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Calculation of Graded Viscosity Banks Profile on the Rear End of The Polymer Slug

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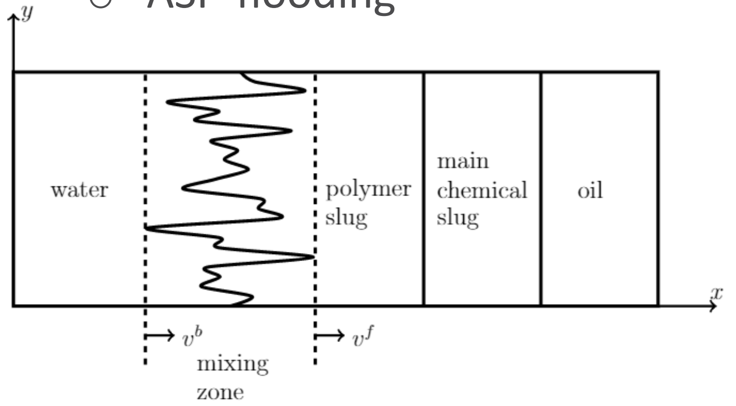
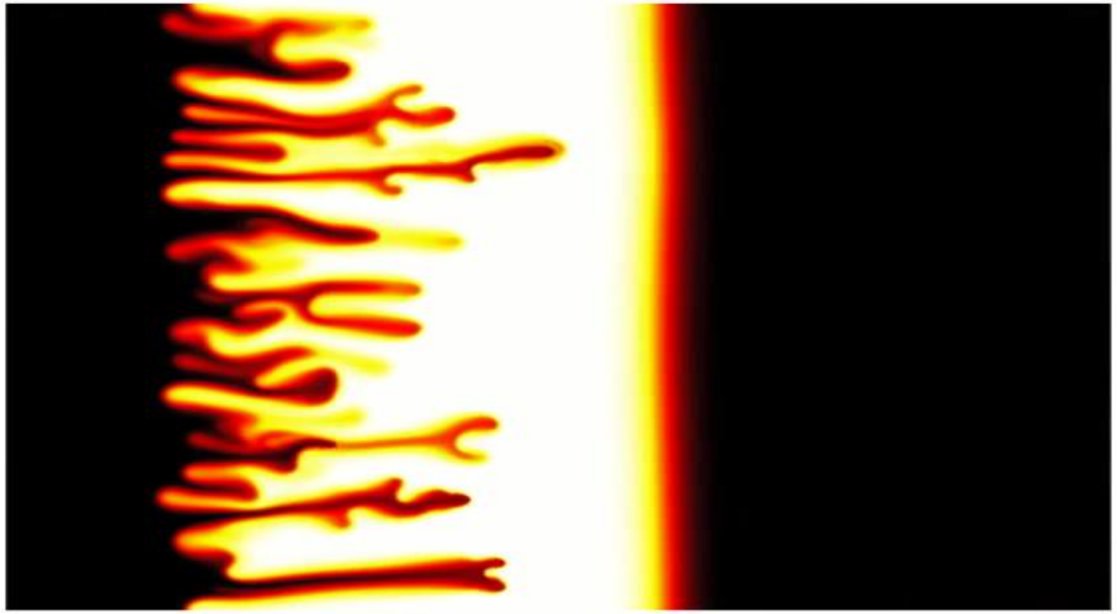
Breakthrough of polymer slug

- Chemical EOR:
  - Polymer flooding
  - Surfactant flooding
  - ASP-flooding



- Homogeneous porous media
- Instability occur due to different viscosities (viscous fingering effect)
- After the breakthrough of the polymer slug the positive effect decreases

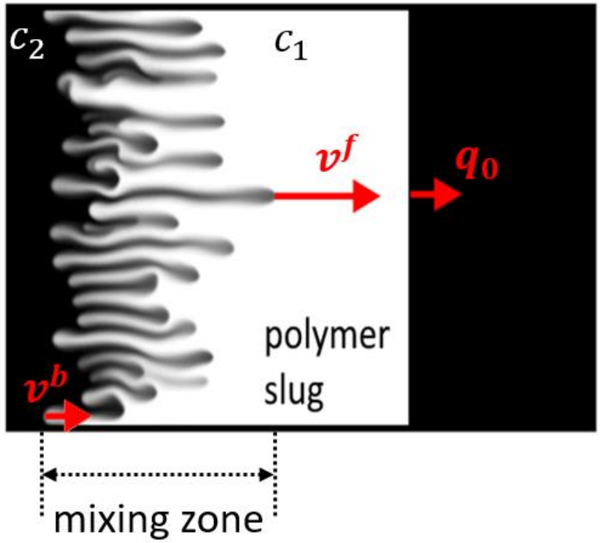


Questions:

What size of polymer slug?

How to reduce amount of polymer?

Velocities of the mixing zone



How to determine the velocity of the mixing zone?

- Development and implementation of an oil-field experiment
- Laboratory tests
- Numerical simulation
- Analytical expressions

q_0 – Velocity of the stable front. Take $q_0 = 1$

v^f – Velocity of the front end of the mixing zone is constant [1]

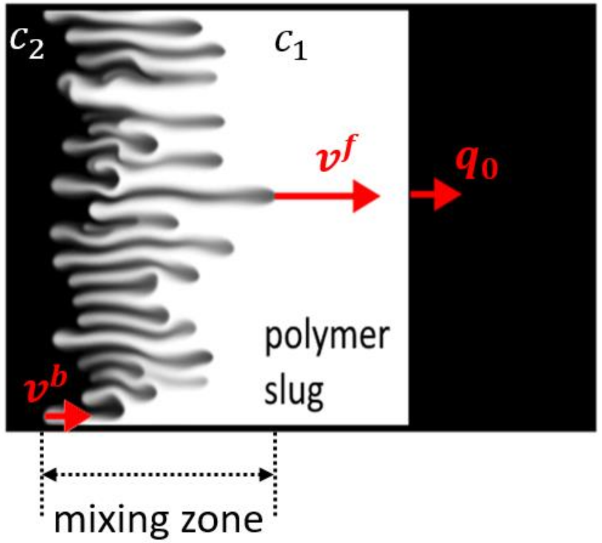
v^b – Velocity of the rear end of the mixing zone is constant [1]

c_1 – concentration of injected polymer
c_2 – decreased concentration of injected polymer
(for one slug $c_2 = 0$ – injection of water)

- v^f is a function of $M = \frac{\mu(c_1)}{\mu(c_2)}$ or the curve $\mu(c)$

[1] *Nijjer, J.S., Hewitt, D.R. and Neufeld, J.A., 2018. The dynamics of miscible viscous fingering from onset to shutdown*

Velocities of the mixing zone



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Empirical models of velocities

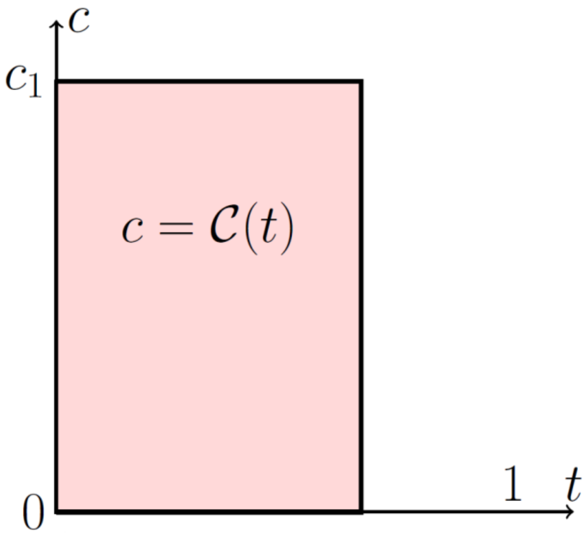
Koval	$v^f = M_e \qquad v^b = \dfrac{1}{M_e} \qquad M_e = \left(\alpha \cdot M^{\frac{1}{4}} + (1-\alpha)\right)^4$
Todd-Longstaff	$v^f = M_e \qquad v^b = \dfrac{1}{M_e} \qquad M_e = M^{\omega}$
TFE	$v^f \le \dfrac{\overline{m}(c_1, c_2)}{m(c_2)}, \qquad v^b \ge \dfrac{v^f}{M}, \qquad m(c) = \dfrac{1}{\mu(c)}, \overline{m}(c_1, c_2) = \dfrac{\int_{c_1}^{c_2} m(c)}{c_2 - c_1}$

- Averaging - “effective viscosity” M_e:
  - Koval (1963)
  - Todd-Longstaff (1972)
- Transverse Flow Equilibrium (TFE)
  Otto-Menon, Yortsos-Salin (2006)
  - $p(x, y) = p(x)$

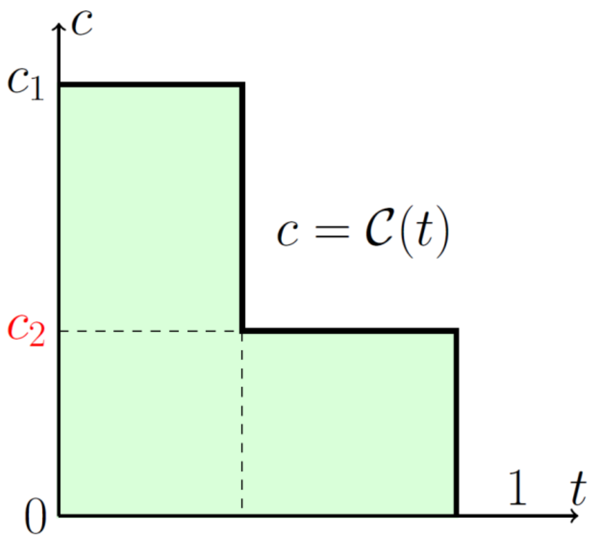
  $M = \dfrac{\mu(c_1)}{\mu(c_2)} > 1 -$ viscosity ratio

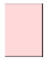
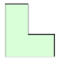
Main idea

Injecting two slugs may give gain in polymer mass (Claridge, 1978)



Add concentration c_2



V  $>$ V 

Problem Statement

- Goal: reduce amount of polymer
- Strategy: graded viscosity banks (GVB, tapering) Claridge (1978)

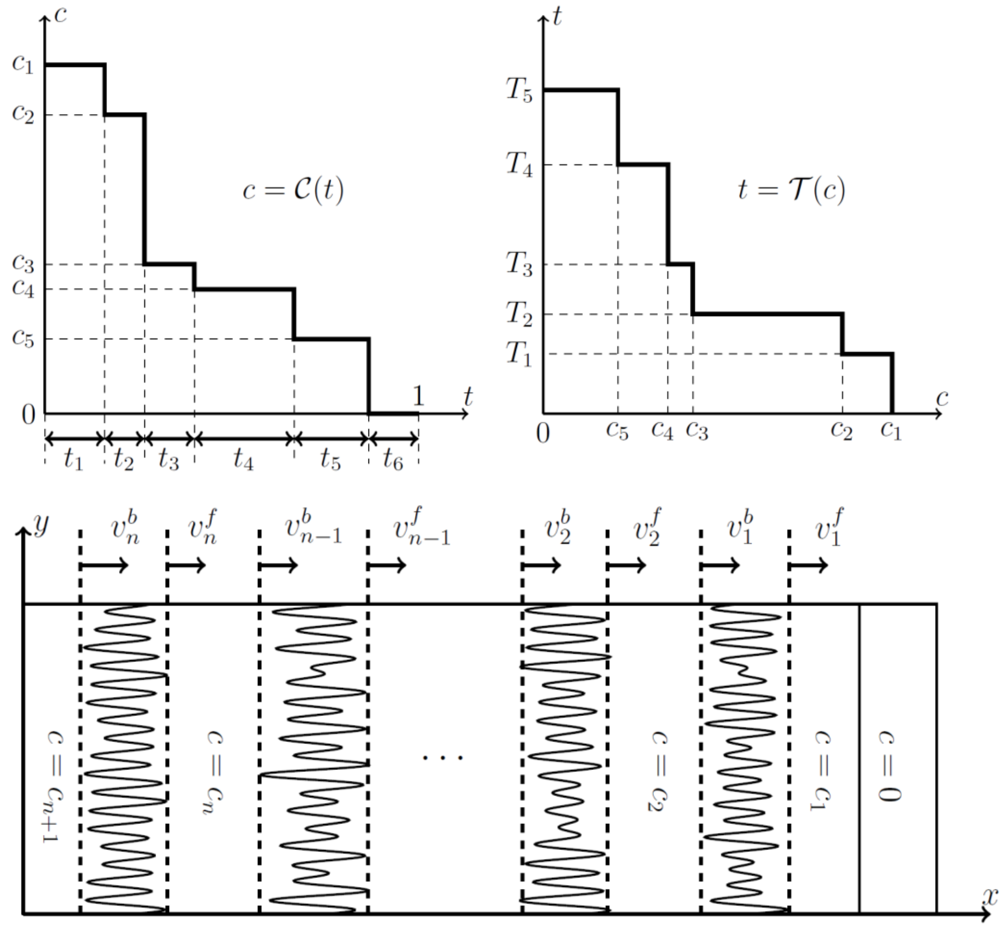
- We want no breakthrough in any slug

- Given concentrations c_n and v^b, v^f we can find sizes of slugs t_n without breakthrough

- Choose concentrations c_n to minimize amount of polymer

$$\mathrm{V_n} = \sum_{i=1}^{n} c_i t_i \to \min$$

- Questions:
  - n – finite ($n = 2, 3, 5$)
  - $n \to \infty$



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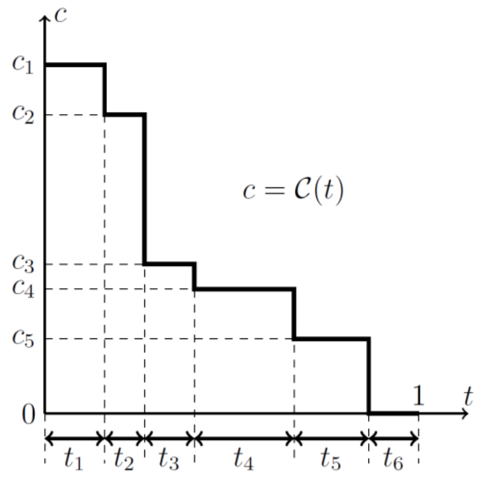
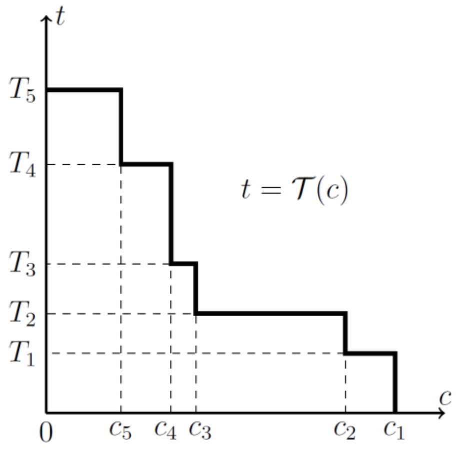
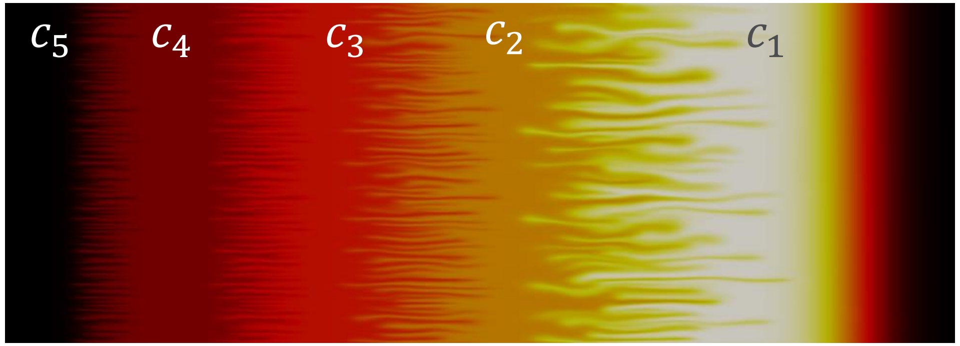




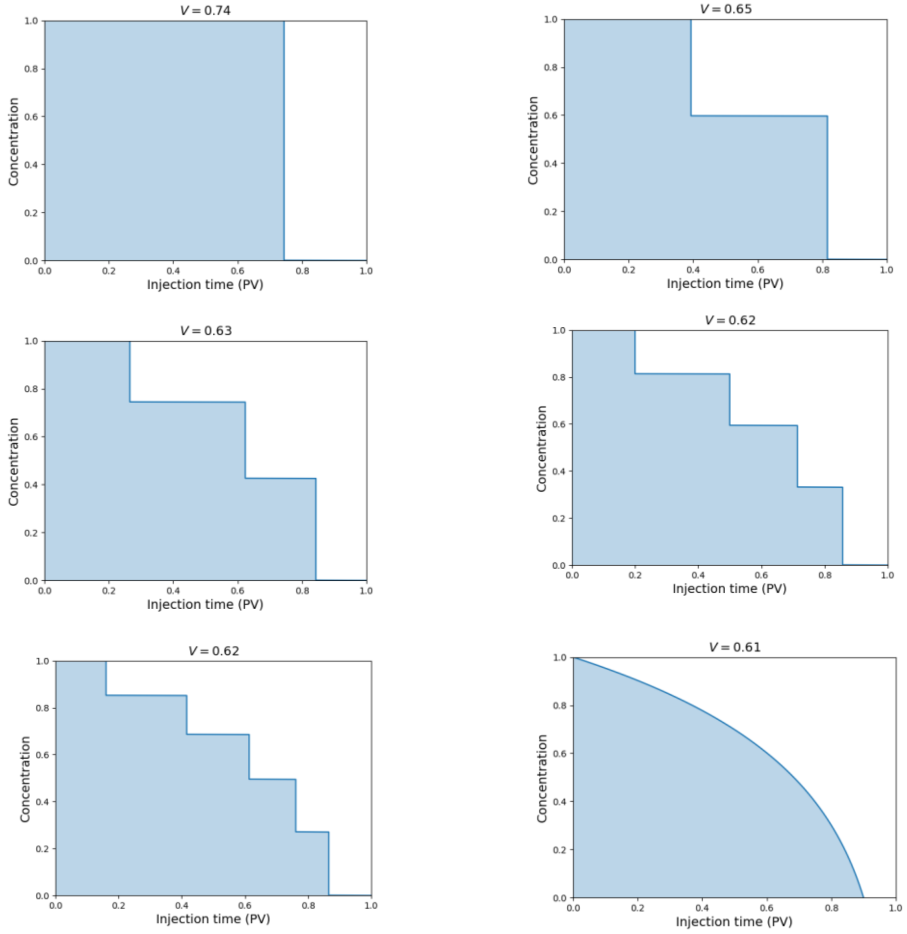


Simulation of GVB in DuMuX

Design for concrete polymer

Polymer viscosity: $\mu(c) = 0.3\exp(\alpha c)$, $\mathrm{M} = 10$

	Optimal concentrations	Optimal injection times (PV)
$n = 1$	$c = 1$	$t = 0.74$
$n = 2$	$c = 1, 0.6$	$t = 0.39, 0.42$
$n = 3$	$c = 1, 0.75, 0.43$	$t = 0.27, 0.36, 0.22$
$n = 4$	$c = 1, 0.81, 0.6, 0.33$	$t = 0.2, 0.3, 0.21, 0.14$
$n = 5$	$c = 1, 0.85, 0.69, 0.5, 0.27$	$t = 0.16, 0.26, 0.2, 0.15, 0,1$



Results for small n

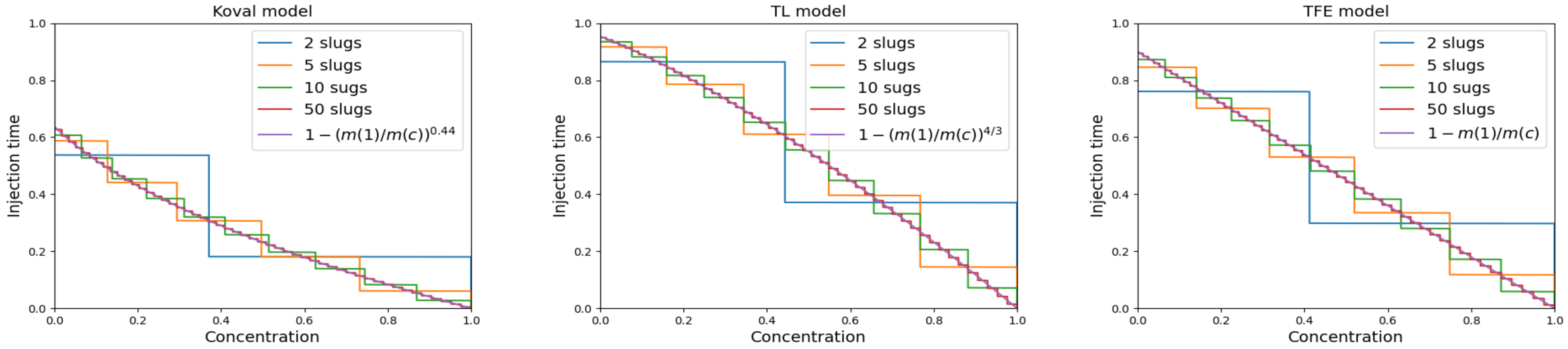
V_n - polymer mass for n slugs

$\eta = \frac{V_1 - V_n}{V_1}$ - percentage of gain in polymer mass

for polymer viscosity: $\mu(c) = 0.3(1+\alpha c)^2, \mathrm{M} = 10$

	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 10$	Limit
Koval	23, 4%	28, 1%	29, 9%	30, 9%	32, 4%	33, 5 %
Todd-Longstaff	17, 0 %	20, 1 %	21, 2 %	21, 7 %	22, 4 %	22, 6 %
TFE	17, 1%	20, 3%	21, 4%	21, 9%	22, 6%	22, 8 %

- Conclusion: in practice it is enough to use 2-3 slugs



Graded viscosity banks: $n \to \infty$

Theorem [Bakharev, Enin, Kalinin, Petrova., Rastegaev, Tikhomirov, 2021: arxiv:2012.03114]

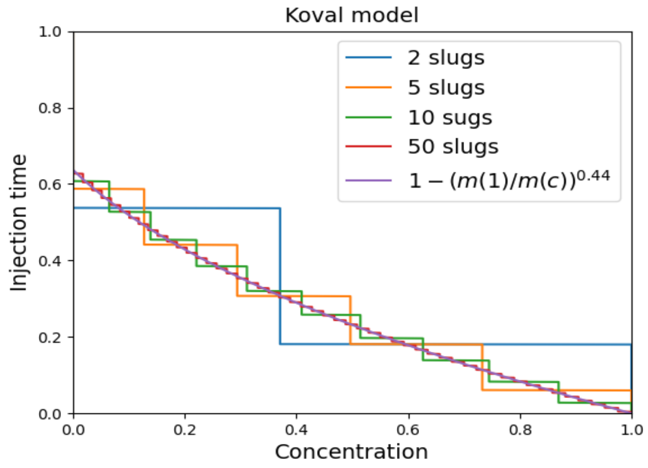
As $n \to \infty$ the optimal limiting injection profile

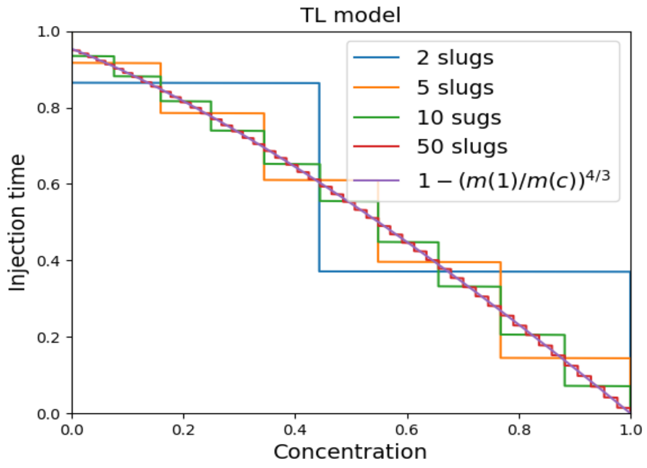
$$T^{\infty}(c) = 1 - \left(\frac{\mu(c)}{\mu(c_1)}\right)^{\beta}$$

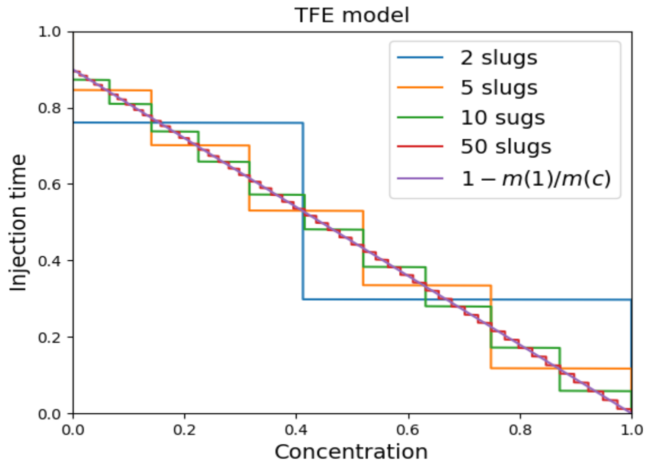
Koval: $\beta = 2\alpha$

Todd-Longstaff: $\beta = 2\omega$

TFE: $\beta = 1$





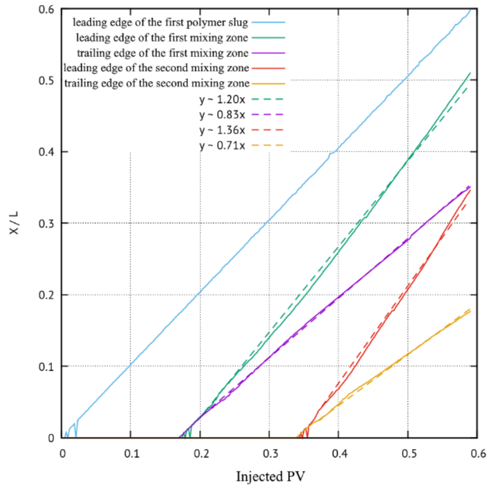


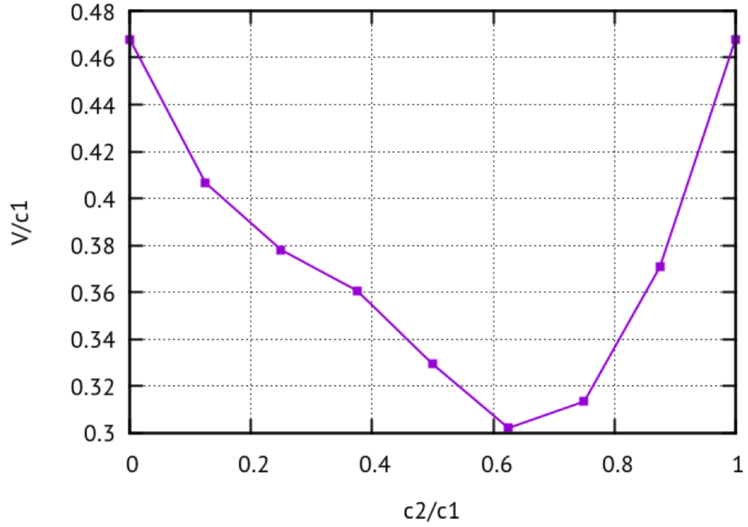
Numerical validation of graded viscosity banks

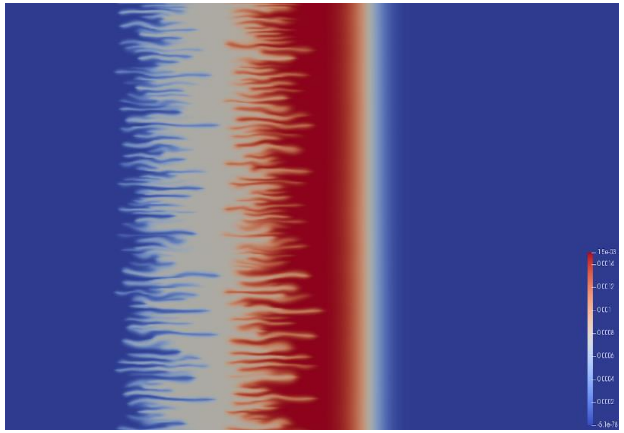
- Simulations in DuMuX, 2 slugs
  Instabilities are initiated by small inhomogeneity
- Velocities are taken from simulations

Theoretical assumptions that need to be validated:

- the velocities of the mixing zones edges remain constant even in the case of the presence of several slugs;
- the velocities of the mixing zones edges do not depend on the presence of additional slugs, on the sizes of the slugs and on the size of the modeling area;







TFE model. Taking into account adsorption

For TFE model one can include **adsorption** into the model

$$v^f \leq q_0 \cdot \frac{\int_{c_2}^{c_1} m(c)\,dc}{m(c_1)} \cdot \frac{1}{1 + a'(c_1)}$$
$$v^b \geq q_0 \cdot \frac{\int_{c_2}^{c_1} m(c)\,dc}{m(c_2)} \cdot \frac{1}{1 + a'(c_2)}$$

$a(c)$ – adsorption function: $a(c) = \frac{(1-\varphi)}{\varphi} \cdot \frac{\rho_s}{\rho_w} \cdot \Gamma(c)$

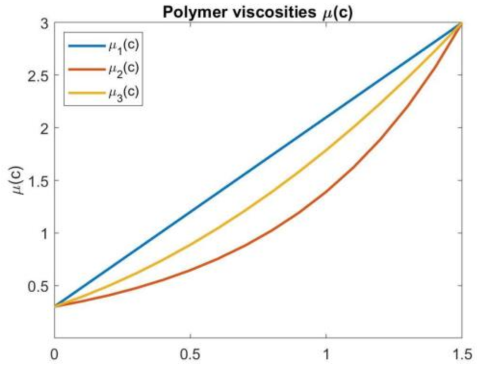
φ – porosity,

ρ_w – water density, ρ_s – soil density,

$\Gamma(c)$ – adsorption isotherm (e.g. Langmuir)

V_n - polymer mass for n slugs

$\eta = \frac{V_1 - V_n}{V_1}$ - percentage of gain in polymer mass



	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 10$
$\mu_1(c)$	7,5%	8,8%	9,3%	9,5%	9,8%
$\mu_2(c)$	6,9%	8,2%	8,7%	8,9%	9,1%
$\mu_3(c)$	5,7%	6,8%	7,2%	7,4%	7,7%

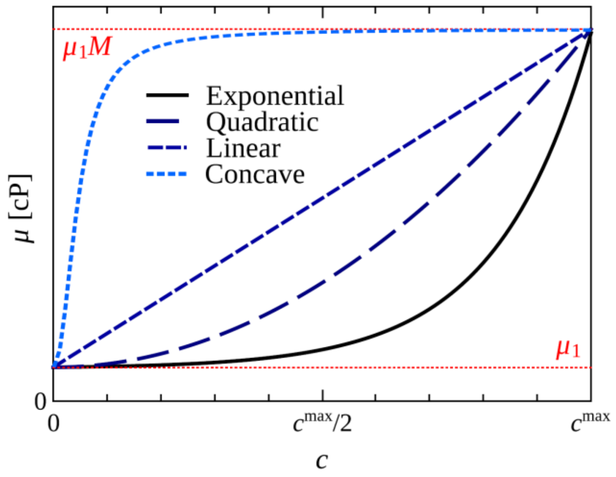
TFE model – always pessimistic?

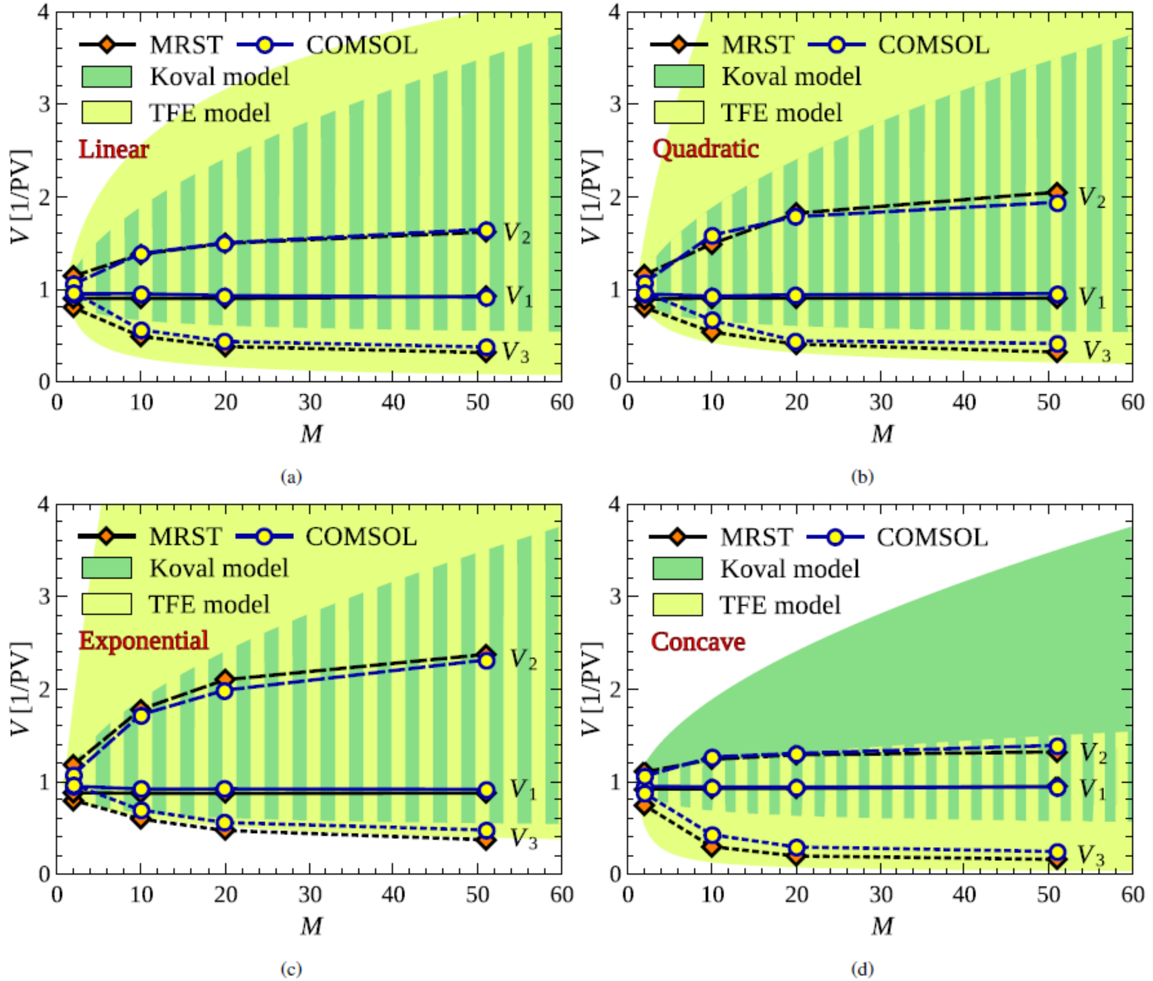
- Numerical validation of TFE model:
  for different viscosity curves:
  always gives a pessimistic estimate

- Koval model not always gives a pessimistic estimate

- Examples when TFE model is exact:

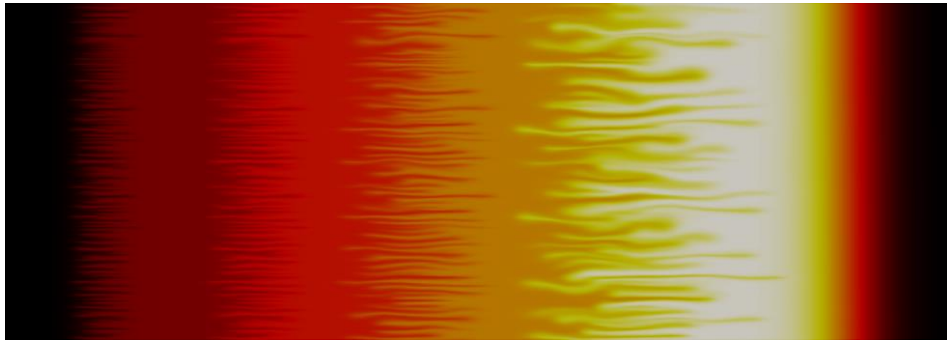
Exponential viscosity – at the rear end
Concave viscosity – at the front end





Conclusions

1. Graded viscosity banks helps to reduce polymer mass with the same efficiency
2. In practice it is enough to inject 2-3 slugs
3. The choice of model for “finger velocities ” is an open problem – no rigorous results – TFE model looks promising
4. Advantages of suggested method
   - Limiting profile is determined by formula
   - No complex computations are needed
   - TFE model allows to take into account viscosity curve and adsorption



Thank you very much for your attention!