Exergy Analysis of Bio-polymer Flooding in Clastic Reservoirs

Anas Hassan [*], Hans Bruining [†] Tagwa Musa [‡] Rouhi Farajzadeh [§]

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1 Abstract

Using a 1-D model of polymer displacement, we analyze the exergy (maximum attainable work) balance of viscosified water, e.g. with Arabic gum. The 1-D model shows the principle how such an analysis can be done;

A comparison as to the displacement efficiency is made between three scenarios, i.e., (1) pure water injection, (2) constant polymer viscosified water injection and (3) polymer slug injection (water-polymer-water) injection. A numerical solution of the enhanced oil recovery (EOR) model is obtained with COMSOL invoking the weak formulation option for solving pde's. At the injection point we specify the injection flux of water and polymer. At the production point, we only specify the convection term. Moreover we compare the exergy of the oil (10.7 ($kWh/liter$)) produced to the pumping exergy for circulating the fluids, which usually approximately accounts for 80% of the exergy used for the recovery of oil. Validation of the model results is achieved with analytical solutions using the method of characteristics, In addition the integrated Darcy velocity × pressure gradient profile is used to compute the power required to circulate the fluids; we make a comparison for the three scenario's. It is argued that this analysis, which circumvents an economic analysis, can be used to show the advantage of using polymer (e.g., Arabic gum) slugs with respect to permanent polymer injection to enhance the recovery behavior.

Keywords: Polymer injection, COMSOL model, Exergy, Oil production, Enhanced Oil Recovery (EOR), Arabic gum.

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[*] TU Delft, Civil Engineering and Geosciences, and Sudan University of Science and Technology SUST, College of Petroleum Engineering and Technology. E-mail: A.M.Hassan@tudelft.nl

[†] TU Delft, Civil Engineering and Geosciences, Stevinweg 1, 2628 CE Delft, The Netherlands. E-mail: J.Bruining@tudelft.nl

[‡] SUST, Sudan University of Science and Technology, College of Petroleum Engineering and Technology, Khartoum, Sudan. E-mail: tagwamusa@sustech.edu

[§] TU Delft, Civil Engineering and Geosciences, Stevinweg 1, 2628 CE Delft, The Netherlands. E-mail: R.Farajzadeh@tudelft.nl

Introduction

The water drive recovery efficiency of medium viscosity oil suffers from low displacement efficiency, vertical sweep efficiency and areal sweep-efficiency ((Lake, Johns, Rossen, & Pope, 2014),(Sheng, 2010),(Lake, 1989)). Consequently, it requires large amounts of water injection to recover all movable oil ((Sheng, 2013)(Taber, Martin, Seright, et al., 1997),(Craig, 1971)). By injection of polymer solutions we can improve these three efficiencies ((K. S. Sorbie, 2013), (Chauveteau & Sorbie, 1991),(K. Sorbie, n.d.),(Wreath, 1989),(K. Sorbie, Parker, Clifford, et al., 1987),(Chauveteau, 1982),(Chauveteau, Kohler, et al., 1974)). This paper uses a 1-D oil displacement model to compare the recovery history for three scenarios, viz. water injection, polymer water injection and polymer slug injection. Both the oil recovery rates and cumulative recovery is calculated. The exergy content of the produced oil 10.7 $(kWh/liter)$ (MacKay, 2008) is compared to the dissipated power $3 \times \int_0^{length} dx \; u \; \Delta P$ to circulate the fluids. The factor of three (Eftekhari, Van Der Kooi, & Bruining, 2012) arises from the conversion of the fuel exergy to electricity and taking into account the efficiency of the pump. Our main interest is to estimate the exergy required for the recovery of oil and compare it to the exergy of the produced oil. The exergy required for recovery of oil mainly consists of the circulation energy of the fluid, which usually accounts for 80% of the energy that is necessary to produce the oil (Eftekhari et al., 2012). For convenience we have also added the result of the analysis for the drilling energy and casing, tubing, and cleaning costs ((Hung, Souchal, Urbanczyk, Fouchard, et al., 2016),(Ahmadi, Dincer, & Rosen, 2013a),(Ahmadi, Dincer, & Rosen, 2013b), (Ahmadi et al., 2013b),(Dincer & Rosen, 2012), (Sankaranarayanan, van der Kooi, & de Swaan Arons, 2010),(Morrell, 2008),(Swaan Arons, Kooi, Sankaranarayanan, Jakob de Swaan Arons, & der Kooi, 2004),(Larson & Morrell, 1980)(W. Somerton, Esfandiari, Singhal, et al., 1969), (W. Somerton et al., 1969), (Hurst, Clark, Brauer, et al., 1968),(W. H. Somerton et al., 1959)).

2 Exergy analysis

A optimal development (Farajzadeh, private communication) of any oil production scheme is considered using a system analysis of the useful energy (exergy) inputs and energy wastes. The focus of this analysis is not on economic, environmental, time and social aspects, but on thermodynamics aspect using the exergy balance. Exergy is the maximum useful work that can be obtained from an energy stream that is brought in equilibrium with the environment or its surroundings. Exergy can be dissipated due to irreversibility and generation of entropy. The environment is assumed to be in a dead state, which means that it cannot deliver useful work. This is in contrast with energy, which is conserved according to the first law of thermodynamics, in which the total energy is always balanced and never lost ((Eftekhari et al., 2012),(Yantovsky, Górski, & Shokotov, 2009),(Bejan, 2002),(Szargut, Morris, & Steward, 1988)).

In view of the limited space we confine ourselves to the results of the analysis.

- Recovery exergy: u_{inj} (m/s) × 10700 (kWh/m^3)
- Circulation exergy: $3 \times \int_0^{length} dx\ u\ \Delta P$
- Drilling exergy: $\sim$ crushing energy $\sim 116(MJ/m)$ (PM)
- Tubing / casing: $35.8(GJ/ton - steel)$ (PM)
- Labour costs: $0.21\ (euro/kWh)$
- Polymer manufacturing costs: expected to be low because the polymer concentration is low $\leq 1000(ppm)$

Remark: Polymer costs

It is to be expected that the exergy manufacturing costs are low because the polymer concentration are low ($\leq 1000\ ppm$)

3 Polymer enhanced oil recovery (EOR) model

We consider a clastic reservoir initially filled with an oleic phase at a saturation of $(1 - S_{wc})$ and an aqueous phase at a saturation of (S_{wc}). We inject water with dissolved polymer. We consider one dimensional incompressible flow at an injection velocity (u_{inj}).

The conservation equations for the water phase and the dissolved polymer phase read

$$\begin{aligned} \varphi \partial_t S_w + \partial_x (u f_w) &= 0 \\ \varphi \partial (c S_w) + \partial_x (u c f_w) &= 0 \end{aligned} \tag{1}$$

where (S_w) is the water saturation and c is the polymer concentration.

The relative permeability for the aqueous phase is

$$k_{rw}(S_w) = \begin{pmatrix} 0 & \text{for} & 0 \leq S_w \leq S_{wc} \\ k'_{rw}(\frac{S - S_{wc}}{1 - S_{wc} - S_{or}})^{nw} & \text{for} & s_{wc} \leq S_w \leq 1 - S_{or} \\ (s_o r - 1 + k'_{rw})/s_{or} + 1 - k'_{rw} s/s_{or} & \text{for} & 1 - S_{or} \leq S_w \leq 1 \\ 1 & \text{for} & 1 \leq S_w \leq 2 \end{pmatrix} \tag{2}$$

The relative permeability for the oleic phase reads

$$k_{ro}(S_w) = \begin{pmatrix} 1 & \text{for} & 0 \leq S_w \leq S_{wc} \\ k'_{ro}(1 - \frac{S - S_{wc}}{1 - S_{wc} - S_{or}})^{no} & \text{for} & s_{wc} \leq S_w \leq 1 - S_{or} \\ 0 & \text{for} & 1 - s_{or} S_w \leq 2 \end{pmatrix} \tag{3}$$

The fractional flow function (f_w) can be written as

$$f_w = \frac{k_{rw}/\mu_w(c)}{k_{rw}/\mu_w(c) + k_{ro}/\mu_o} \tag{4}$$

where the polymer (Arabic gum) concentration dependent viscosity of the aqueous phase is given by

$$\mu_w(c) = \mu_{w0} + \mu_{wp}\ c/c_{bound} \tag{5}$$

where $\mu_{wp} = 0.02$ and (c) is the concentration in (ppm).

Three scenarios are implemented by defining

- scenario1 : $c = 0$
- scenario2 : $c = c_{bound} = 0.001$
- scenario3 : $c_{bound} * (tannh(t - tijd1) - tannh(t - tijd2))$ [see Figure (4)]

with

$$tannh(x) = 0.5 + 0.5 * tanh(x/\delta) \tag{6}$$

where $\delta = 0.1$

4 Results and discussions

We show for the three scenarios the production rate, the cumulative production, the dissipated power and the ratio between the produced fossil fuel energy and the dissipated power using the parameters summarized in Table (1).

Figure (1) shows the oil production rate $(m^3/m^2/s)$ versus the injected pore volume $(u_{inj}t/(\phi \times length))$. For scenario (1), i.e. pure water injection we observe that the production rate declines from (1×10^{-5}) rapidly with injected pore volume. There is a long production tail. For scenario (2), pure polymer injection we observe a constant production rate of (1×10^{-5}) until water breakthrough occurs, after which the production rate decreases by 34%, until almost complete recovery has been achieved after 0.68 pore volume (PV). For scenario (3), i.e. slug injection we observe a production rate that is identical to scenario (1) until we switch to polymer injection. Subsequently the production rate rises to (6.57×10^{-6}) before it declines to very small values. Finally we inject water and some minor amounts of oil are still produced.

Figure (2) shows the integrated pressure gradient × the injection velocity (u_{inj}) (W/m^2) versus the injected pore volume $(u_{inj}t/(\phi length))$. For scenario (1), i.e. pure water injection we observe that the power is steadily declining until a constant power is reached. This corresponds to the circulation energy when almost all oil has been produced and the saturation has become uniform and equal to $(1 - S_{or})$. For scenario (2), pure polymer injection we observe steadily declining power dissipation until a final constant power has been reached, corresponding to a core at constant value is reached at a water saturation of $(1 - S_{or})$ but now with an aqueous phase containing polymer. For scenario (3), i.e. slug injection we observe a power dissipation that is identical to scenario (1) until we switch to polymer injection. Subsequently the power shows an increase due to the increased viscosity. After this the power decreases as the polymeric aqueous phase is again replaced by pure water with its lower viscosity. Consequently the limiting power dissipation for water injection is slightly higher than for slug injection due to small amounts of remaining oil.

Figure (3) of produced power derived from the oil production divided by the pumping power multiplied by three shows the ratio versus the pore volume $(u_{inj} \times /(\phi \times length))$. For scenario (1), i.e. pure water injection we observe that the produced ratio is steadily declining after an initial increase until all oil has been produced. For scenario (2), pure polymer injection we observe that after water breakthrough the produced exergy declines below the pumping power and continuing means that less exergy is produced than required for pumping water; there is a net exergy loss. For scenario (3), i.e. slug injection we observe that the produced ratio is identical to scenario (1) until we switch to polymer injection. The power for circulating the fluids increases due to the increased viscosity leading to a decline in the ratio between (1 and 1.5) pore volume. After this the ratio drops below one meaning that the power to circulate the fluids exceeds the power of the produced oil, and the project should be stopped.

Remark: Polymer enhanced oil recovery analytical model

For the slug injection we consider the case that we inject water during a time (t_1), then polymer injection and at time (t_2) we switch back to water without polymer injection. Lake page (341) chapter (8) (Lake, 1989) shows that the analytical solution in the absence of adsorption consists from left to right consists of a Buckley-Leverett solution for $(t - t_2)$, of the polymer solution ((Isaacson & Temple, 1995)) from $(t - t_2)$ to $(t - t_1)$, and again of a Buckley Lever solution from $t - t_2$ ((Lake et al., 2014), (Lake, 1989)), which shows good agreement with our COMSOL numerical solution.

The simulations use the parameters summarized in the table 1

Table 1: Summary of physical input parameters and variables

Physical quantity	Symbol	Value	Unit
Initial concentration	$c - init$	0.001	[-]
Boundary concentration	c	0	[-]
End point oil permeability	k'_{ro}	1.0	[-]
End point water permeability	k'_{rw}	0.5	[-]
Steepness of tangent hyperbolic	δ	0.1	[-]
Porosity	φ	0.3	[-]
Peclet number	$1/Pe$	50000	[-]
Residual oil	S_{or}	0.3	[-]
Connate water saturation	S_{wc}	0.2	[-]
Water saturation exponent	n_w	2	[-]
Time to polymer injection for slug	$\varphi L/u_{inj}$	4.5×10^6	[s]
Time to water injection for slug	$2\ \varphi L/u_{inj}$	9×10^6	[s]
Injection velocity	u_{inj}	1.0×10^{-5}	[m/s]
Length reservoir	L	150	[m]
Permeability	k	$1.0e - 12$	[m^2]
Pore volume (PV)	φ × L × 1	45	[m^3]
Rock porosity	φ	0.3	[m^3/m^3]
Oil viscosity	μ_o	0.11	[Pa s]
Water viscosity	μ_{w0}	1e-3	[Pa s]
Viscous slope	μ_{wp}	0.02	[Pa s]
Injection concentration	c	120	[ppm]

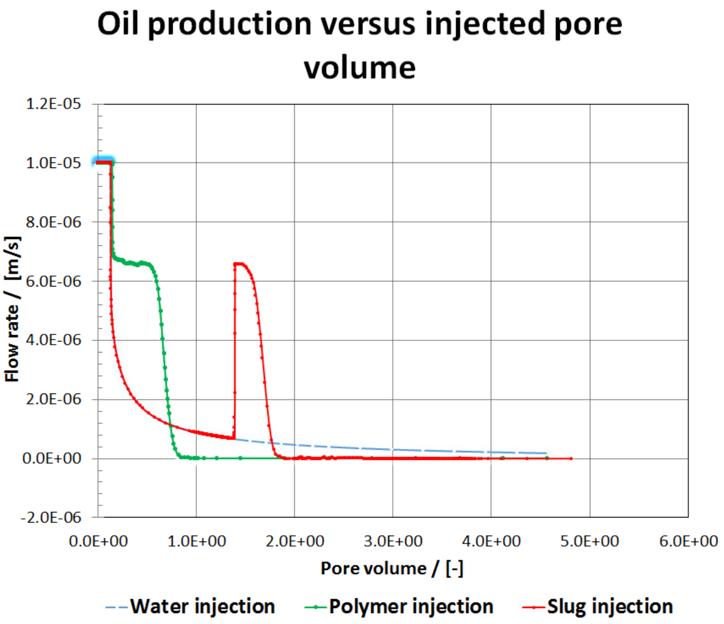

Figure 1: The produced oil ($m^3/m^2/s$) versus the injected pore volume ($u_{inj}t/(\phi \times length)$).

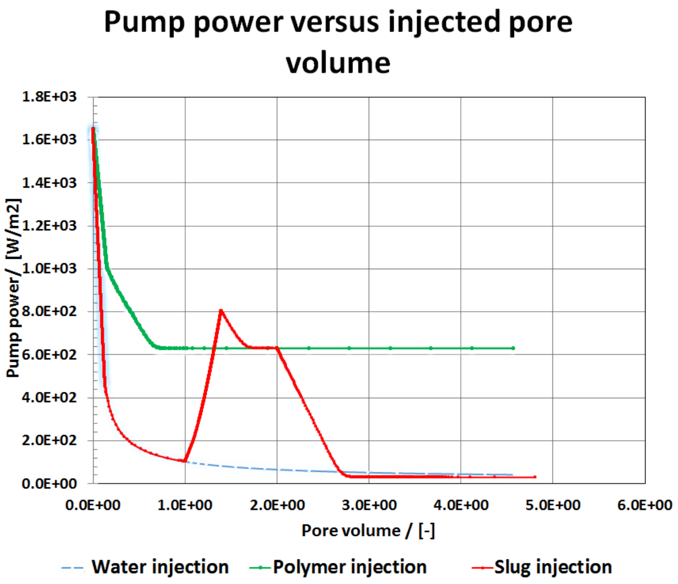

Figure 2: The integrated pressure gradient time the injection velocity (u_{inj}) (W/m^2) versus the injected pore volume ($u_{inj}t/(\phi \times length)$).

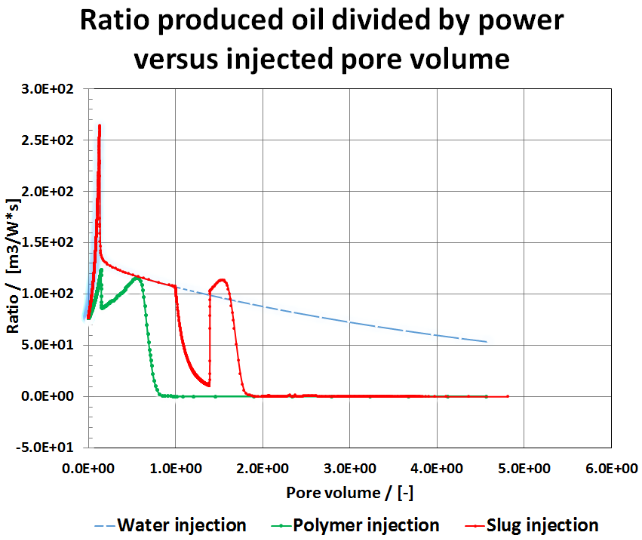

Figure 3: The ratio (between oil production divided by the dissipated pumping power) versus the pore volume ($u_{inj} \times /(\phi \times length)$).

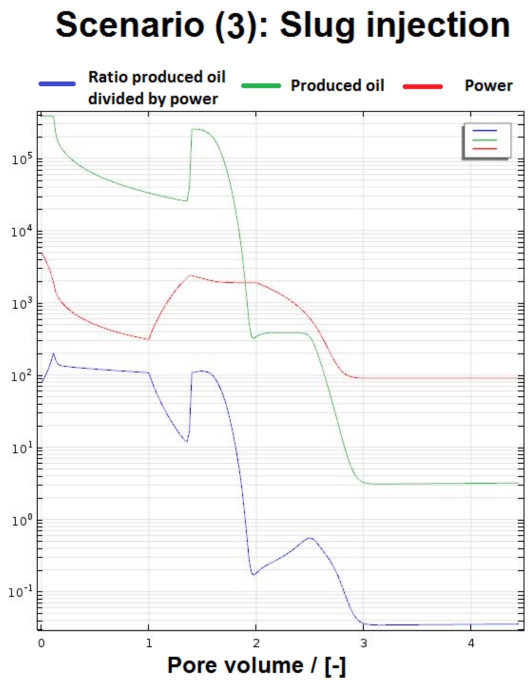

Figure 4: Scenario 3, the produced oil ($m^3/m^2/s$), dissipated pumping power (W/m^2), and the ratio (between oil production divided by the dissipated pumping power) ($1/pa$) versus the injected pore volume ($u_{inj}t/(\phi \times length)$).

5 Conclusion

- Using a 1-D model of polymer displacement it is possible to analyze the exergy (maximum attainable work) balance of viscosified water injection.
- The circulation exergy exceeds the exergy costs for drilling, casing, tubing and cleaning.
- The analysis shows that polymer injection leads to slightly higher exergy costs for circulation of the fluids, but can for the conditions considered accelerate the production.
- A consideration for more cases is necessary to decide whether permanent polymer injection can compete with optimized slug injection.
- The analysis shows that at the end of the project, both for permanent polymer injection and slug injection, the circulation exergy exceeds the exergy to be retrieved from the produced oil.

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