The University of Tulsa
Petroleum Reservoir Exploitation Projects

Optimization of the CO_2 Huff-n-Puff Process in an Unconventional Reservoir Using a Machine Learning Proxy

Azad Almasov, Mustafa Onur, and Albert Reynolds

4th BIENNIAL CO_2 FOR EOR AS CCUS CONFERENCE
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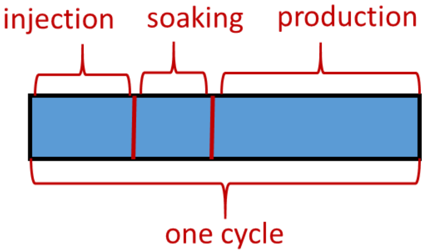
Outline

- Introduction
- Objectives
- Transport Mechanisms of CO_2
- NPV Formulation
- LS-SVR Proxy
- Optimization of Well-Control Variables
- Conclusions

Introduction

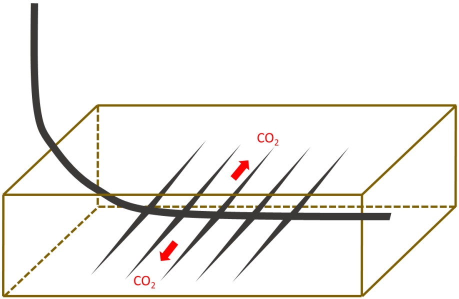
- The recovery factor (RF) of unconventional oil reservoirs is usually less than 10 %
- Miscible CO_2 injection as an Huff-n-Puff process seems to be preferable EOR method for such reservoirs



One cycle of Huff-n-Puff process

Introduction: CO_2 Huff-n-Puff

- CO_2 Huff-n-Puff is a cyclic miscible CO_2 EOR method



- Purpose: lower viscosity and density of oil; maintain pressure
- In this study, reservoir type: unconventional tight-oil or shale-oil; Injected gas: CO_2

Transport Mechanisms in Unconventional Reservoirs

- Hydrodynamic dispersion
- Convection
- Multicomponent adsorption-Langmuir Model. Normally, only the adsorption of light components (e.g. C_1, C_2, N_2, CO_2) is significant

$$\frac{\partial}{\partial t}\left((1-\phi)\rho_s w_{is} + \phi \sum_{j=1}^{N_p} \rho_j S_j w_{ij}\right) + \nabla \cdot \left(\sum_{j=1}^{N_p} \rho_j w_{ij} \mathbf{u_j} - \phi \rho_j S_j \mathbf{K_{ij}} \nabla w_{ij}\right) = 0$$

where

$$(K_{xx})_{ij} = \frac{(D_{xx})_{ij}}{\tau} + \frac{\alpha_{lj} u_{xj}^2 + \alpha_{tj}(u_{yj}^2 + u_{zj}^2)}{\phi S_j |\mathbf{u_j}|}$$

and

$$(K_{xy})_{ij} = \frac{(\alpha_{lj} - \alpha_{tj}) u_{xj} u_{yj}}{\phi S_j |\mathbf{u_j}|}$$

where l refers longitudinal direction, t - any direction perpendicular to direction l
Lake et al. (2014).

Modeling: Transport Mechanisms in CMG-GEM

- We need to achieve miscibility for molecular diffusion of CO_2
- We define molecular diffusion of CO_2 in oil phase (in our cases $D_{CO_2,oil}$= 0.0008 cm^2/sec)
- Non-Darcy flow can be included using different type of correlations (When a *general correlation* is used, it includes, porosity, saturation permeability dependent flow of *each phase*)

Modeling: Case Study (CMG-GEM) (SPE 169575): Composition-Bakken Shale-Oil

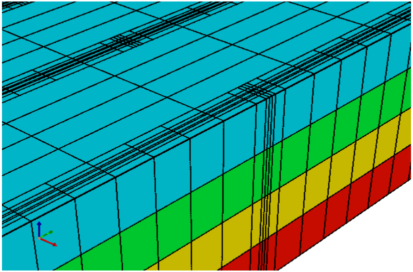
- Primary (production fluid) and secondary (injection fluid, CO_2) are modelled in CMG-WinProp commercial fluid package
- Peng-Robinson EOS model is used
- MCMMP $=$ 4,875 psi; FCMMP$=$10,000 psi, p_i=8,000 psi, T_i=240 °F
- MCM mechanism is: *vaporizing and condensing combined gas drive*
- CO_2 is injected at supercritical conditions

Component	Primary	Secondary
CO2	0.01	100
N2-C1	22.03	0
C1-C4	20.63	0
C5-C7	11.7	0
C8-C12	28.15	0
C13-C19	9.4	0
C20-C30	8.08	0
Sum	100	100

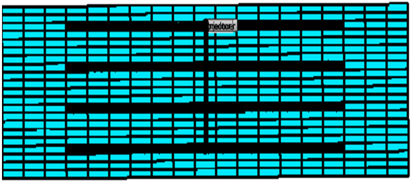
Mass percentage of each element in primary (reservoir) fluid and secondary (injected) fluid.

Modeling: Case Study (CMG-GEM) (SPE 169575): Reservoir

- Grid: uniform Cartesian; fracture: LS-LR (logarithmically spaced-locally refined) grid is used
- Hydraulic fracture is modeled using CMG-planar fracture
- No geomechanical effects are considered



(a) 3D grid



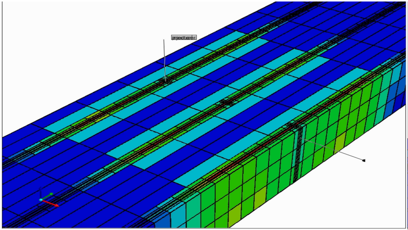
(b) Areal grid, top view

Modeling: Case Study (CMG-GEM) (SPE 169575): Reservoir

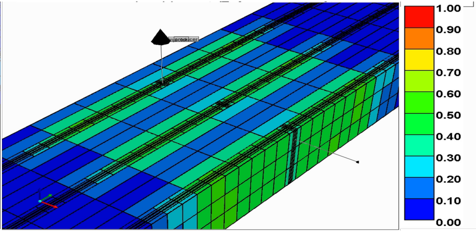
Table: Reservoir parameters for CO_2 Huff-n-Puff process.

Parameter	Value	Unit
The model dimensions	340x1300x40	ft
Initial reservoir pressure	8000	psi
Reservoir temperature	240	°F
Initial water saturation	0.2	fraction
Total compressibility	1e-6	1/psi
Matrix permeability	50 to 5000	nD
Matrix porosity	0.08	fraction
Space between fractures	80	ft
Fracture conductivity	50	mD-ft
Fracture permeability	5	D
Fracture half-length	350	ft
Fracture height	40	ft

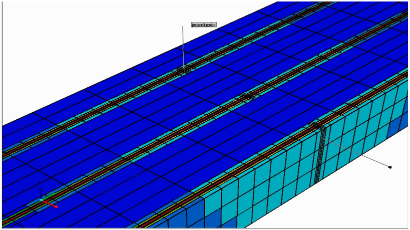
Importance of Diffusion



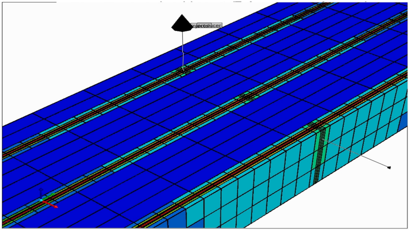
(a) end of injection of 1^{st} cycle (**DIFF**)



(b) end of soaking of 1^{st} cycle (**DIFF**)



(c) end of injection of 1^{st} cycle (**NONDIFF**)



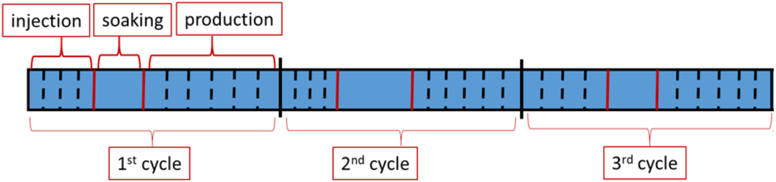
(d) end of soaking of 1^{st} cycle (**NONDIFF**)

Life-cycle Production Optimization: NPV Formulation

- We fix the number of cycles (N_c), and duration of each cycle. We define fractions as follows:

$$\widehat{\Delta t}_p^n = \frac{\Delta t_p^n}{\Delta t^n} \qquad \widehat{\Delta t}_i^n = \frac{\Delta t_i^n}{\Delta t^n} \qquad \widehat{\Delta t}_{soak}^n = 1 - \widehat{\Delta t}_p^n - \widehat{\Delta t}_i^n$$

- Injection and production periods of each cycle are divided into N_i^n and N_p^n control steps, respectively ($\delta\Delta t_p^n$ and $\delta\Delta t_i^n$). Soaking time does not need to be divided.



Objective Function: NPV

- n is cycle, and N_c is the total number of cycles.

$$J(u) = \sum_{n=1}^{N_c} \frac{\Delta t^n}{(1+b)^{\frac{t_n}{365}}} \left[\frac{\widehat{\Delta t}_p^n}{N_p^n} \sum_{j=1}^{N_p^n} (r_o^n \bar{q}_{o,j}^n - c_{CO2,p}^n \bar{q}_{CO2,p,j}^n) - \frac{\widehat{\Delta t}_i^n}{N_i^n} \sum_{j=1}^{N_i^n} (c_{CO2,i}^n \bar{q}_{CO2,i,j}^n) \right]$$

$N_p^n = \dfrac{\Delta t_p^n}{\delta \Delta t_p^n}$ - number of control steps of production period for the n^{th} cycle

$N_i^n = \dfrac{\Delta t_i^n}{\delta \Delta t_i^n}$ - number of control steps of injection period for the n^{th} cycle

- Well control variables (u): $q_{CO_2,i,j}^n$, $p_{wf,j}^n$, $\widehat{\Delta t}_p^n$, $\widehat{\Delta t}_i^n$
- Total number of control variables: $N_u = \sum_{n=1}^{N_c} (N_i^n + N_p^n) + 2N_c$
- Total number of control time steps: $N_t = \sum_{n=1}^{N_c} (N_i^n + N_p^n)$

Constraints

- Constraints used in optimization procedure are:

$$0.3 \leq \widehat{\Delta t}_p^n \leq 1 \qquad \text{and} \qquad \frac{1-\widehat{\Delta t}_p^n}{2} \leq \widehat{\Delta t}_i^n \leq 1-\widehat{\Delta t}_p^n$$

- Bound constraints for production BHP (psi) and injection rate (MSCF/Day) are:

$$1500 < p_{bh} < 2400 \qquad \text{and} \qquad 20 < q_i < 60$$

LS-SVR Proxy

- Normalization of control variables and NPV

$$\underline{u} = \frac{u - u^{min}}{u^{max} - u^{min}}$$
$$\underline{J}(\underline{u}) = \frac{J(u) - J^{min}}{J^{max} - J^{min}}$$

- LS-SVR - Least Square Support Vector Regression Approximation of normalized NPV:

$$\underline{\hat{J}}(\underline{u}) = \sum_{k=1}^{N_s} \alpha_k K(\underline{u}_k, \underline{u}) + b$$

where α_k is Lagrange multiplier of the error term of set k;
b is bias term.

- They are determined by using constraint optimization.
K is a RBF used as the Kernel function:

$$K(\underline{u}_k, \underline{u}) = \exp\left(-||\underline{u}_k - \underline{u}||_2^2 / \sigma^2\right)$$

where, σ is taken as $0.5\sqrt{N_u}$ as rule of thumb (Guo et al., 2018)

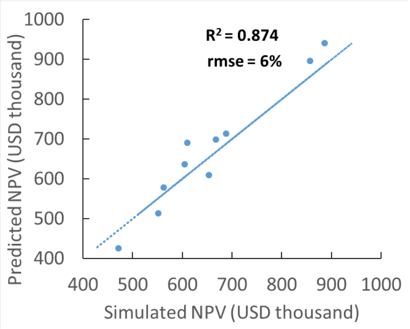
Sampling Procedure

- A single-porosity model with 4 hydraulic fractures with Darcy flow is considered (k_f=5 D, k_M=5000 nD)
- 5 cycles are considered. Each cycle is 600 days
- To start, simplified problem is considered: $N_p^n = N_i^n = 1$ for each cycle n
- Coefficients used in NPV are as follows $r_o = 63$ \$/STB, $b = 0.0217$, $c_{CO_2,p} = 9$ \$/1000 lb, $c_{CO_2,i} = 5$ \$/MSCF
- $\widehat{\Delta t}_p$, $q_{CO_2,i}$, p_{bh} for each cycle are sampled using LHS between their lower and upper bounds
- Then using the following constraint $\widehat{\Delta t}_i$ is sampled

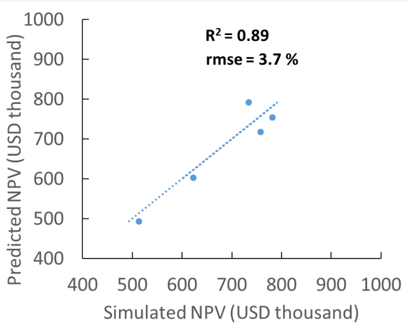
$$\frac{1-\widehat{\Delta t}_p^n}{2} \leq \widehat{\Delta t}_i^n \leq 1-\widehat{\Delta t}_p^n$$

Training Procedure

- 35, 10, and 5 samples are generated, separately
- After training 35 samples, to improve accuracy extra 10 samples included to training set one-by-one from sample giving maximum validation error to lowest
- After training 45 samples, the LS-SVR model is validated using 5 samples



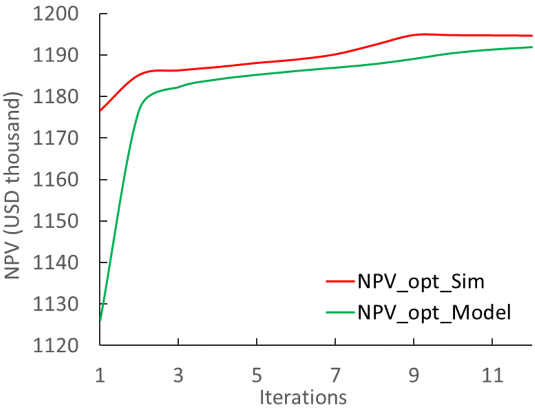
(a) Trained 35, validated 10



(b) Trained 45, validated 5

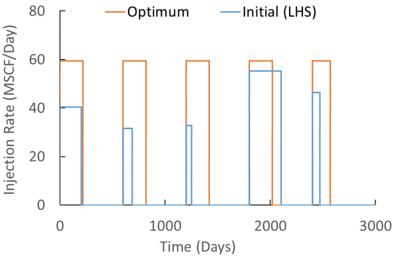
Optimization Procedure

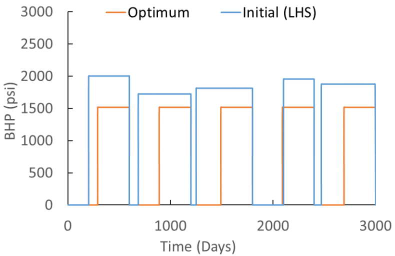
- The sequential quadratic programming (SQP) algorithm is used. Analytical gradients of the LS-SVR model are provided
- Results of iterative sampling



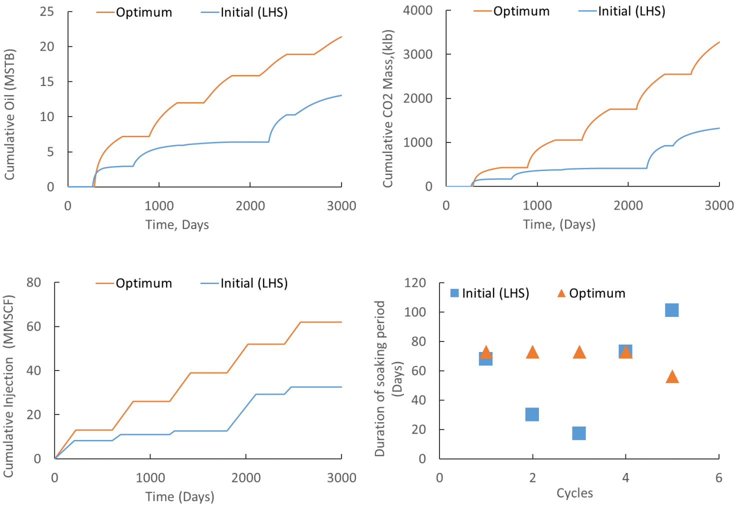
Optimization Results

- Well-control variables of initial and optimum cases





Optimization Results



Conclusions

- With good training strategy, LS-SVR model can predict NPV due to CO_2 Huff-n-Puff process
- This LS-SVR model can be used in maximization process, accurately and efficiently
- Training strategy affects optimization
- Molecular diffusion was found to be important
- Duration of soaking period was found to be important

Acknowledgements

- Companies supporting The University of Tulsa Petroleum Reservoir Exploitation Projects (TUPREP)

Why Huff-n-Puff and Why CO_2 In Unconventional Oil Reservoirs?

- Applicable in reservoirs with nanopores
- It can extract oil from nanoscale matrix through molecular diffusion
- Abundant CO_2 from different sources; ecologically is also favourable to inject underground
- Miscibility should be achieved

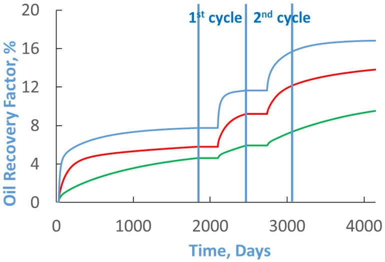
Sensitivity Analysis

- After 5 years of production, we consider 2 cycles of Huff-n-Puff and then a 3-year production period after Huff-n-Puff

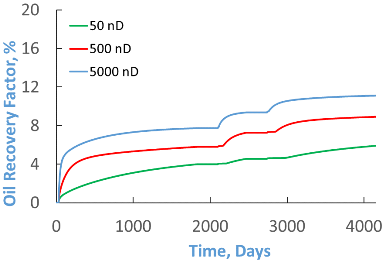
Parameters	**Cases**		
Matrix permeability, nD	50	500	5000
Injection rate, MSCF/Day	50	100	150
Production BHP, psi	1500	2000	2500
Soaking time at each cycle, months	0	3	6
Production time at each cycle, months	12	12	12
Molecular diffusion of CO_2 in oil phase	on/off	on/off	on/off
Dual porosity	off	on/off	off
Dual permeability	off	on/off	off
Total number of cycles	2	2	2

Sensitivity Analysis: Matrix Permeability-Single Porosity

$q_{CO2,i}$=100 MSCF/Day
p_{bh}=2000 psi
Δt_i=6 months
Δt_{soak}=3 months



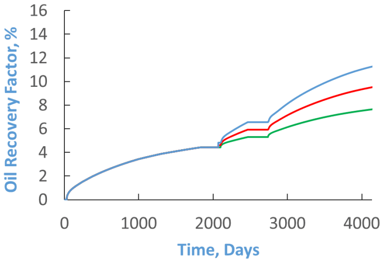
(a) Diffusion



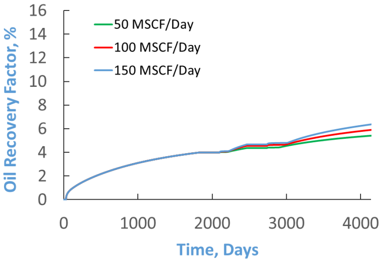
(b) Non-Diffusion

Sensitivity Analysis: Injection Rate-Single Porosity

k_M=50 nD
p_{bh} =2000 psi
Δt_i=6 months
Δt_{soak}=3 months



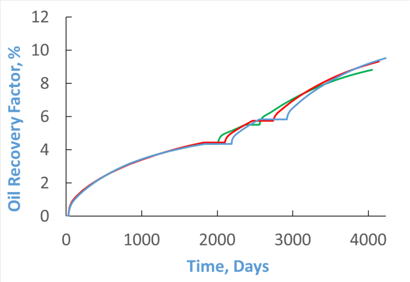
(a) Diffusion



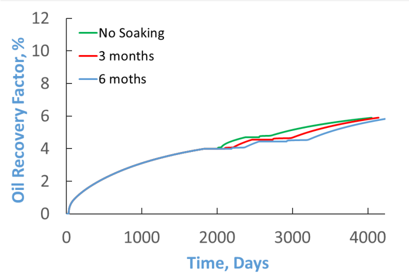
(b) Non-Diffusion

Sensitivity Analysis: Duration of Soaking Period-Single Porosity

k_M=50 nD
$q_{CO_2,i}$=100 MSCF/Day
p_{bh}=2000 psi
Δt_i=6 months



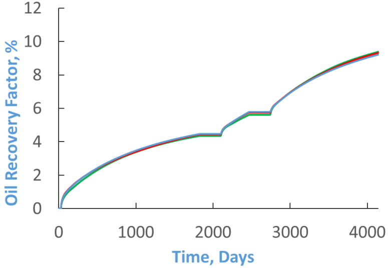
(a) Diffusion



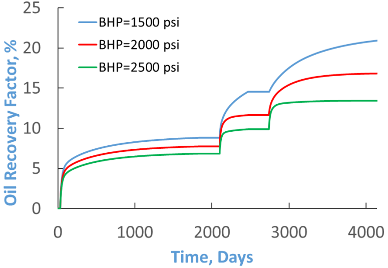
(b) Non-Diffusion

Sensitivity Analysis: Production BHP-Single Porosity

k_M=50 nD and 5000 nD
$q_{CO_2,i}$=100 MSCF/Day
Δt_i=6 months
Δt_{soak}=3 months



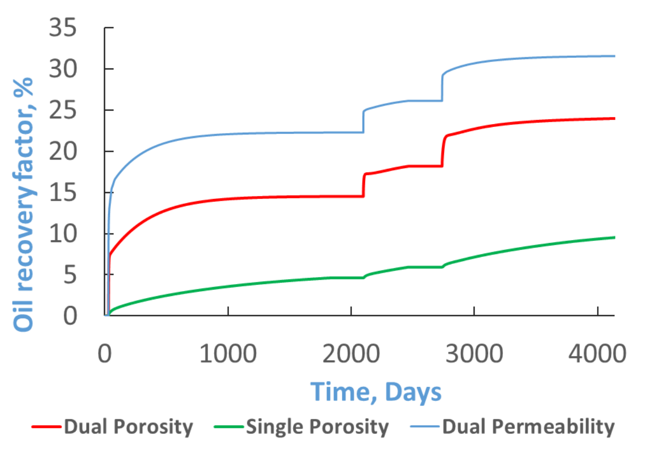
(a) Diffusion, k_M=50 nD



(b) Diffusion, k_M=5000 nD

Sensitivity Analysis: Effect of Natural Fractures

k_M=5000 nD; $q_{CO_2,i}$=100 MSCF/Day; p_{bh}=2000 psi
Δt_i=6 months; Δt_{soak}=3 months; k_f=500 mD
Molecular diffusion is considered



Summary of Sensitivity Results

- Molecular diffusion of CO_2 in oil phase plays important role in Huff-n-Puff performance
- In natural fractured reservoirs, we need to inject more CO_2, and for a longer time to be able to achieve miscibility
- We see benefits of soaking period in diffusion case
- Increasing injection rate increases RF
- Increasing matrix permeability increases RF
- Production BHP does not seem to influence RF very low permeable reservoir since diffusion is more dominant than convection

Optimization Procedure

- The sequential quadratic programming (SQP) algorithm is used. Analytical gradients of the LS-SVR model are provided
- Usually after 4 iterations, we reach maximum
- Different initial guesses yield the same NPV value
- Training affects optimization results
- Simulator and LS-SVR outputs at the optimum are close around 3% relative error