Exergy Analysis of Polymer Flooding in Clastic Reservoirs

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Introduction

The water drive recovery efficiency of medium viscosity oil suffers from low displacement efficiency, vertical sweep efficiency and areal sweep-efficiency. By injection of polymer solutions we can improve these three efficiencies. This paper uses 1-D displacement of oil to compare the recovery history for three scenarios, viz. water injection, polymer water injection and polymer slug injection. We leave a two dimensional or three dimensional version of the model for future work. Both the oil recovery rates and cumulative recovery is calculated. The exergy content of the produced oil 10.7 [kWh/liter] is compared to the dissipated power $3 \times \int_0^{length} dx\, u\, \Delta P$ to circulate the fluids. The factor of three arises from the conversion of the fuel exergy to electricity and taking into account the efficiency of the pump. Our main interest is to calculate 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. . It is argued that this 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 behaviour.

Objectives of this study

- To develop a workflow for exergy analysis for enhanced oil recovery (EOR) by polymer injection
  - Numerical simulation for three scenarios viz., water injection, polymer injection and slug injection
  - Comparison of production rates, cumulative production, dissipated power during fluid circulation and ratio of oil production rate and dissipated power.
- To investigate whether at the end of the project the dissipated power exceeds the exergy obtained from the oil

Polymer recovery 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 equation for the water phase and the dissolved polymer phase read

$$\varphi\partial_t S_w + \partial_x(uf_w) = 0$$
$$\varphi\partial(cS_w) + \partial_x(ucf_w) = 0$$

The relative permeability for the aqueous phase and oleic phase

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

$$k_{ro}(S_w) = \begin{pmatrix} 1 & \text{for} & 0 \le S_w \le S_{wc} \\ k'_{ro}\left(1-\frac{S-S_{wc}}{1-S_{wc}-S_{or}}\right)^{n_o} & \text{for} & s_{wc} \le S_w \le 1-S_{or} \\ 0 & \text{for} & 1-s_{or} S_w \le 2 \end{pmatrix}$$

The fractional flow function (f_w) an be written as

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

The where the polymer (Arabic gum) concentration dependent viscosity of the aqueous phase is giv-- --

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

where μ_{wp} = 0.02 and (c) is the concentration in [ppm].

Three scenarios are implemented by defining

- *Scenario 1*: c = 0
- *Scenario 2*: c = c_{bound} = 0.001
- *Scenario 3*: $c_{bound} \times (\tan nh(t - tijd1) - \tan nh(t - tijd2))$
  with, $\tan nh(x)$ = (0.5+0.5) × $\tan nh$ (x/ δ); where δ = 0.1

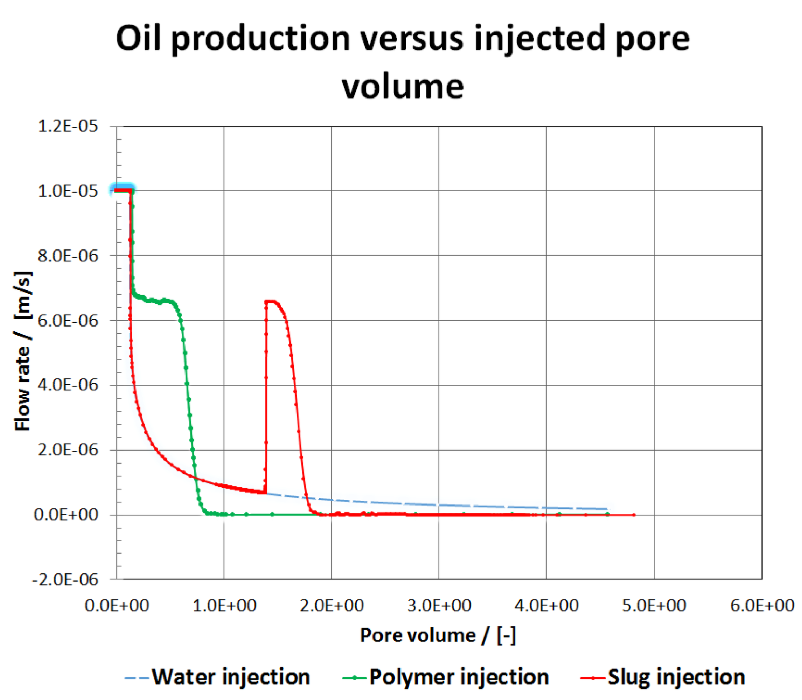
Exergy contributors

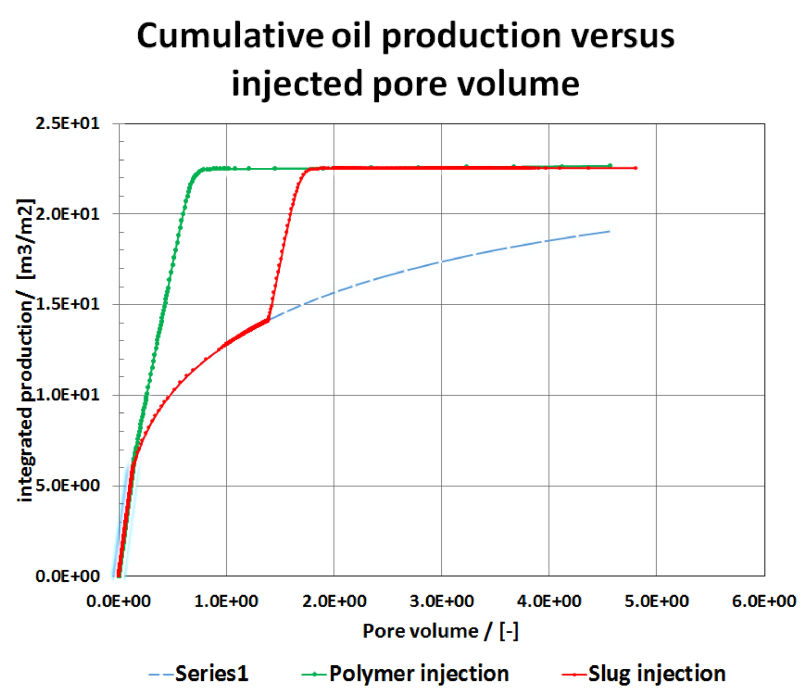
- Recovery exergy: u_{inj} [m/s] × 10700 [kWh/m3]
- Circulation exergy: $3 \times \int_0^{length} dx\, u\, \Delta P$
- Drilling exergy: ~ crushing energy ~ 116 [MJ/m] (PM)
- Tubing / casing: 35.8 [GJ/ton-steel] (PM)
- Labour costs: 0.21 [€/kWh]
- Polymer manufacturing costs: expected to be low because polymer concentration is low (< 1000 [ppm])

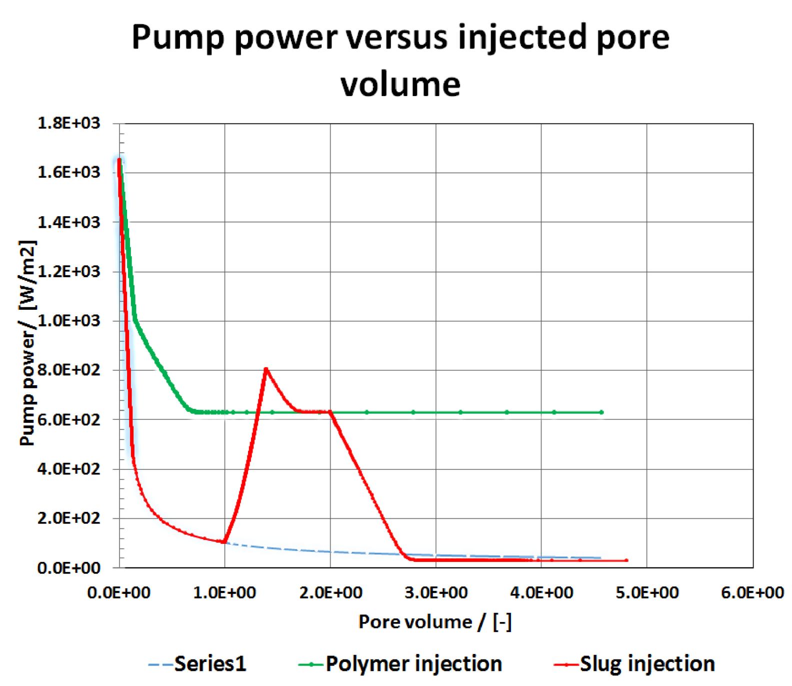
Results and discussion

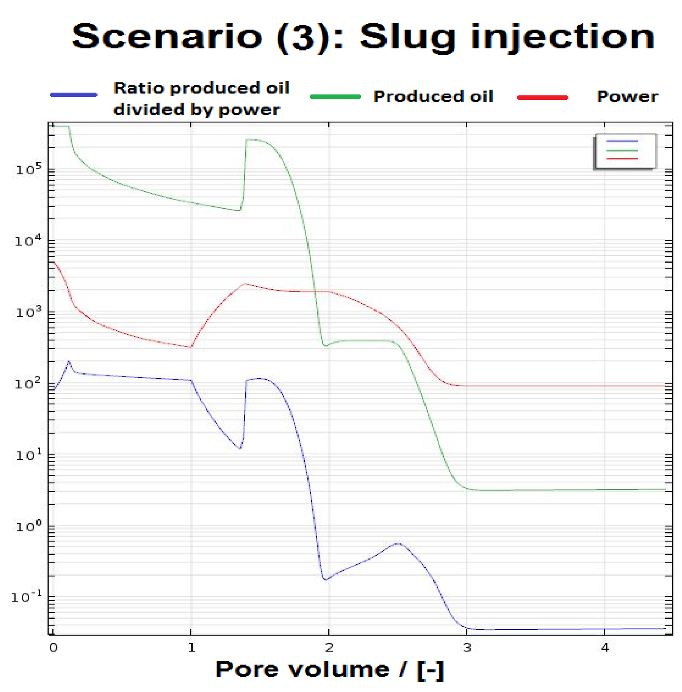
Table 1: Summary of physical input parameters and variables

Physical quantity	Symbol	Value	Unit
End point oil permeability	k'_{ro}	1.0	[-]
End point water permeability	k'_{rw}	0.5	[-]
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)	$\varphi \times$ L $\times$ 1	45	[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]









Conclusion

- Using a 1-D model of polymer displacement it is possible to analyse the exergy (maximum attainable work) balance of viscosified water.
- The circulation exergy costs exceeds the exergy 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 more extensive analysis 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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