water channeling with crossflow. We postulate that one of the mechanisms contributing to transition zone expansion is a transfer of water into the oil across moving OWC– transverse dispersion.

Transverse dispersion is a hydrodynamic mixing process caused by a concurrent segregated two-phase flow [1=Ewing, 2000]. One reason for the mixing is loss of stability at the flowing fluids interface. In the Hele-Shaw cell flow experiments, where the flow is constricted by solid surface, Gondret [2] showed that the interface would be more stable for smaller gap of the cell plates. Later, Duan and Wojtanowicz [3] used a Hele-Shaw cell to study the effect of shear stress on the interface stability. Their experiments revealed cyclic perturbation of the interface in segregated flow. The size of the perturbation zone would increase at higher shearing rate gradient resulting from the velocity difference of oil and water.

Using granular-packed cell experiments, Blackwell [4], Bijeljic and Blunt [5], and Jha *et al.* [6] demonstrated the mechanisms and effect of factors controlling two dimensional transition zone in miscible flow. Transverse dispersion was quite small comparing to the longitudinal diffusion or dispersion, which would explain why transverse dispersion in miscible flow doesn't attract enough attention. In immiscible flow, on the other hand, Perkins [7] flow experiments with a sand packed model showed progressive symmetric transition zone perpendicular to the direction of flow for two fluids having similar mobilities.

The objective of this study was to demonstrate the effects of fluid viscosities' contrast and granular size of the porous medium on the size and shape of the transition zone in linear segregated flow of oil and water, at flow velocities beyond the validity of Darcy's Law. It was also important to understand the physical mechanisms contributing to the dispersion, develop mathematical models and formulate criteria for the process, as well as relate the transverse dispersion process to the actual oil well inflow conditions.

2. Key Features

Duan and Wojtanowicz [8] designed a granular pack cell and conducted a series of flow experiments for different pressure drop values, using fluids with different viscosities and granular packs with different grain sizes. The experiments were videotaped and water saturation in the transition zone was analyzed with a color-sensing software. An example of the analysis is shown in Figure 1.

We hypothesize that the vertical phase invasion, transverse dispersion, occurs in Non-Darcy flow where inertial effects are significant. The two fluids collide at grains, so the bifurcated flow generates transverse dispersion.

Using a Non-Darcy coefficient, we modified dimensionless groups, namely the Richardson and Weber numbers, and defined criteria for transverse dispersion. We also evaluated the size of the zone around oil well where transverse dispersion may significantly contribute to the growth of transition zone. A simple mechanistic mathematical model has been derived featuring coefficient of transverse dispersion that shall be determined experimentally by testing fluids in the flow cells.

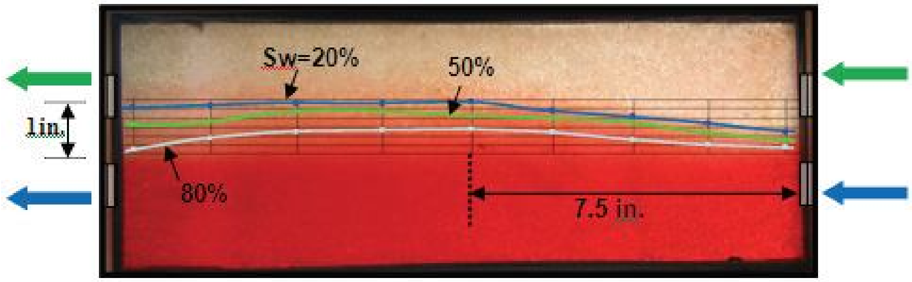
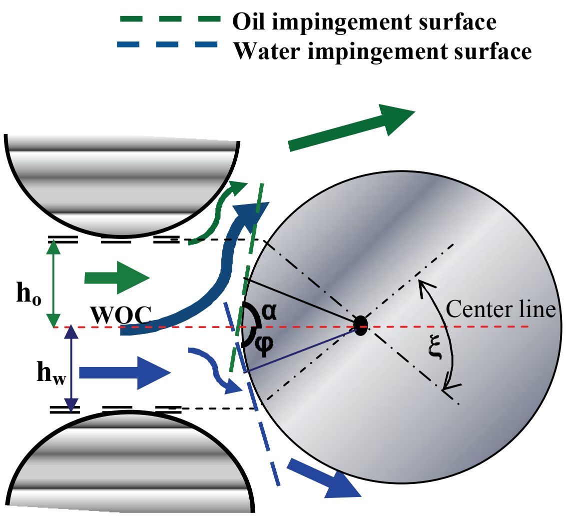


Figure 1. Flow experiment shows transition zone due transverse dispersion [8].



Solution for S_w>50%

Water saturation before collision is:

$$S_w = \frac{A_{w1}}{A_{o+w1}} = 1 - \frac{\arcsin(\frac{\sqrt{h_o h_w}}{r})r^2 - \frac{(h_w - h_o)*\sqrt{h_o h_w}}{2}}{\pi r^2}$$

Water saturation (up) after collision is:

$$S_{w3} = \frac{1+\cos^2\theta}{4} + \frac{1+\cos^2\alpha_w}{2}(\frac{1}{2} - S_o)$$

where r and D_p can be derived from Carman-Kozeny:

$$r = \sqrt{\frac{8\tau k}{\varphi}} \text{ and } D_p = \sqrt{\frac{72\tau(1-\varphi)^2 k}{\varphi^3}}$$

$$\alpha_w = 90^o - \frac{\gamma_2}{2}$$

$$\gamma_2 = \arcsin\frac{(h_w + h_o)}{d_p *}$$

Figure 2. Microscopic (pore scale) dispersion model.

3. Conclusions

- Transverse dispersion criteria for segregated flow in porous media were developed using modified dimensionless groups.
- The radial size of the transverse dispersion zone can be up to 40 ft away from a well.
- A simplified macroscopic mathematical model has been derived. The model defines a transverse dispersion coefficient and a method for computing its value from experiments.
- A microscopic fluid-grain-collision model has been formulated and described mathematically using principles of momentum balance for a single grain collision. The model explains the mechanism of water transfer to oil.
- Transverse dispersion has been verified in flow experiments with a granular-pack cell. The results show that the intensity of transverse dispersion is a function of flow velocity (pressure gradient), fluids' viscosity contrast, and grain size (pore structure) of the porous media.

4. References and Bibliography

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Author Biographies

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Dr. Andrew K. Wojtanowicz, Texaco Environmental Chair in the Craft and Hawkins Petroleum Engineering Department at Louisiana State University, is presently a Visiting Distinguished Professor of Petroleum Engineering at The Petroleum Institute in Abu Dhabi, U.A.E. Over his academic career, he has been on the faculty of the New Mexico Institute of Mining and Technology and the AGH University of Science and Technology in Krakow, Poland. A UN expert in drilling engineering, Dr. Wojtanowicz has also worked as a drilling engineer, drilling supervisor, and drilling fluids technologist in Europe and Africa. He holds a M.S. degree in mining/petroleum engineering, and Ph.D. and D.Sc. degrees in petroleum engineering from the AGH University of Science and Technology. Dr. Wojtanowicz studies have been reported in 182 publications and six books. Since 1997, Dr. Wojtanowicz has directed a Joint Industry Project (JIP) concerning R&D and field implementation of smart well completions for downhole water control. He has also served as the 2003-04 SPE Distinguished Lecturer of the Downhole Water Separation technology, received the SPE Health Environment and Safety Award in 2003, the SPE Distinguished Achievement for Petroleum Engineering Faculty Award in 2008, and has served as the Editor-in Chief of ASME Transactions, Journal of Energy Resources Technology since 2000.