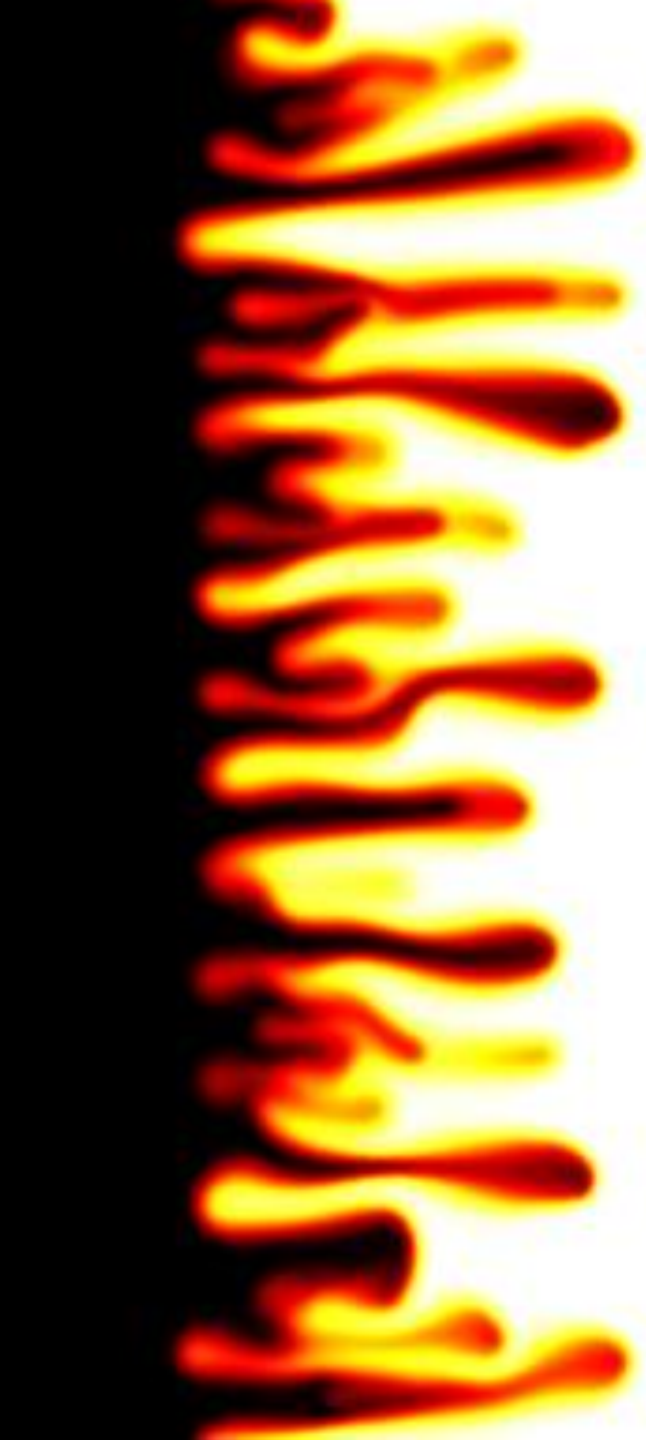


Graded viscosity banks on the rear end of the polymer slug

Yulia Petrova[1,2]

[1] Saint-Petersburg State University, Russia
Faculty of Mathematics and Computer Science

[2] IMPA, Instituto de Matematica Pura e Aplicada, Brazil

1 June 2021

Joint work with F. Bakharev, A. Enin,
K. Kalinin, N. Rastegaev, S. Tikhomirov

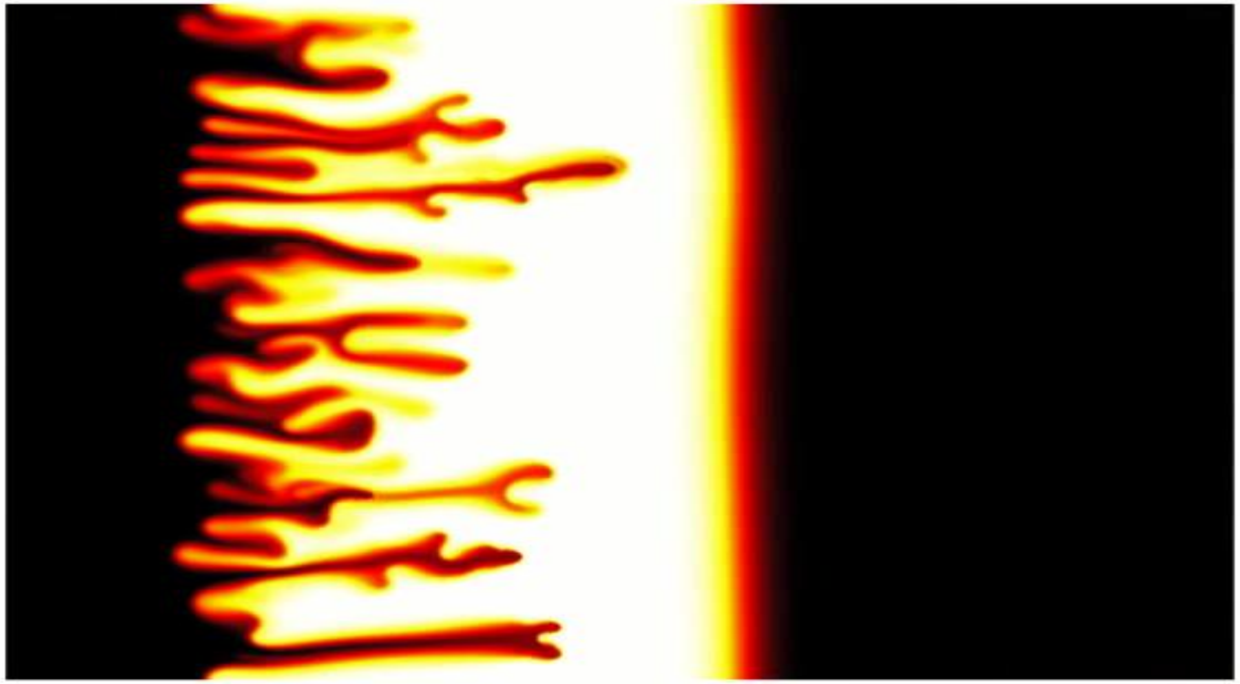
InterPore2021 Online

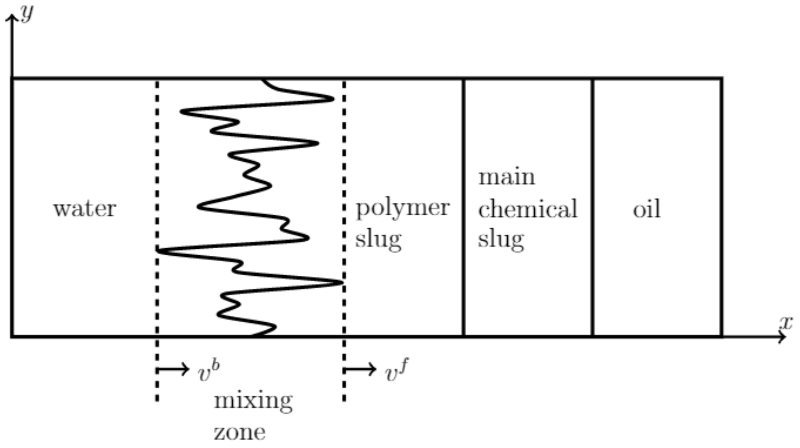
Supported by
GAZPROM NEFT
RSF Russian Science Foundation

Breakthrough of polymer slug

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

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





Question: what size of polymer slug?

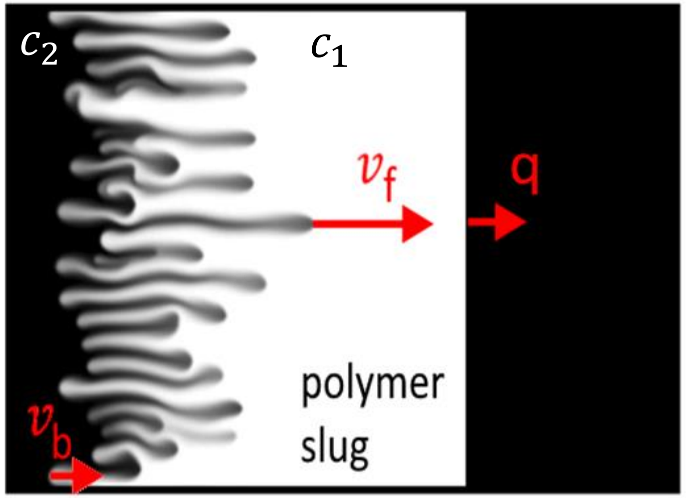
Mathematical models

- One-phase miscible displacement (Peaceman model)

$$c_t + u \cdot \nabla c = \varepsilon \, \Delta c$$
$$div\, u = 0$$
$$u = -\frac{k}{\mu(c)} \nabla p$$

c – polymer concentration

$\mu(c)$ – water viscosity



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

v_f – Velocity of the front end of the mixing zone is constant

v_b – Velocity of the rear end of the mixing zone is constant

Empirical models of velocities

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

$M = \frac{\mu(c_1)}{\mu(c_2)} > 1$ – ratio of viscosities

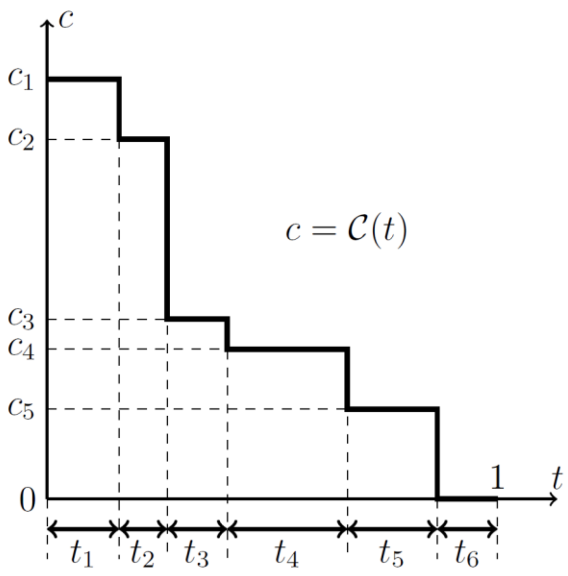
Koval	$v_f = M_e \quad v_b = \frac{1}{M_e} \quad M_e = \left(\alpha \cdot M^{\frac{1}{4}} + (1-\alpha)\right)^4$
Todd-Longstaff	$v_f = M_e \quad v_b = \frac{1}{M_e} \quad M_e = M^{\omega}$
TFE	$v_f \le \frac{\overline{m}(c_1, c_2)}{m(c_2)} \quad v_b \ge \frac{v_f}{M} \quad m(c) = 1/\mu(c)$

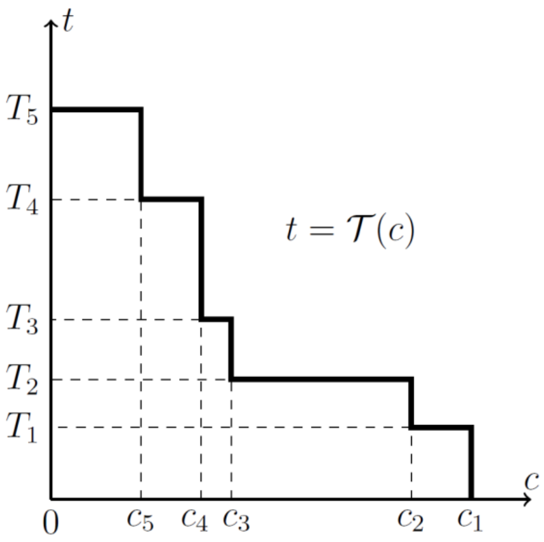
Problem Statement

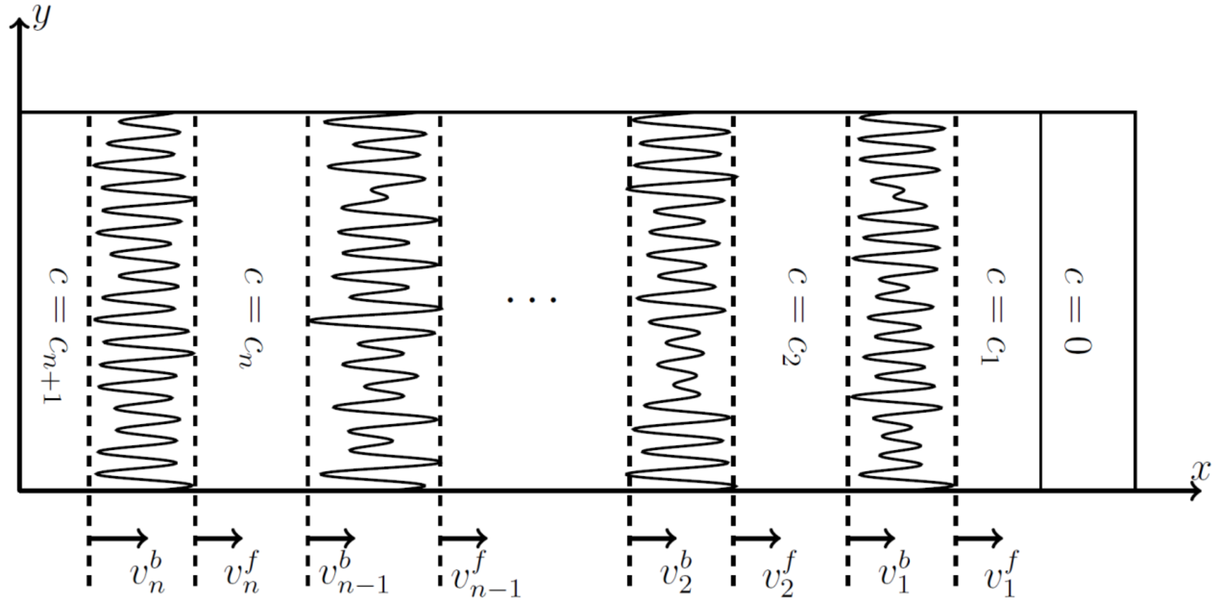
- Goal: reduce amount of polymer
- Strategy: graded viscosity banks (GVB, tapering) Claridge (1978)
- We want no breakthrough in any slug
- Given concentrations c_n and v_b, v_f we can find sizes of slugs t_n without breakthrough
- Choose concentrations c_n to minimize amount of polymer

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

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







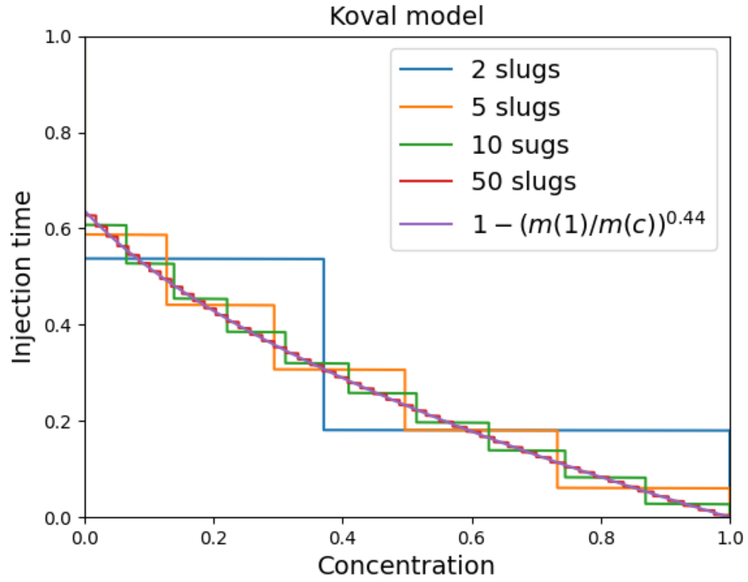
Results for small n

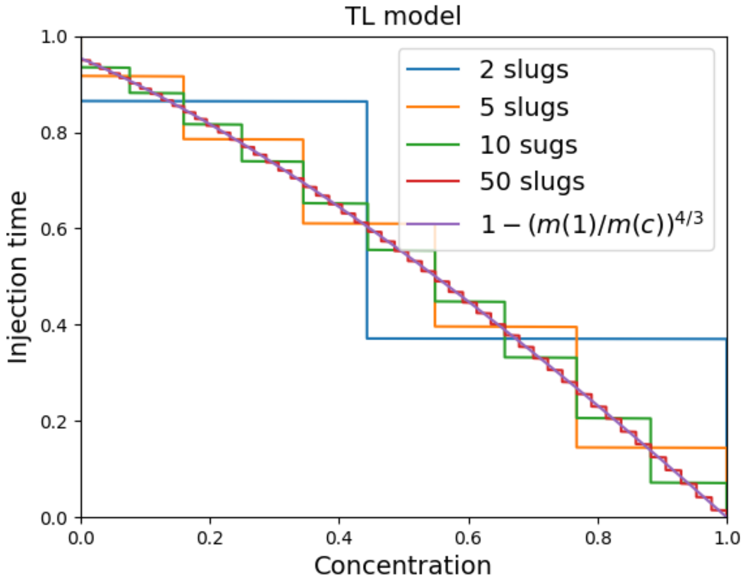
V_n - polymer mass for n slugs

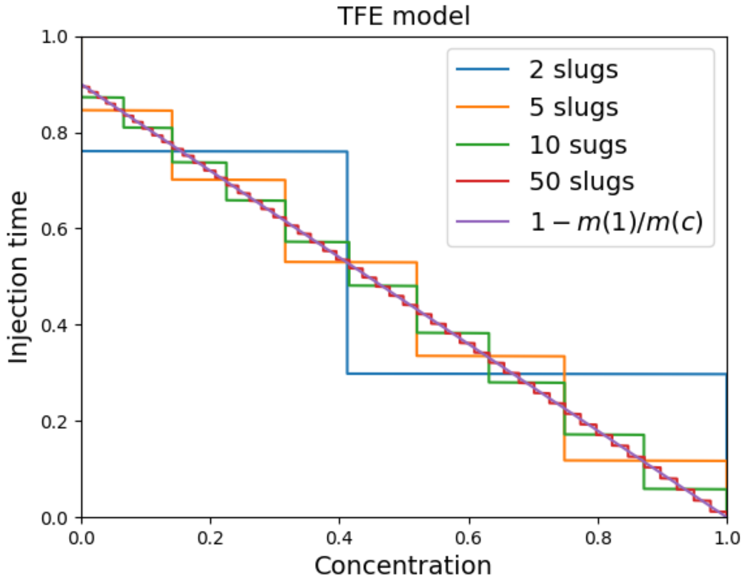
$\eta = \frac{V_1 - V_n}{V_1}$ - percentage of gain in polymer mass

	n = 2	n = 3	n = 4	n = 5	n = 10	Limit
TFE	19,83%	23,35%	24,57%	25,13%	25,88%	26,12%
Todd-Longstaff	24,84%	29,36%	30,93%	31,66%	32,63%	32,95%
Koval	33,21%	39,24%	41,46%	42,55%	44,24%	45,28%

- Conclusion: in practice it is enough to use 2-3 slugs
- For detailes see arxiv:2012.03114







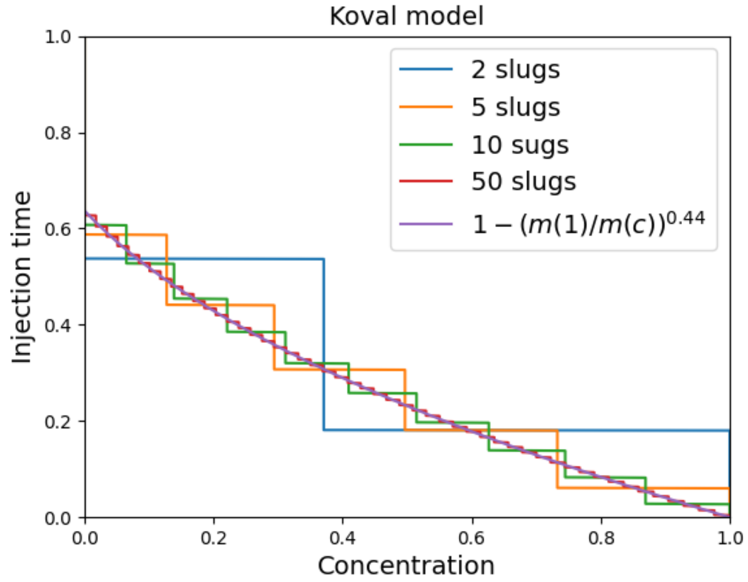
Graded viscosity banks: $n \to \infty$

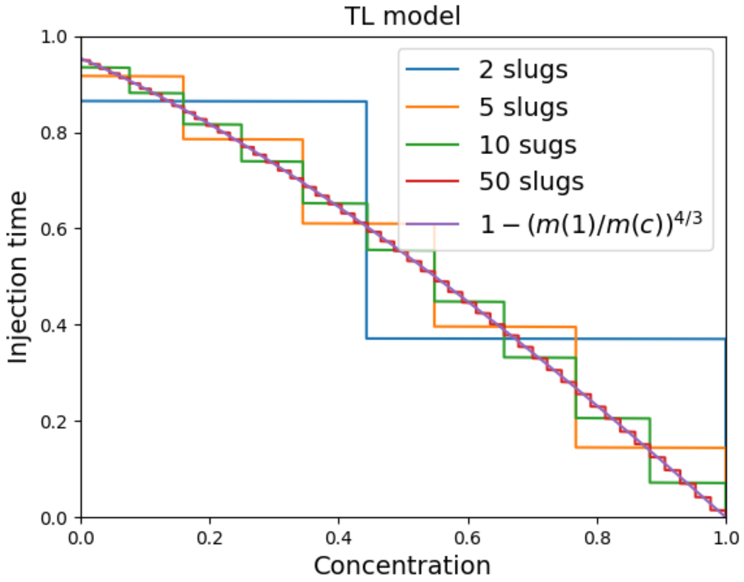
Theorem [Bakharev, Enin, Kalinin, P., Rastegaev, Tikhomirov, 2021]

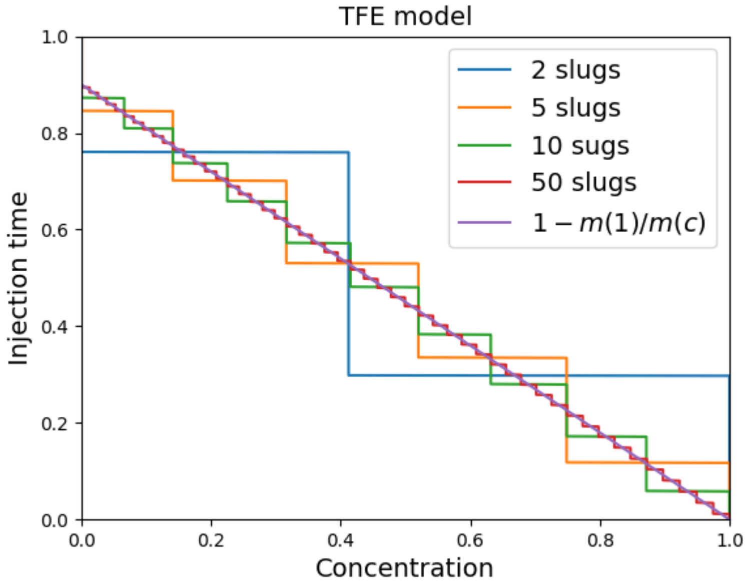
As $n \to \infty$ the optimal limiting injection profile

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

Koval: $\beta = 2\alpha$	Todd-Longstaff: $\beta = 2\omega$	TFE: $\beta = 1$



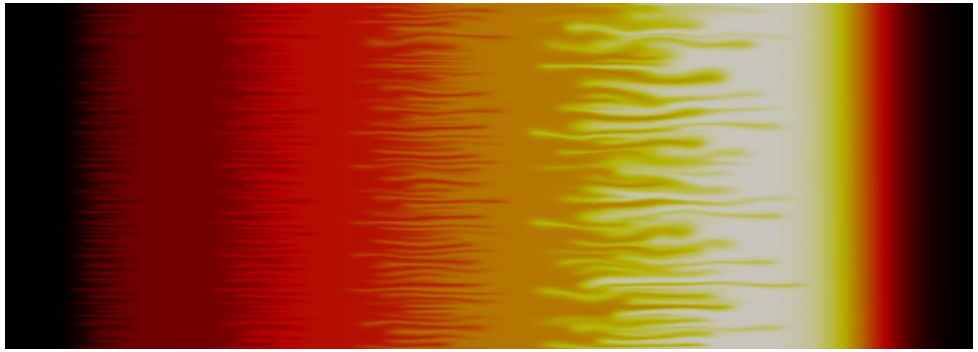




For detailes see arxiv:2012.03114

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, only empirical



Simulation of GVB in DuMuX by our group in SPSU

The talk is based on:

- https://arxiv.org/abs/2012.03114 - “Optimal polymer slugs injection profiles”
  F. Bakharev, A. Enin, K. Kalinin, Yu. Petrova, N. Rastegaev, S. Tikhomirov

- https://arxiv.org/abs/2012.02849 - “Velocity of viscous fingers in miscible displacement”
  F. Bakharev, A. Enin, A. Groman, A. Kalyuzhnuk, S. Matveenko, Yu. Petrova, I.Starkov, S. Tikhomirov

If you have any questions, please, ask me: yu.pe.petrova@yandex.ru Yulia Petrova

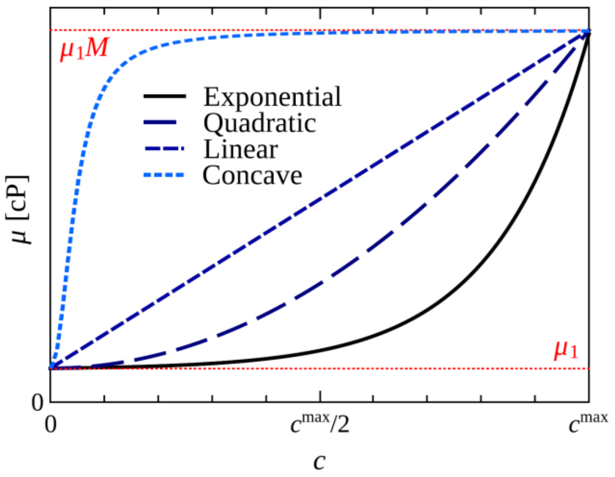
Acknowledgements:

- the work was supported by the Russian Science Foundation grant 19-71-30002 and PJC “GazpromNeft”

Koval & TFE model. Numerical validation

- Numerical validation of TFE (Otto-Yortsos) 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

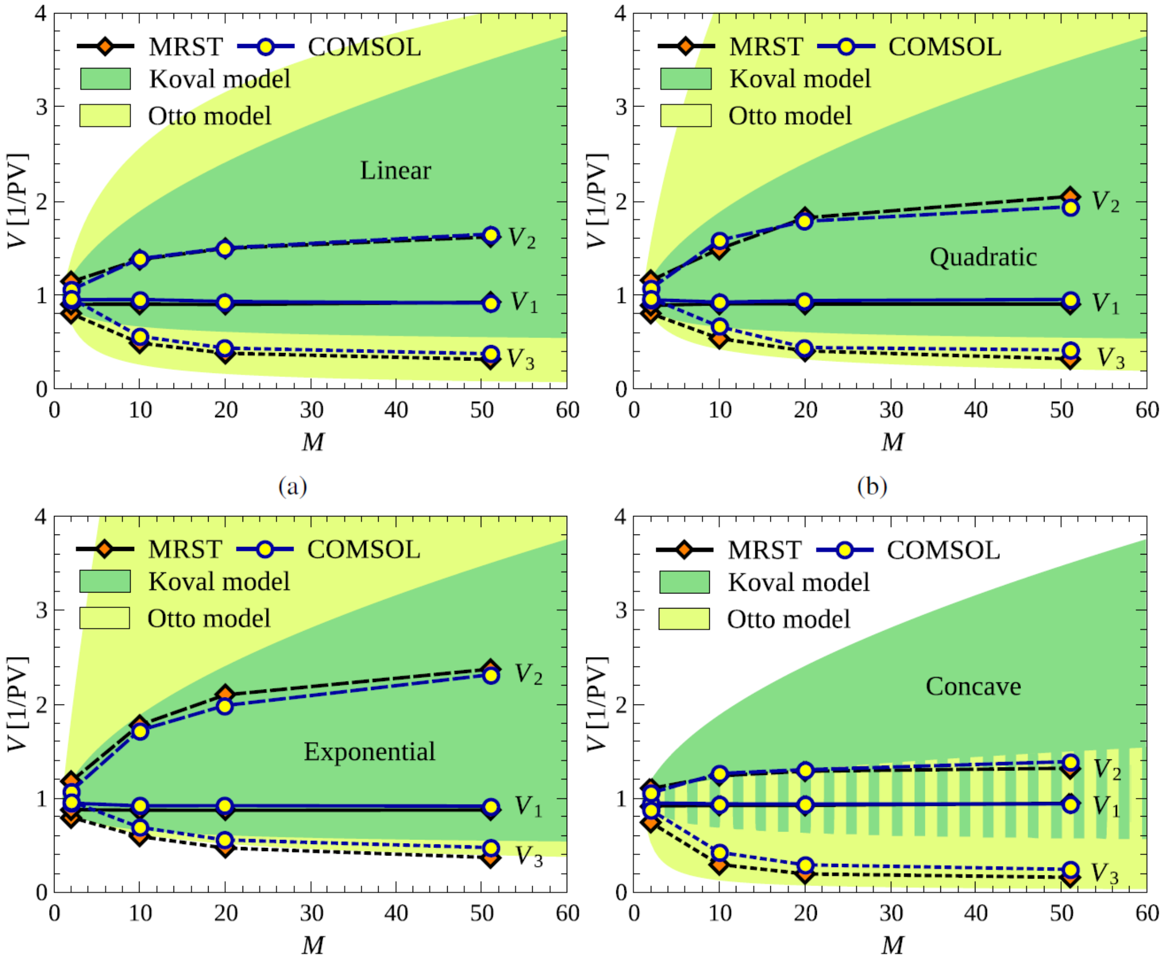


Exponential viscosity

$$u^x = \frac{m(c)}{\overline{m(c)}} u \approx u \cdot \frac{m(c)}{m(0)}$$

Concave viscosity

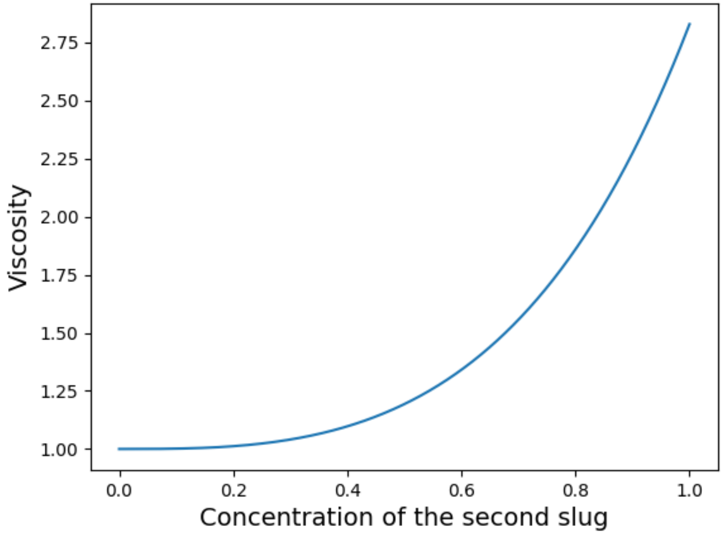
$$u^x = \frac{m(c)}{\overline{m(c)}} u \approx u \cdot \frac{m(c)}{m(1)}$$

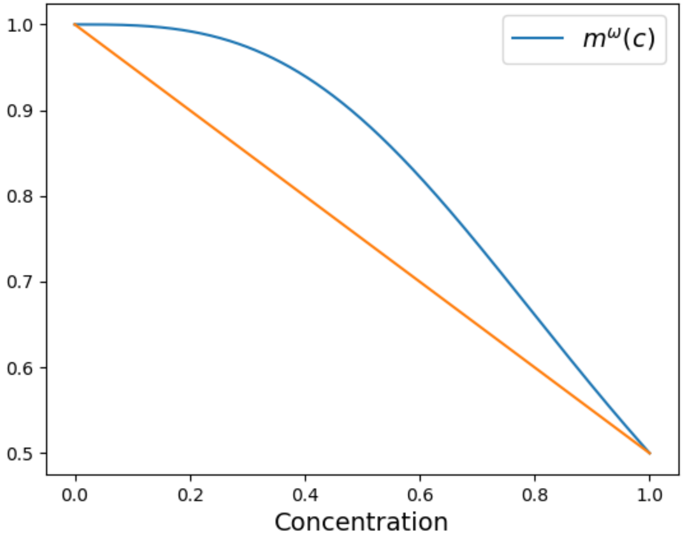


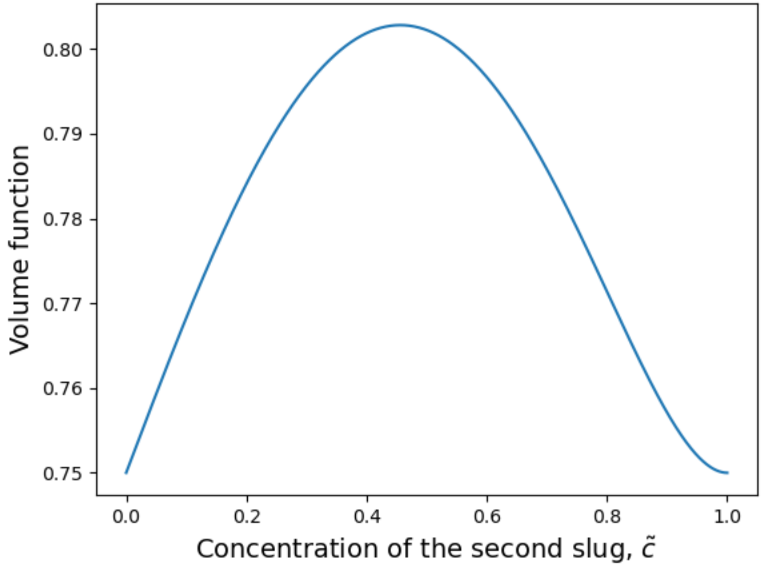
For detailes see arxiv:2012.02849

GVB gives gain not for all viscosities

- Counterexample – Todd-Longstaff model and $\mu = (1 + c^3)^{\frac{3}{2}}$







- There is no gain in polymer mass even if you change 1 slug for 2 slugs!
- In the Theorem we have extra assumptions