SINGLE-PHASE POLYMER FLOW IN POROUS MEDIA: NUMERICAL MODEL FOR EXPERIMENTAL PLANNING AND ANALYSIS

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Abstract. *Polymer flow in porous media is relevant in the oil industry since there are uses for polymeric solutions in drilling fluids and enhanced oil recovery, for example. Aiming to implement these processes, several experiments are needed to characterize the solution and its interactions with the medium. However, polymer flooding experiments offer challenges in planning and analyzing. The objective of this work is to develop a computer algorithm to aid experimentalists in these cases. This goal is achieved by modeling a system with two coupled partial differential equations: hydraulic diffusion and reaction-advection-dispersion of polymer. Constitutive equations also take part to represent rheological behavior and fluid-rock iterations. A dimensionless numerical model is developed using finite differences discretization. The solution is achieved in an implicit fashion for both pressure and concentration, but all coupled phenomena are evaluated explicitly. Validation for the model is achieved by comparison with analytical solutions, established for simplified situations. A broad sensitivity analysis is performed. The analyzed variables are polymer concentration, injection rate, permeability, diffusion coefficient, inaccessible pore volume, adsorption, residual resistance factor and non-Newtonian viscosity. Additionally, a space-time discretization criterion is developed to minimize approximation errors. The proposed model has potential in simple and low-cost laboratory experiment planning and analysis.*

Keywords: *Flow in Porous Media, Polymeric Solutions, Coupled Phenomena, Sensitivity Analysis, Finite Differences.*

Nomenclature

A	-	core cross-section area	N_{PE}^{ref}	-	Peclét number
b_p	-	Langmuir equilibrium constant for polymer	p	-	hydrostatic pressure
c_p	-	concentration of polymer	Q_v	-	fluid flow rate
c_t	-	system total volumetric compressibility	RRF_p	-	residual resistance factor for polymer
D_{pp}	-	diffusion coefficient of polymer in free solution	t	-	time
f_p	-	accessible fraction of pore space	x	-	length
F_R	-	retardation factor	α	-	porous media shear rate parameter
j	-	space iteration	α_f	-	system hydraulic diffusivity
$\overrightarrow{J_p}$	-	mass flow of polymer per unit area	Γ_p	-	adsorbed quantity of polymer (ratio between polymer and rock mass)
$\overrightarrow{J_v}$	-	volumetric flow per unit area	$\Gamma_{p,sat}$	-	adsorption saturation limit for polymer
k_f	-	permeability of porous media	$\dot{\gamma}$	-	shear rate
L	-	core length	η_0	-	fluid characteristic viscosity constant
m	-	flow behavior index	μ_f	-	fluid dynamic viscosity
n	-	time iteration	ρ_r	-	rock specific mass
N_{LA}^{ref}	-	Langmuir number	ϕ	-	porosity

1. INTRODUCTION

Polymer additives are frequently used in the oil industry to grant desired properties to drilling and injection fluids.

Drilling fluids are critical to the success of well drilling operations as they fill several roles. According to Rodrigues Jr. et al. (2007) the primary functions of the drilling fluids are: 1. Cleaning, cooling and lubrication of the drill bit and drillpipe; 2. Prevent invasion of fluids from the wellbore; 3. Form a thin low permeability film to prevent drilling fluid migration to the rock formation; 4. Stabilize the shale gravel generated in the drilling process; 5. Drive the gravel to the surface while maintaining these solids suspense during drilling interruptions. 6. Stabilize the well to prevent collapsing. Almeida & Moreno (2011) report that polymer additives act in the suspension of solids, drill bit lubrication and well stabilization. As reported by Caen & Chillingar (1996), much of the development work on drilling fluids is focused on developing new and/or improved polymers.

Injection fluids with polymer additives are used in enhanced oil recovery (EOR). This kind of EOR focuses in the reduction of the mobility ratio between reservoir oil and injected fluid. Sheng (2011) states that this is achieved through viscosity increase and relative permeability reduction for the injected fluid. This in turn reflects in a better areal sweep efficiency, as reported by Almeida & Moreno (2011). As Littmann (1988) reports, polymer EOR improves the oil recovery in the form of earlier oil production at lower water cut, thus anticipating profit and reducing water processing costs.

Fluid characterization and its interaction with the medium are essential for application of these processes, so several experiments must be conducted. The fluid properties are often easier to characterize through use of rheometers and density meters. Fluid-rock iterations, however, are more complicated and need fluid injection in porous media experiments. These experiments aim to measure important properties such as inaccessible pore volume (IPV), important to polymer EOR, or mud filtrate loss, critical to drilling fluids. However, complex instrumentation and experimental planning are required for such experiments.

Inexperienced experimentalists can face difficulties to plan these experiments and choose the right measurement equipment. That said, computer simulation tools can be of invaluable

aid to prevent experimental errors such as: 1. insufficient accuracy or full scale of measuring equipment; 2. inadequate data acquisition rate; 3. fail to achieve steady-state flow regimen when needed; 4. inaccurate laboratory experiments' chronogram.

Similar results can be achieved through use of commercial simulators, but these tools are costly and require proper training. A custom implementation of a simpler numerical model than those employed in these simulators, however, is a low-cost and easy to use solution to the problem stated. The focus of this work is to present, validate and discuss this model.

The model presented in this work is dimensionless and the numerical solution is achieved by finite difference discretization and a Matlab® implementation. This work considers one-dimensional and single phase conditions of polymer flow through porous media, which is adequate for the experiments it aims to simulate.

As in all numerical solutions, the problem of discretization must be addressed. Ideally, a discretization should provide an accurate and stable solution as fast as possible. Thus, a criterion for time and space discretization is important and is developed for this work's case.

2. MODEL

The model consists of two coupled dimensionless partial differential equations (PDE): hydraulic diffusion and reaction-advection-dispersion of polymer. Along with these, other coupled effects are represented by constitutive equations, such as: non-Newtonian viscosity, retention and inaccessible pore volume.

The dimensionless variables and reference values are defined as stated in Tables 1 and 2 respectively.

Table 1. Dimensionless variables

$t_D = \alpha_f^{ref} \cdot t/L^2$	$k_{fD} = k_f/k_f^{ref}$	$\dot{\gamma}_D = \dot{\gamma}/\dot{\gamma}^{ref}$	$\overrightarrow{J_{vD}} = \overrightarrow{J_v}/\overrightarrow{J_v^{ref}}$
$x_D = x/L$	$\mu_{fD} = \mu_f/\mu_f^{ref}$	$\Gamma_{pD} = \Gamma_p/\Gamma_p^{ref}$	$\overrightarrow{J_{pD}} = \overrightarrow{J_p}/\overrightarrow{J_p^{ref}}$
$p_D = \Delta p/\Delta p^{ref}$	$c_{pD} = c_p/c_p^{ref}$	$b_{pD} = b_p \cdot c_p^{ref}$	

Table 2. Reference values and dimensionless numbers associated

$t^{ref} = L^2/\alpha_f^{ref}$	$\dot{\gamma}^{ref} = \overrightarrow{J_v^{ref}} \Big/ \sqrt{k_f^{ref} \cdot \phi}$	$\mu_f^{ref} = \mu_f^{ini}$ **a**	$N_{PE}^{ref} = \overrightarrow{J_v^{ref}} \cdot c_p^{ref} \Big/ \left(\phi_p \cdot \overrightarrow{J_p^{ref}}\right)$
$x^{ref} = L$	$\alpha_f^{ref} = k_f^{ref}/(\phi \cdot \mu_f^{ref} \cdot c_t)$	$c_p^{ref} = c_p^{inlet,max}$ **b**	$N_{LA}^{ref} = \rho_r \cdot \Gamma_p^{ref}/(\phi_p \cdot c_p^{ref})$
$k_f^{ref} = k_f^{max}$	$\overrightarrow{J_p^{ref}} = D_{pp} \cdot c_p^{ref}/L$	$\Gamma_p^{ref} = \Gamma_{p,sat}$	
At constant inlet pressure		**At constant flow rate**	
$\Delta p^{ref} = \Delta p^{inlet} - \Delta p^{ini}$		$\Delta p^{ref} = \left(\mu_f^{ref}/k_f^{ref}\right) \cdot L \cdot \overrightarrow{J_v^{inlet}}$	
$\overrightarrow{J_v^{ref}} = \left(k_f^{ref}/\mu_f^{ref}\right) \cdot (\Delta p^{ref}/L)$		$\overrightarrow{J_v^{ref}} = \overrightarrow{J_v^{inlet}}$	

a– Viscosity of the fluid that initially saturates the porous medium; **b**– For successive polymer injections the maximum inlet concentration is used as the reference.

2.1. Conservation equations

Both PDEs are derived from mass balance and consider a single phase in a one-dimensional porous medium. The model is based on Moreno (2000).

The hydraulic diffusion, Eq. (1), considers Darcian flow in a porous medium saturated entirely with one slightly compressible fluid. The reaction-advection-dispersion of polymer species, Eq. (2), considers the diffusion coefficient constant in space, and the retardation factor as presented in Eq. (3).

$$\frac{\partial p_D}{\partial t_D} = \frac{\partial}{\partial x_D}\left(\frac{k_{fD}}{\mu_{fD}} \cdot \frac{\partial p_D}{\partial x_D}\right) \quad (1)$$

$$F_R \cdot \frac{\partial c_{pD}}{\partial t_D} = \frac{D_{pp}}{\alpha_f^{ref}} \cdot \left[\frac{\partial^2 c_{pD}}{\partial x_D^2} - N_{PE}^{ref} \cdot \frac{\partial (c_{pD} \cdot \overrightarrow{J_{vD}})}{\partial x_D}\right] \quad (2)$$

$$F_R = 1 + N_{LA}^{ref} \cdot \frac{\partial \Gamma_{pD}}{\partial c_{pD}} \quad (3)$$

Note that the classical formulations for hydraulic diffusion and advection-dispersion PDEs (Rosa et al., 2006; Sorbie, 1991) are reduced forms of the Eqs. (1) and (2). After the finite difference discretization, the numerical form to Eqs. (1) and (2) are Eqs. (4) and (5).

$$\left\{-\left(\frac{k_{fD}}{\mu_{fD}}\right)_{j-1}^{n} \cdot \frac{\Delta t_D}{(\Delta x_D)^2}\right\} \cdot \Delta p_{D,j-1}^{n+1} + \left\{1 + \frac{\Delta t_D}{(\Delta x_D)^2} \cdot \left[\left(\frac{k_{fD}}{\mu_{fD}}\right)_{j+1}^{n} + \left(\frac{k_{fD}}{\mu_{fD}}\right)_{j-1}^{n}\right]\right\} \cdot \Delta p_{D,j}^{n+1} + \left\{\left(\frac{k_{fD}}{\mu_{fD}}\right)_{j+1}^{n} \cdot \frac{\Delta t_D}{(\Delta x_D)^2}\right\} \cdot \Delta p_{D,j+1}^{n+1} = \Delta p_{D,j}^{n} \quad (4)$$

$$\left\{-\left(\frac{D_{pp}}{\alpha_f^{ref}}\right)_{j}^{n} \cdot \left(\frac{1}{\Delta x_D} + N_{PE,j}^{ref,n} \cdot J_{vD,j-1}^{n}\right)\right\} \cdot c_{pD,j-1}^{n+1} + \left\{F_{R,j}^{n} \cdot \frac{\Delta x_D}{\Delta t_D} + \left(\frac{D_{pp}}{\alpha_f^{ref}}\right)_{j}^{n} \cdot \left(\frac{2}{\Delta x_D} + N_{PE,j}^{ref,n} \cdot J_{vD,j}^{n}\right)\right\} \cdot c_{pD,j}^{n+1} + \left\{-\left(\frac{D_{pp}}{\alpha_f^{ref}}\right)_{j}^{n} \cdot \frac{1}{\Delta x_D}\right\} \cdot c_{pD,j+1}^{n+1} = F_{R,j}^{n} \cdot \frac{\Delta x_D}{\Delta t_D} \cdot c_{pD,j}^{n} \quad (5)$$

Note that this is a fully implicit solution for pressure and polymer concentration. All other variables (permeability, viscosity, retardation factor and fluid superficial velocity) are evaluated explicitly. This approach enables a fast solution by the Thomas algorithm.

2.2. Constitutive equations

To be able to solve the problem of polymer flow in porous media, some constitutive equations must be solved along with the conservation equations. The dimensionless forms of these equations, and the references for their dimensional forms, are presented in Table 3.

Table 3. Dimensionless constitutive equations and references

Property	Equation	Reference
Non-Newtonian viscosity	$\mu_{fD} = \left(\eta_0/\mu_f^{ref}\right) \cdot (\dot{\gamma}^{ref} \cdot \dot{\gamma}_D)^{m-1}$	Power-law model (Sochi, 2010)
In-situ shear rate	$\dot{\gamma}_D = 4 \cdot \alpha \cdot \overrightarrow{J_{vD}} / \sqrt{8 \cdot k_{fD}}$	Hatzignatiou et al., 2013
Adsorption	$\Gamma_{pD} = b_{pD} \cdot c_{pD} / \left(1 + b_{pD} \cdot c_{pD}\right)$	Langmuir isotherm (Ruthven, 1984)
Permeability reduction	$k_{fD} = k_{fD}^{ini} / \left[1 + \left(RRF_p - 1\right) \cdot \Gamma_{pD}\right]$	STARS, 2013
Inaccessible pore volume	$\phi_p = f_p \cdot \phi$	Sorbie, 1991

As reported by Lopes et al. (2014), a rheological study must be performed to determine the parameters (η_0 and m) of the viscosity model for the polymer in the region of work, which generally results in a shear-thinning relation. According to Hatzignatiou et al. (2013), the shear rate parameter $\alpha = 2{,}5$ is adequate for porous medium with angular particles.

3. DISCRETIZATION CRITERION

Every numerical solution is subject to error induction to the results. Intuitively, a finer time-space discretization reflects in a better outcome, although this also requires higher

computational resources. That said, a discretization criterion that minimizes the approximation errors is important. This criterion is based on Moreno (2000) and takes into account the errors of highest magnitude resulted from the finite difference approximations on the model presented, as summarized in Table 4.

Table 4. Errors of highest magnitude for each portion of the PDE's in the model

PDE	Hydraulic diffusion	Reaction-advection-dispersion of polymer
Time portion	$\frac{\Delta t_D}{2} \cdot \frac{\partial^2 p_D}{\partial t_D^2}$	$\frac{\Delta t_D}{2} \cdot \frac{\partial^2 c_{pD}}{\partial t_D^2}$
Diffusive portion	$\left[\left(\frac{k_{fD}}{\mu_{fD}}\right)_j^n - \left(\frac{k_{fD}}{\mu_{fD}}\right)_{j+1}^n\right] \cdot \frac{\Delta x_D}{24} \cdot \frac{\partial^3 p_D}{\partial x_D^3}$	$\left(\frac{D_{pp}}{\alpha_f^{ref} \cdot F_R}\right)_j^n \cdot \frac{\Delta x_D^2}{24} \cdot \frac{\partial^4 c_{pD}}{\partial x_D^4}$
Advective portion	-	$\left(\frac{D_{pp} \cdot N_{PE}^{ref}}{\alpha_f^{ref} \cdot F_R}\right)_j^n \cdot \frac{\Delta x_D}{2} \cdot \frac{\partial^2 \left(c_{pD} \cdot \overrightarrow{J_{vD}}\right)}{\partial x_D^2}$

In the hydraulic diffusion equation, the error associated with time is a second order derivative, while the diffusive one is a third order. So, it's possible to reduce the error on Eq. (4) by using a finer time-step. In the reaction-advection-dispersion equation, errors associated with time, diffusive and advective portions are second, fourth and second order derivatives, respectively. Numerical dispersion is mostly induced by the second order derivatives.

Because the problem is solved in its dimensionless form, it's expected that time and space variations have impacts of similar order of magnitude on the state variable (polymer concentration, in this case). If that's true, the errors induced by second order derivatives (time and advection, in this case) can be minimized by taking the equality between these two error portions, resulting in Eq. (6). The only parameter that isn't constant in this formulation is the retardation factor. It's safe to say that $F_R \geq 1$ since there isn't desorption. So the safest discretization criterion is achieved by taking Δt_D as a constant with $F_R = 1$ because $\Delta x_D(\Delta t_D, F_R > 1) > \Delta x_D(\Delta t_D, F_R = 1)$.

$$\frac{\Delta t_D}{\Delta x_D} = \frac{1}{F_R} \cdot \frac{D_{pp}}{\alpha_f^{ref}} \cdot N_{PE}^{ref} \tag{6}$$

3.1. Model validation and discretization criterion discussion

Model validation can be achieved through comparison with classical analytical solutions. The conditions and the analytical solutions are presented in Table 5.

Table 5. Hydraulic diffusion and advection-dispersion PDEs, initial and boundary conditions and analytical solutions

PDE	Initial Condition	Boundary conditions		Solution
$\frac{\partial p_D}{\partial t_D} = \frac{\partial^2 p_D}{\partial x_D^2}$	$p_D(x_D, 0) = 0$	$p_D(0, t_D) = 1$	$p_D(1, t_D) = 0$	Eq. (7)
$\frac{\partial c_{pD}}{\partial t_D} = -\frac{\partial c_{pD}}{\partial x_D} + \frac{1}{N_{PE}} \cdot \frac{\partial^2 c_{pD}}{\partial x_D^2}$	$c_{pD}(x_D, 0) = 0$	$c_{pD}(0, t_D) = 1$	$\lim_{x_D \to \infty} c_{pD}(x_D, t_D) = 0$	Eq. (8)

The analytical hydraulic diffusion considers a one-dimensional, homogeneous and isotropic porous medium completely saturated with a Newtonian fluid. The analytical advection-dispersion considers a non-reactive polymer under constant fluid flow in a one-dimensional, horizontal, homogeneous and isotropic porous medium completely saturated. To simulate these conditions, the input parameters shown in Table 6 were chosen.

$$p_D(x_D, t_D) = (1 - x_D) + \frac{2}{\pi} \cdot \sum_{m=1}^{\infty} \left\{ \frac{(-1)^m}{m} \cdot e^{-m^2 \cdot \pi^2 \cdot t_D} \cdot \sin[m \cdot \pi \cdot (1 - x_D)] \right\}, x_D \geq 0, t_D \geq 0 \quad (7)$$

$$c_{iD}(x_D, t_D) = \frac{1}{2} \cdot \left\{ erfc\left[\sqrt{\frac{N_{PE}}{4 \cdot t_D}} \cdot (x_D - t_D) \right] + exp(N_{PE} \cdot x_D) \cdot erfc\left[\sqrt{\frac{N_{PE}}{4 \cdot t_D}} \cdot (x_D + t_D) \right] \right\}, \; x_D \geq 0, t_D \geq 0, N_{PE} > 0 \quad (8)$$

Table 6. Parameters used for algorithm validation and discretization criterion discussion

$\frac{k_{fD}}{\mu_{fD}} = 1$	$N_{PE}^{ref} = N_{PE} = \left(\frac{D_{pp}}{\alpha_f^{ref}} \right)^{-1} = 500$	$F_R = 1$

Note that two simulations were made: 1. constant injection pressure and; 2. constant injection flow rate. So that respective comparisons with Eqs. (7) and (8) could be made. Also keep in mind that these conditions are advection-dominated.

Several cases were simulated with varying time and space discretization while maintaining the same number of iterations. Then the results were compared with the analytical solutions for error calculations in all numerically evaluated space-time points. The results are summarized in Table 7 and can be visualized in Fig. 1. Note that only the case 3 satisfy the discretization criterion.

Table 7. Maximum and mean errors for cases of different time and space discretization

Case	Δx_D	Δt_D	Number of iterations	Hydraulic Diffusion		Advection-Dispersion of Polymer [b]	
				Maximum Error [a]	Mean Error [a]	Maximum Error [a]	Mean Error [a]
1	10^{-1}	10^{-5}	10^6	0.06585	0.000178	0.46590	0.031463
2	10^{-2}	10^{-4}	10^6	0.09753	0.000022	0.27549	0.006865
3	10^{-3}	10^{-3}	10^6	0.12403	0.000195	0.38972	0.001852
4	10^{-4}	10^{-2}	10^6	0.12404	0.002525	0.60299	0.024036
5	10^{-5}	10^{-1}	10^6	0.12669	0.014637	0.56759	0.076162

a– Absolute values; **b**– Errors calculated for $0 \leq x_D \leq 0.5$ due to the comparison being valid only for positions far from the production face.

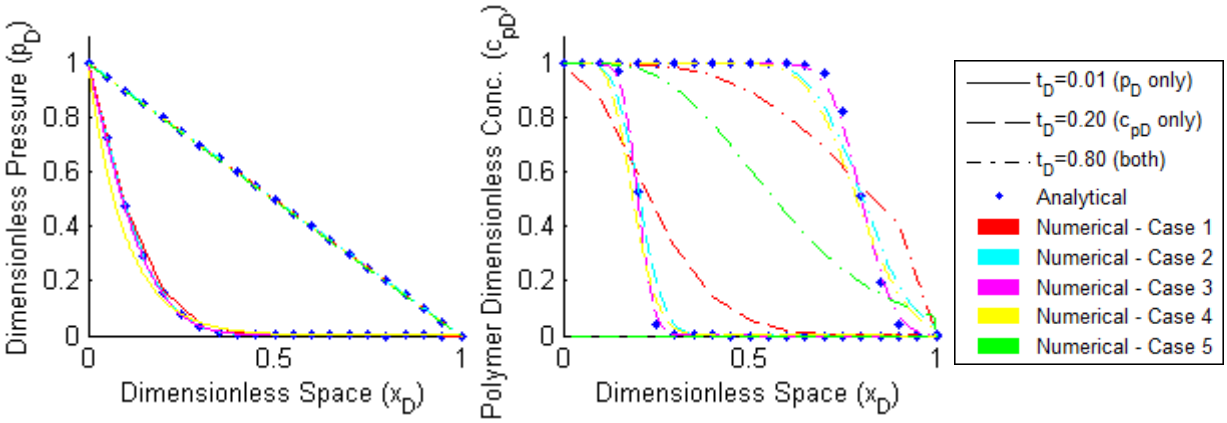

Figure 1. Profiles of p_D (top) and c_{pD} (bottom) for various t_D.Comparison between analytical answer (blue) and numerical cases: 1 (red), 2 (cyan), 3 (magenta), 4 (black) and 5 (green)

Analyzing the mean absolute errors for the hydraulic diffusion equation, it's evident that a finer time step results in better coherence between analytical and numerical values, except for case 1, which is very coarsely space discretized. The pressure curves reveal that cases 1, 2 and 3 have a good match with the analytical result. The mean absolute errors for the advection-dispersion equation show that the discretization criterion was successful in

minimizing the errors in this equation. Also, the profile curves for polymer concentration reveal a good match only by case 3, while the extreme cases (1 and 5) are really far from the analytical result. Additionally, it's worth mentioning that all the maximum absolute errors are observed in really small x_D and t_D, since those points are under the highest pressure and concentration differentials.

4. SENSITIVITY ANALYSIS

In order to increase the understanding of the relation between the inputs and the outputs of the proposed model, a sensitivity analysis is made. The conditions simulated are stated in Table 8 and were chosen to align with those of laboratory experiments of polymer transport in porous media. The cases studied are presented in Table 9.

Table 8. Numerical input parameters common to every case studied

$L = 0.25m$	$A = 0.00114m^2$	$b_p = 20$	$\rho_r = 2650\, kg/m^3$	$\Delta p^{ini} = 10^{-5} Pa$	$c_p^{ini} = 0$
	$\mu_f^{ini} = 10^{-3} Pa \cdot s$	$\phi = 0.25$	$c_t = 7x10^{-10} Pa^{-1}$	$\Delta p^{outlet} = 10^{-5} Pa$	$c_p^{outlet} = 0$

Table 9. Parameters modified for each case studied, the rest remained as the base case

Parameter	n	Case $(2 \cdot n - 1)$	Base	Case $(2 \cdot n)$
${c_p}^{inlet}$	$n = 1$	$100\ ppm$ [a]	$800\ ppm$ [a]	$1500\ ppm$ [a]
${Q_v}^{inlet}$	$n = 2$	$0.1\ cm^3/min$	$0.3\ cm^3/min$	$0.5\ cm^3/min$
k_f	$n = 3$	$10\ mD$ [b]	$100\ mD$ [b]	$1000\ mD$ [b]
D_{pp}	$n = 4$	$3x10^{-9}\ cm^2/min$	$3x10^{-6}\ cm^2/min$	$3x10^{-3}\ cm^2/min$
f_p	$n = 5$	0.5	0.8	1.0
$\Gamma_{p,sat}$	$n = 6$	$10\ \mu g\ pol/g\ rock$	$30\ \mu g\ pol/g\ rock$	$50\ \mu g\ pol/g\ rock$
RRF_p	$n = 7$	1.0	2.0	5.0
μ_f	$n = 8$	See Fig. 2		

a– Parts per million relative to weight; **b**– $1mD = 986.9(\mu m)^2$.

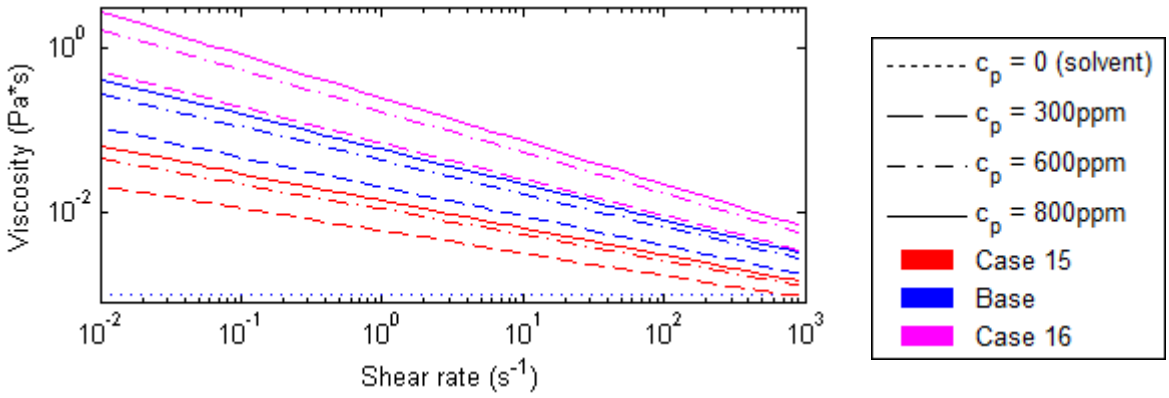

Figure 2. Log-linear plot of the viscosity versus shear rate for various c_p used in cases 15 (red), base (blue) and 16 (green)

Graphs of the history, in terms of injected pore volumes (inj. PV), for all cases are presented in Figs. 3 and 4. The graph for RRF_p was omitted because it's very similar to those of k_f. The Δp and c_p behavior are insensitive to alterations in the D_{pp} under these high Peclét number conditions ($> 10^3$), that said, these graphs were also omitted.

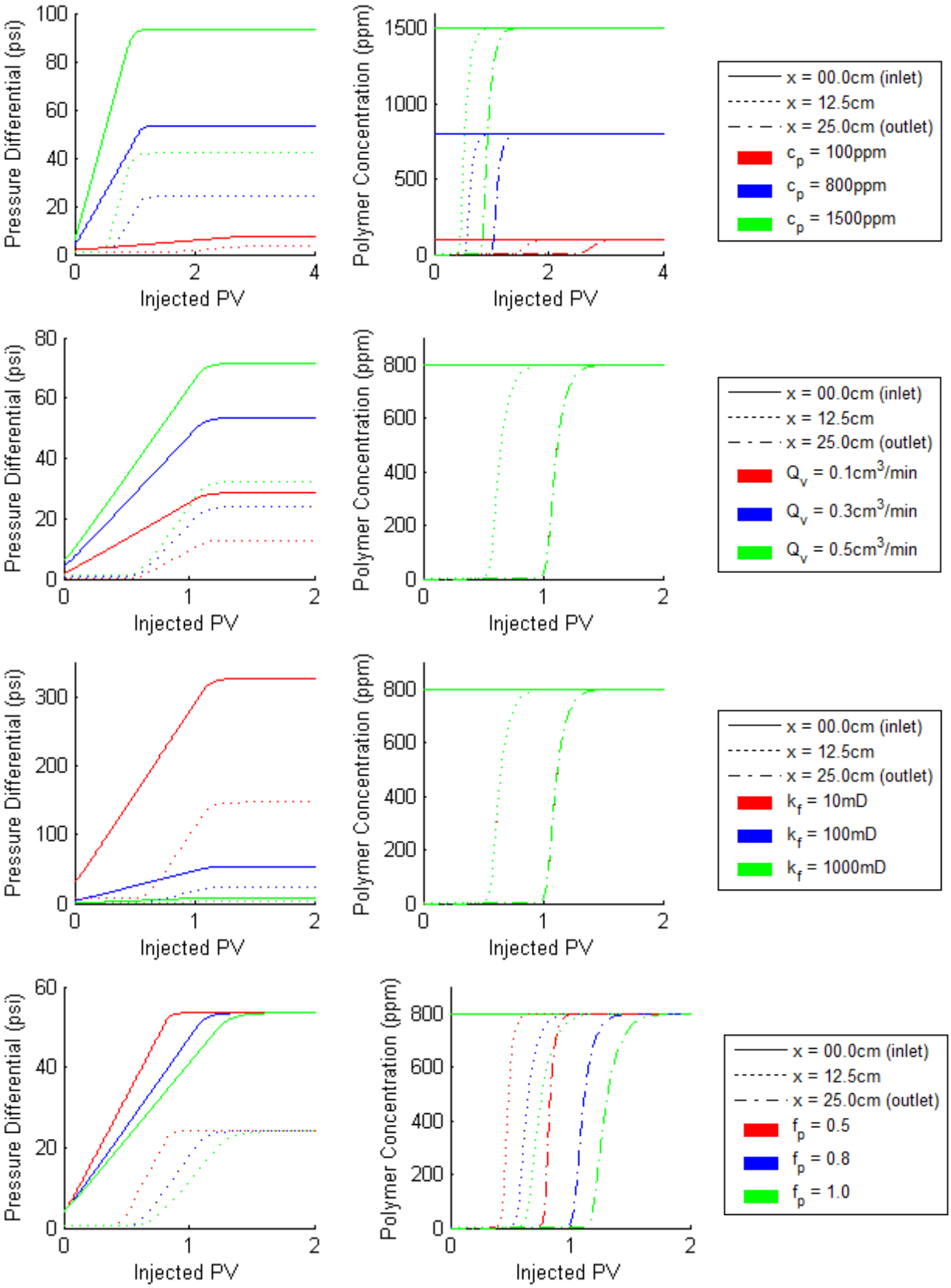

Figure 3. History of pressure differential (left) and polymer concentration (right) for cases varying (top to bottom): $c_p{}^{inlet}$, $Q_v{}^{inlet}$, k_f, and f_p ($1psi = 6894.7Pa$)

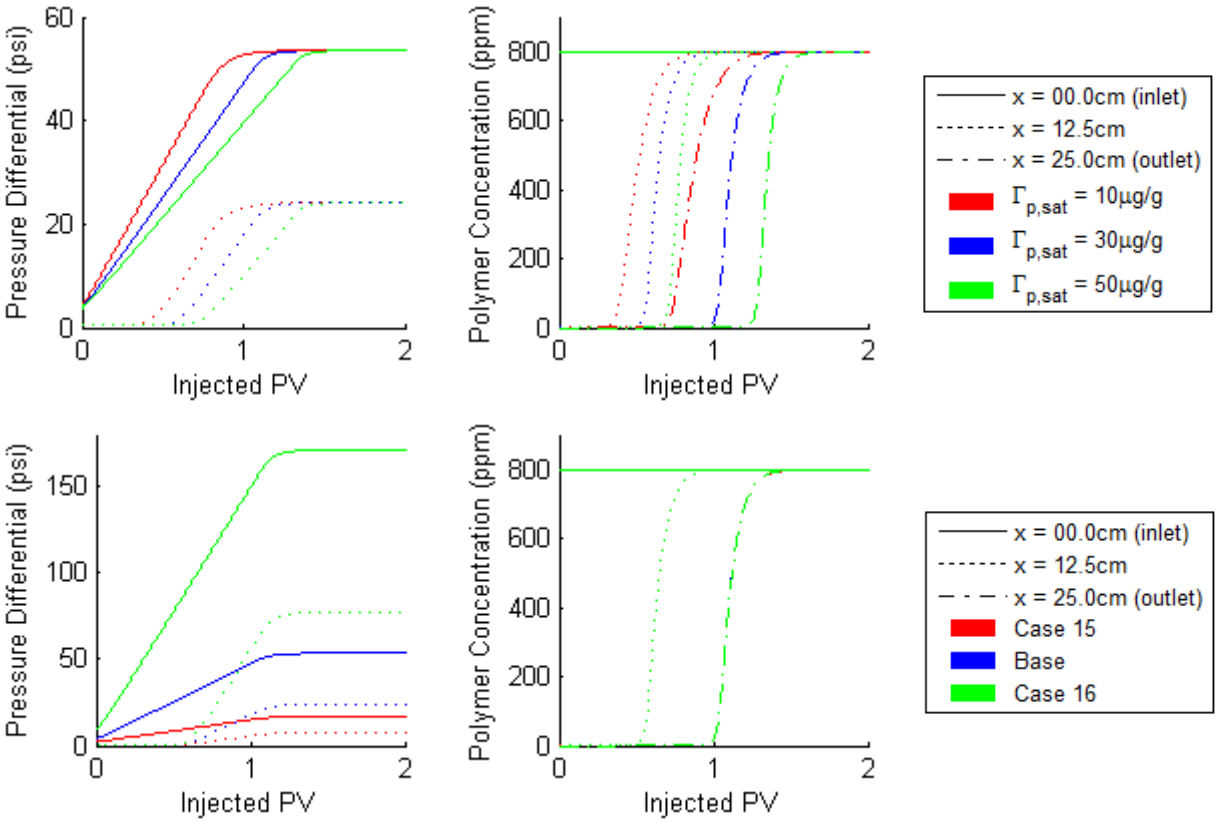

Figure 4. History of pressure differential (left) and polymer concentration (right) for cases varying (top to bottom): $\Gamma_{p,sat}$, and μ_f ($1psi = 6894.7Pa$)

A higher c_p results in a higher Δp and an earlier breakthrough. The Δp is due to the increased μ_f while the breakthrough is explained by the fact that the adsorption level is less relevant, which can be seen directly by the lower N_{LA}^{ref} (3.983 for case 1, of higher c_p and 0.265 for case 2, of lower c_p).

A higher Q_v reflects in a higher Δp, as expected, although the pressure gain is not linear with the flow rate increase due to the shear-thinning nature of polymeric solutions.

A lower k_f implies in a higher Δp, however this increase is attenuated due to the fact that a lower k_f leads to a higher $\dot{\gamma}$, which reflects in lower μ_f due to the shear-thinning behavior of the solution.

A lower f_p results in an earlier breakthrough due to the speed enhancement effect of the IPV, also this reflects in a steeper Δp curve and less diffuse c_p curve.

A higher $\Gamma_{p,sat}$ reflects in a later breakthrough due to the retardation effect of the adsorption. Also this implies in a less steep Δp curve and less diffusive c_p curve.

The RRF_p reduces the k_f as the polymeric solution saturates the medium, that said, a higher RRF_p has similar effects to a lower k_f.

A higher μ_f results in a linear increase in Δp, which is different from the non-linear relation observed in Q_v and k_f cases.

Also, note that all the curves presented in Figs. 3 and 4 are commonly seen in the experiments that the proposed model aims to mimic.

5. CONCLUSIONS

This work presented a numeric model for single-phase one-dimensional flow of polymeric solutions in porous media.

The discretization criterion developed proved to minimize the calculation errors for the same computational effort. The methodology used to develop this criterion can be used to develop similar criterions for any other dimensionless problems.

The sensitivity analysis allowed for a broader vision of the model, with the non-linear relations between inputs and outputs. This approach also proved the dimensionless numbers to be a valuable resource for analysis enhancement.

The model presented has great potential for application in experimental planning and analysis and can prove to be a low-cost and easy to use tool compared to commercial simulators.

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