

Modeling of Non-equilibrium Effects in the Gravity Driven Countercurrent Imbibition

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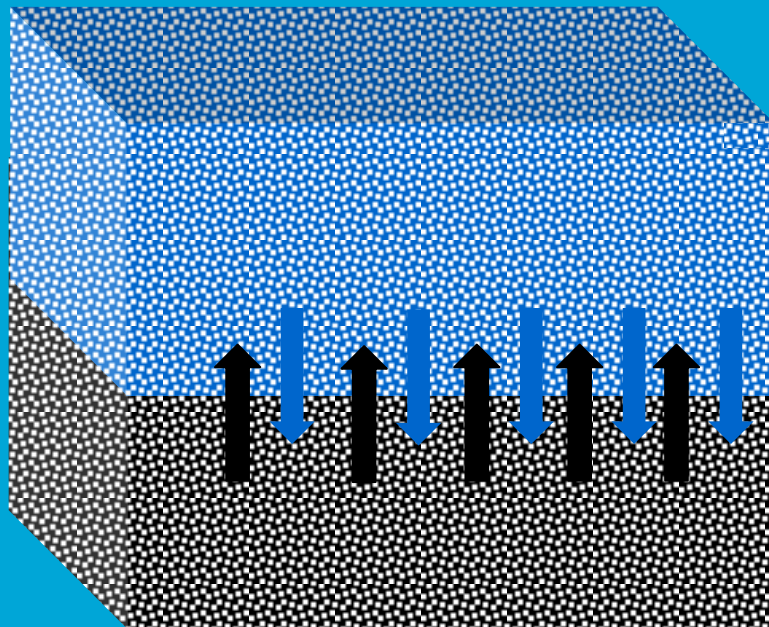
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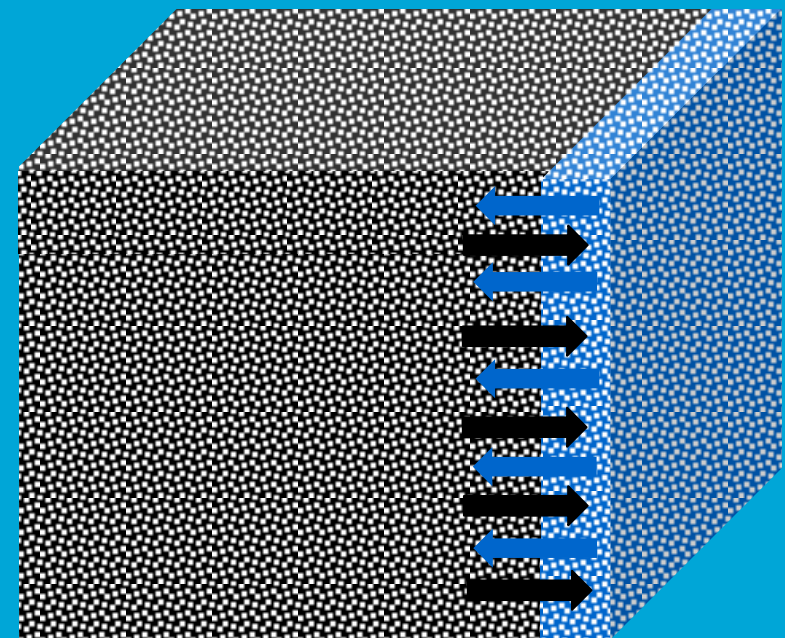
Introduction

- Countercurrent flow is an important mechanism in Fractured oil Reservoirs and secondary migration into reservoirs



Migration

Oil 

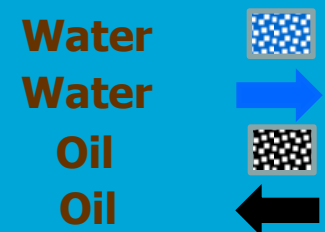
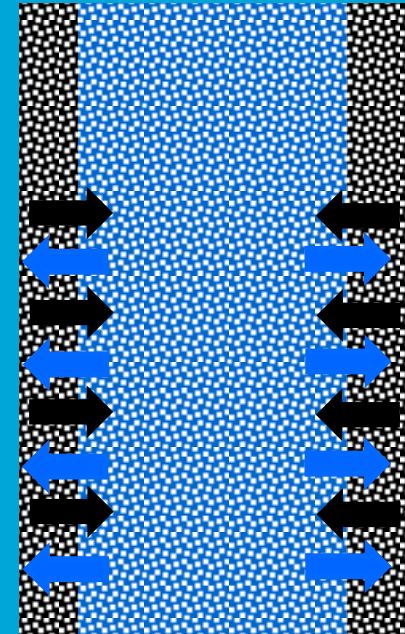


Enhanced oil recovery in FR

Water 

Introduction

- Conventional theories for multiphase immiscible fluid flow in porous media are established based on instantaneous equilibrium of phases.
- After displacement phases are not redistributed instantaneously.
- A non-equilibrium approach for capillary imbibition was developed by Barenblatt et al. (2003)



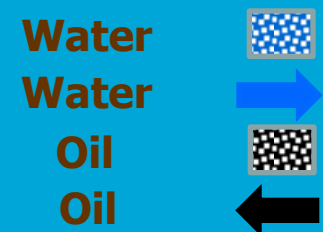
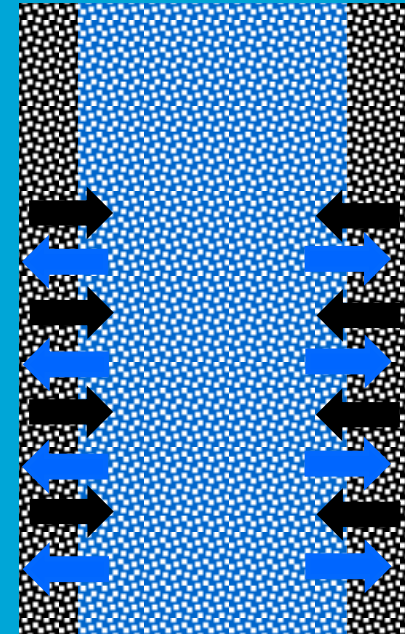
Barenblatt proposed

- The same constitutive relations (rel-perm + capillary pressure), but now with a dynamic saturation

$$\eta_w(z, t) = S_w(z, t) + \tau \frac{\partial S_w(z, t)}{\partial t}$$

instead of the static saturation S_w

- Example application for modeling of a gravity dominated fluid flow problem in porous media



Mathematical Model; classical description with stationary saturation

$$a^2 \frac{\partial}{\partial z} \left(f_w(S_w(z, t)) k_{ro}(S_w(z, t)) \frac{\partial J(S_w(z, t))}{\partial z} \right) - b^2 \frac{\partial}{\partial z} (f_w(S_w(z, t)) k_{ro}(S_w(z, t))) = - \frac{\partial S_w(z, t)}{\partial t}$$

$$a^2 = \frac{\sigma}{\mu_o} \sqrt{\frac{k}{\varphi}}$$

$$b^2 = \frac{\Delta \rho g k}{\varphi \mu_o}$$

Mathematical Model; non-equilibrium Model, effective water saturation, η_w

Nonlinear system of equations: time dependent model

$$\frac{\partial \eta_w(z, t)}{\partial t} + a^2 \frac{\partial}{\partial z} \left(\frac{\partial \phi(\eta_w(z, t))}{\partial z} + \tau \frac{\partial \phi(\eta_w(z, t))}{\partial t} \right) - b^2 \left(\frac{\partial \psi(\eta_w(z, t))}{\partial z} + \tau \frac{\partial \psi(\eta_w(z, t))}{\partial t} \right) = 0$$

Mathematical Model

Initial condition:

nonlinear system of equations: stationary model

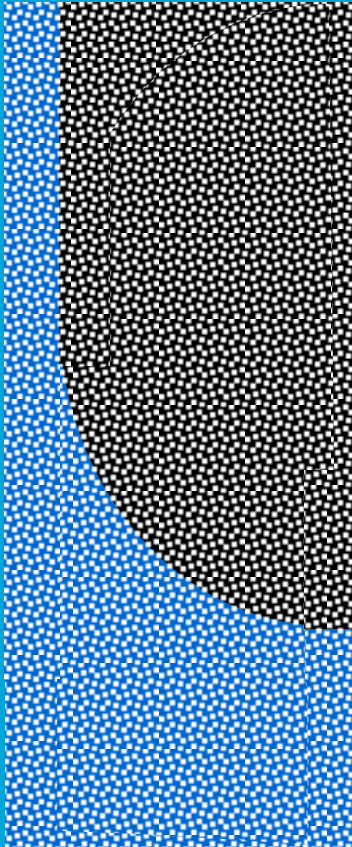
$$\eta_w^0(z) + \tau \frac{\partial}{\partial z} (a^2 \phi(\eta_w^0(z)) - b^2 \psi(\eta_w^0(z))) = S_w^0(z)$$

$$\phi(\eta_w(z, t)) = \int_0^{\eta_w(z, t)} f_w(u) k_{ro}(u) J'(u)$$

$$\psi(\eta_w(z, t)) = f_w(\eta_w(z, t)) k_{ro}(\eta_w(z, t))$$

Case study:

Initial distribution of phases

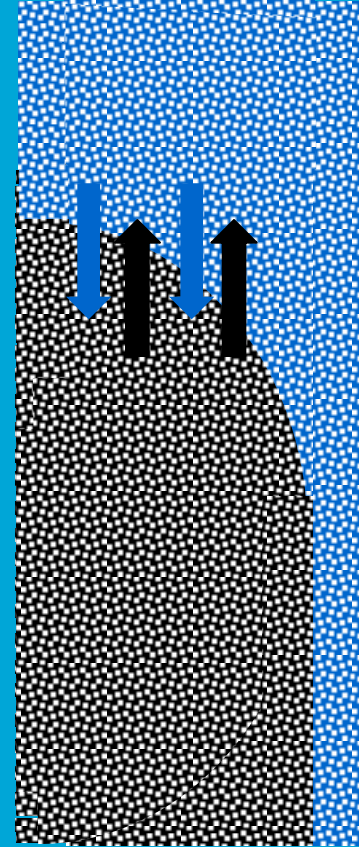


Water 
Oil 



**A guaranteed
countercurrent
imbibition process**

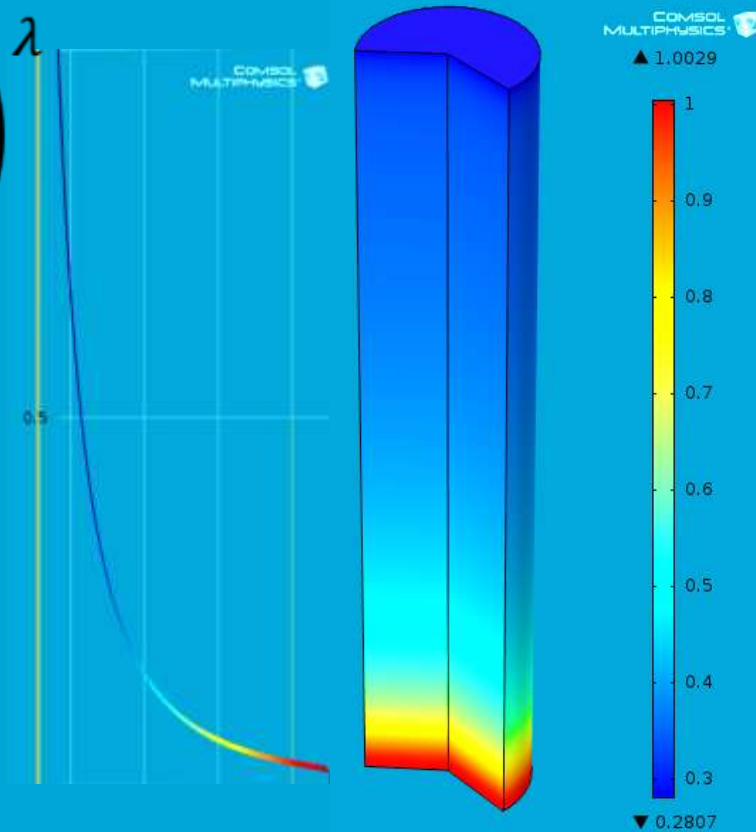
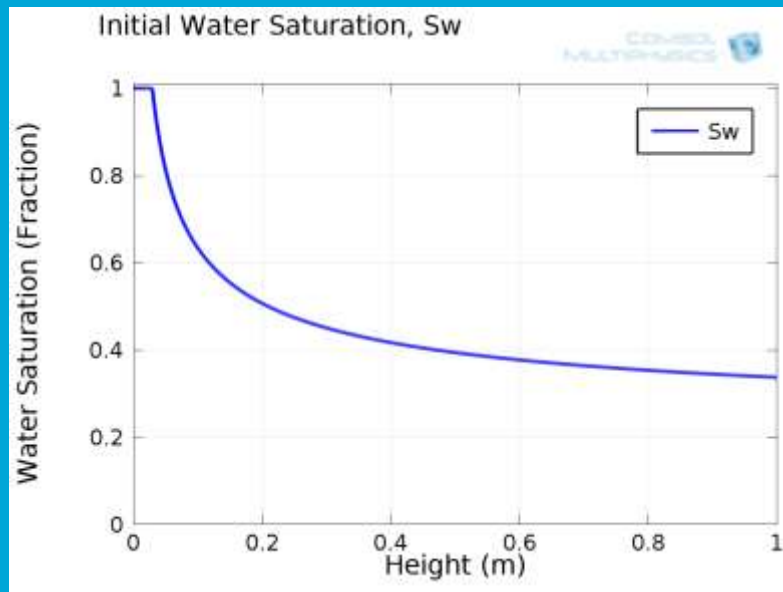
**Turning the core
180 degree,
vertically**



Initial distribution of static saturation, S_w

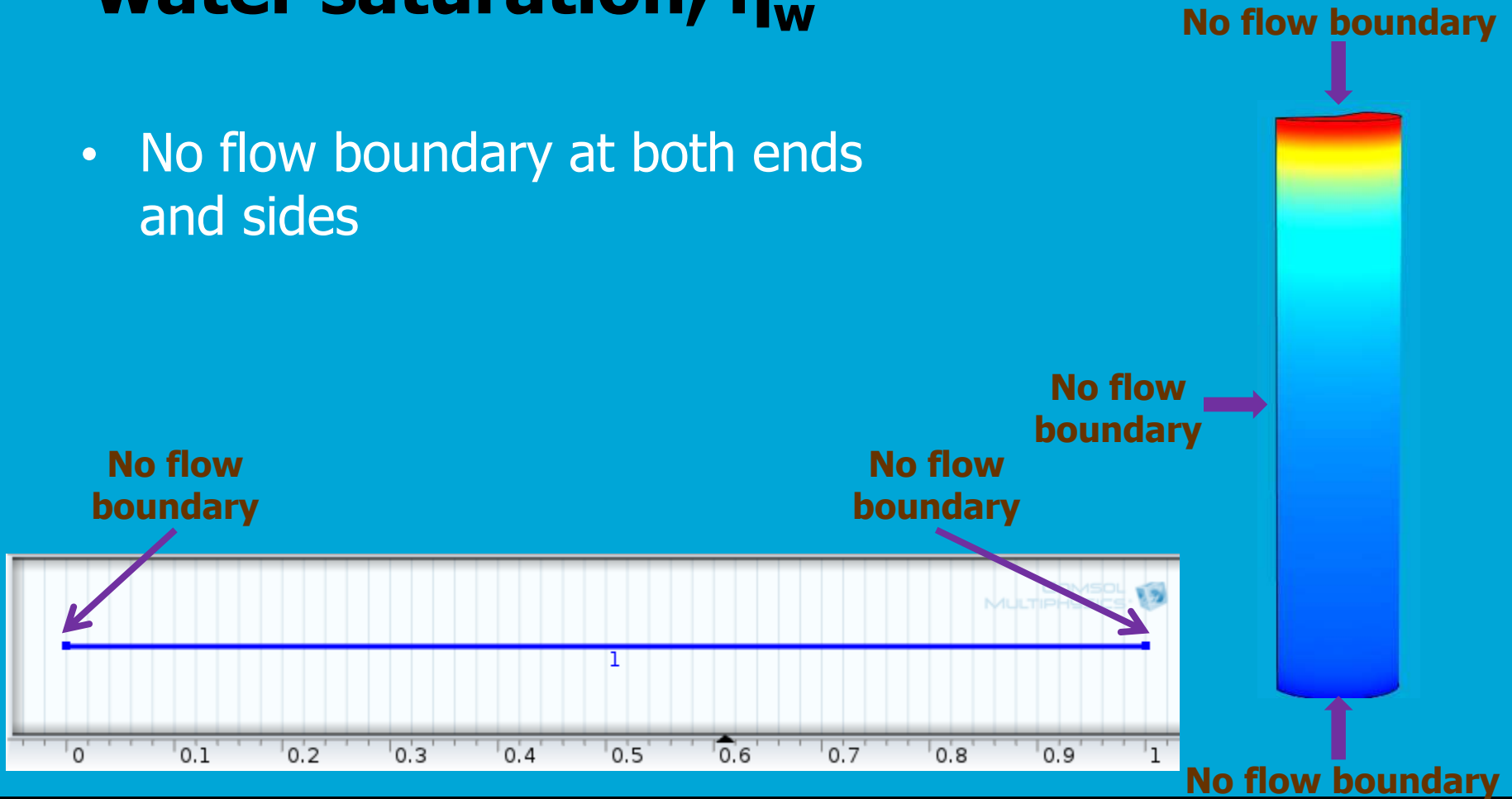
Gravity-capillary equilibrium for initial current saturation, S_w

$$S_w^0(z, t) = S_{wc} + \left(\frac{1}{2} - S_{wc} \right) \left(\frac{a^2}{b^2 z} \right)^\lambda$$



Boundary condition for effective water saturation, η_w

- No flow boundary at both ends and sides



Equation-based modelling

- Weak Form PDE, including a very small artificial diffusion coefficient

▼ Weak Expressions

weak $(\tau \cdot (a^2 \cdot d\phi(u) \cdot u_x - b^2 \cdot f_{wkro}(u))) \cdot test(u)$

▼ Weak Expressions

weak $(u^2 \cdot test(u^2) - (a^2 \cdot (d\phi(u^2) \cdot u^2_x + \tau \cdot d(d$

Equation-based modelling

- Study 2(eta)
 - Step 1: Time Dependent
 - Solver Configurations
 - Solver 2
 - $\frac{\partial u}{\partial t}$ Compile Equations: Time Dependent
 - u,v,w Dependent Variables 1
 - Time-Dependent Solver 1
 - Direct
 - Advanced
 - Fully Coupled 1

General

Defined by study step: User defined

Initial Values of Variables Solved For

Method: Initial expression

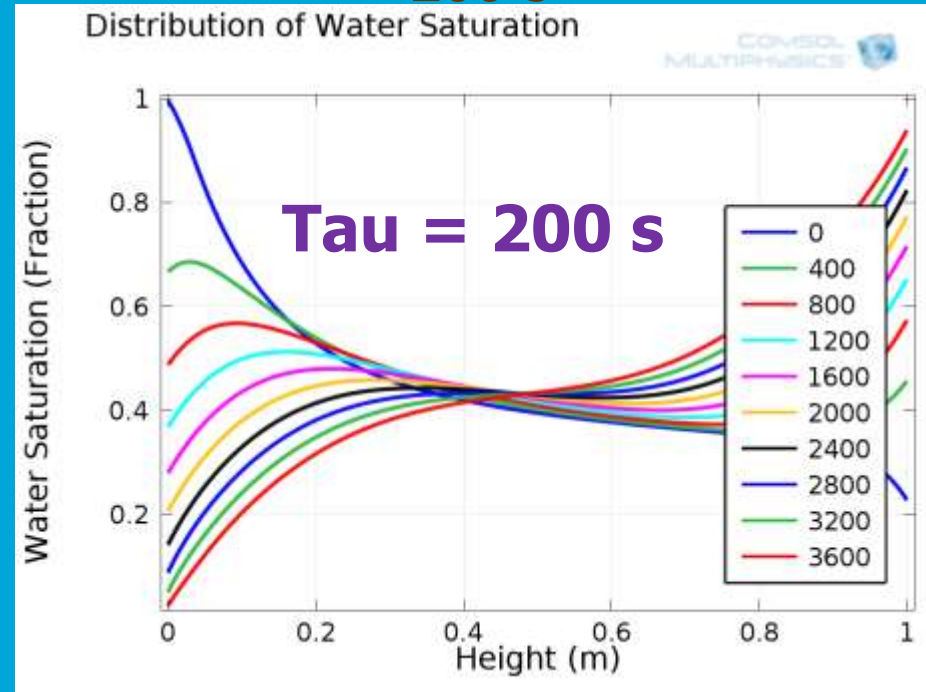
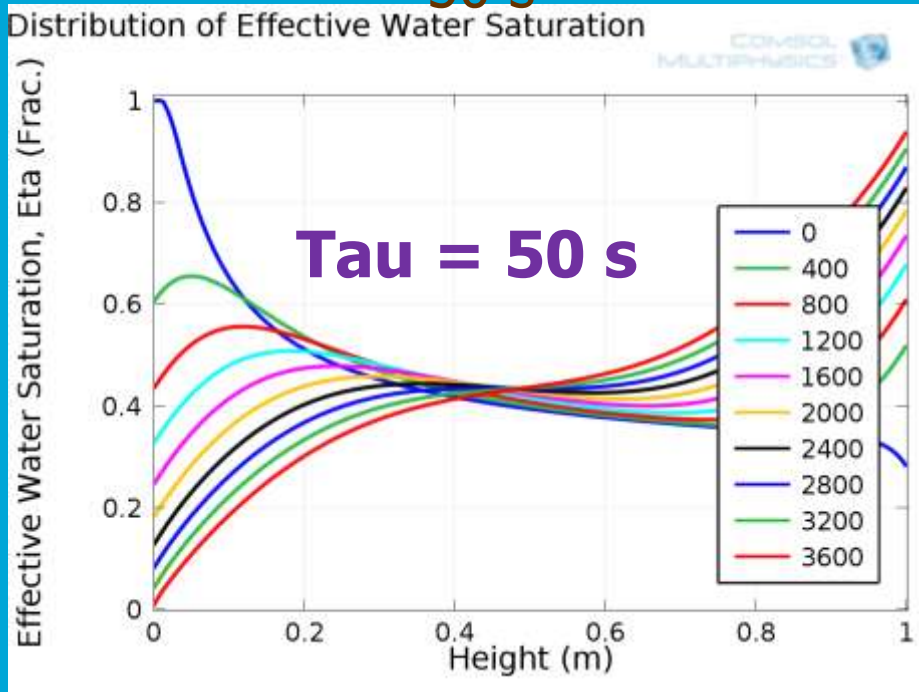
Solution: Solver 1

Time: Automatic

Results

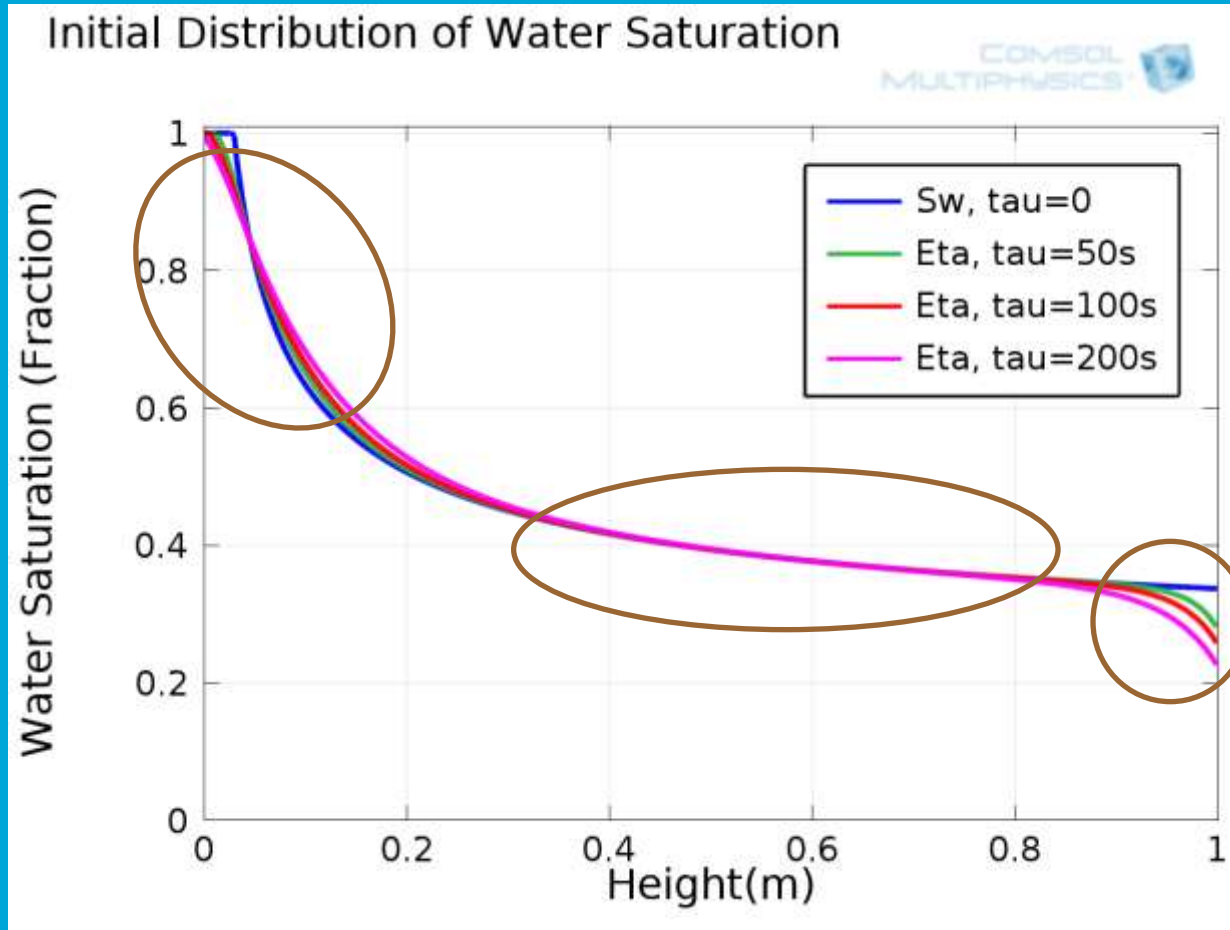
Distribution of effective water saturation with relaxation time of 50 s

Distribution of effective water saturation with relaxation time of 200 s



Results:

initial distribution differs for different relaxation time



Conclusion

- The procedure can be used as a basis for quantifying recovery from fractured media
- This formulation can be used for both capillary and gravity dominated enhanced oil recovery processes like ultra-low IFT method.
- Developing a relaxation time as a function of saturation rate may improve the model.

Thanks for your attention

