Fracture to Matrix Transfer in Unconventional Reservoirs

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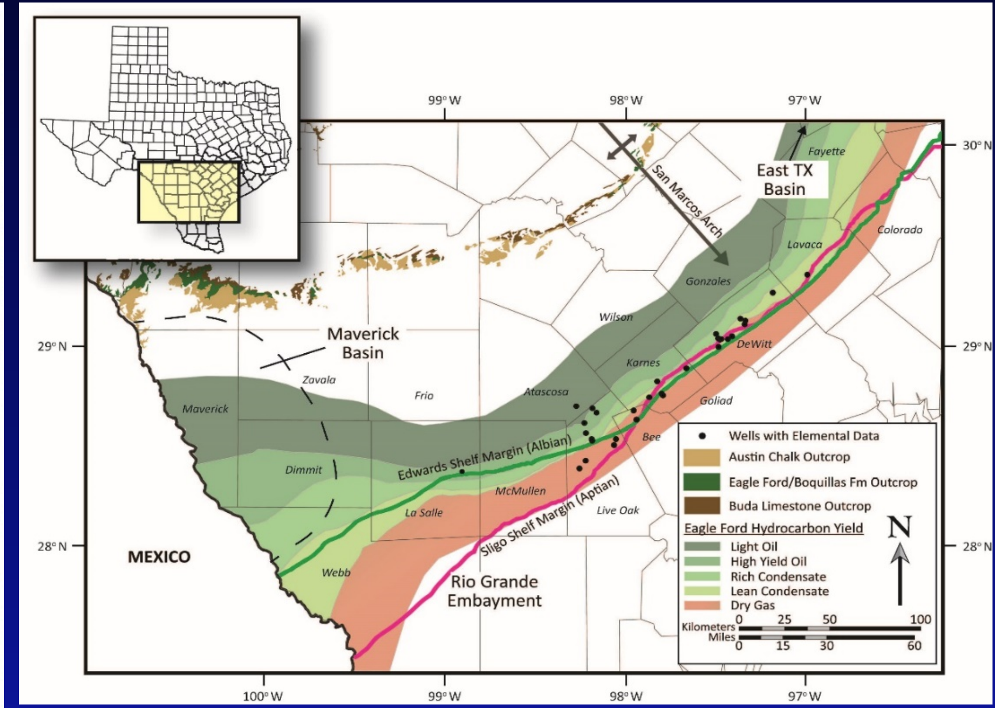
Objectives

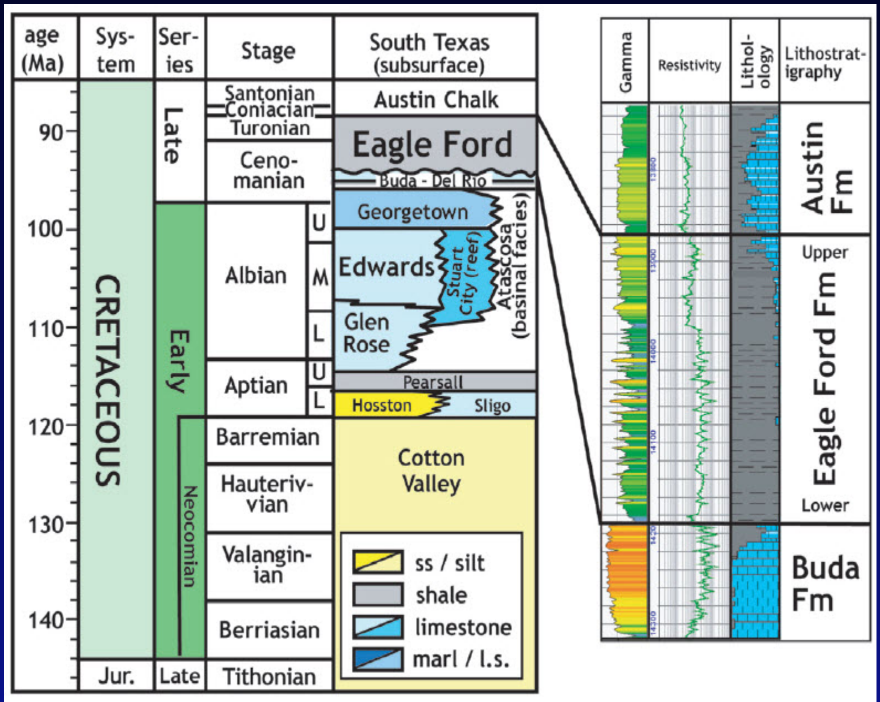
- Develop a physically transparent and flexible **compositional dual-porosity implicit numerical solution** method for evaluating **primary production** and **Gas Injection EOR** in stimulated **shale** reservoirs
- Understand the **transport mechanism** at the **fracture-matrix interface** for both primary production and Gas EOR for shale reservoirs
- Quantify molecular diffusion mass transport across fracture-matrix interface between **a static gas column and a static oil column**
- Evaluate unconventional reservoir performance via **production data analysis**

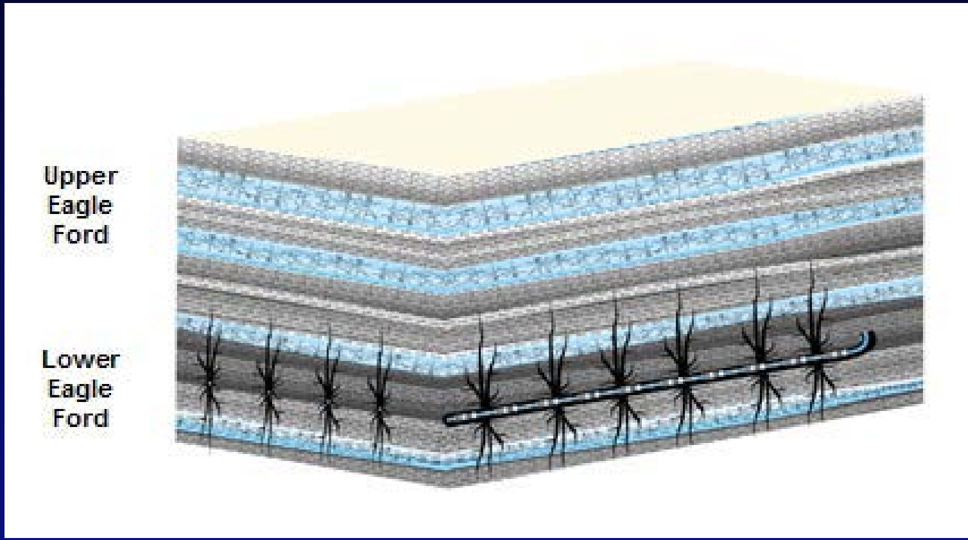
Eagle Ford Reservoir Characterization

Eagle Ford formation was deposited at the end of Western Interior Sea of North America during Late Cretaceous, an interval of 9 million years.

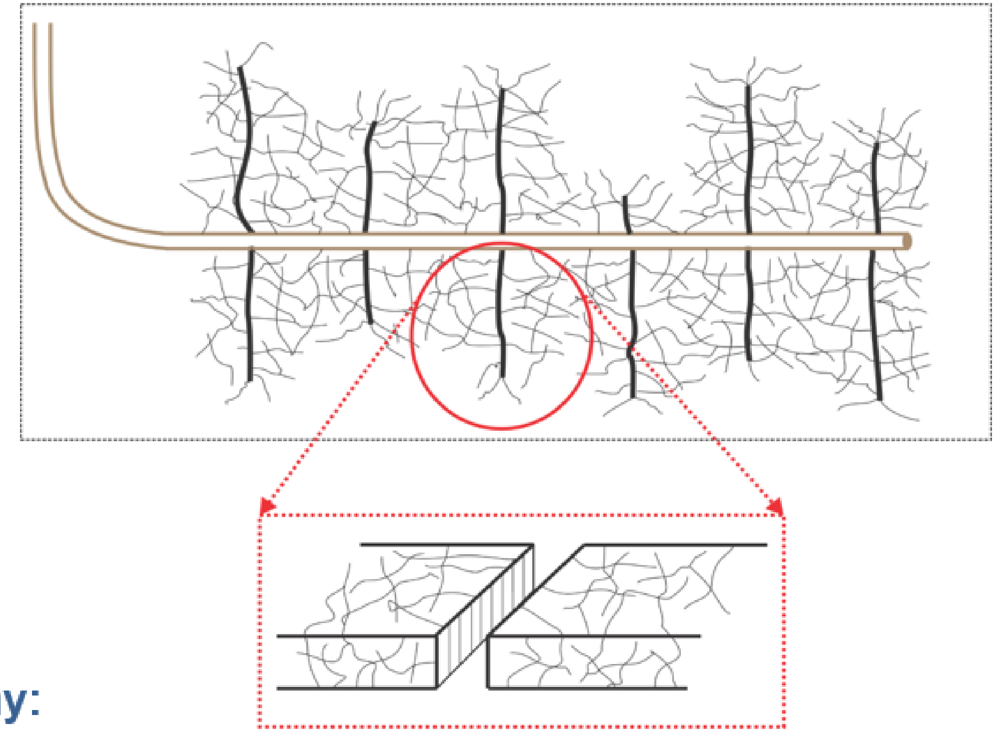


Eagle Ford Reservoir Characterization





Dual-Porosity Model



Flow Hierarchy:

$$Matrix \xrightarrow{FEEDS} Fracture \xrightarrow{FEEDS} Hydraulic\ Fracture \qquad k_{f,eff} = k_f \phi_f + k_m$$

Compositional Model

Solution Methods:

Unknowns:

Solution Methods	Unknowns
Conventional Fully Implicit Single-Porosity Solution	$p, \{x_1, x_2, \ldots, x_{nc}\}, \{y_1, y_2, \ldots, y_{nc}\}, S_o, S_w, S_g$
1980s Sequential Single-Porosity Solution (Volume Balance)	p $\{z_1, z_2, \ldots, z_{nc}\}$ $\{x_1, x_2, \ldots, x_{nc}\}, \{y_1, y_2, \ldots, y_{nc}\}$ S_o, S_w, S_g
This Thesis Implicit Dual-Porosity Solution	$\{p, z_1, z_2, \ldots, z_{nc}\}$ $\{x_1, x_2, \ldots, x_{nc}\}, \{y_1, y_2, \ldots, y_{nc}\}$ $\{S_o, S_w, S_g\}$

Dual-Porosity Compositional Model

Fracture:

$$\left\{ \begin{array}{l} \nabla \cdot k_{f,eff} \begin{bmatrix} \lambda_{of} \xi_{of} x_{cf} \left(\nabla p_{of} - \gamma_o \nabla D \right) \\ + \lambda_{gf} \xi_{gf} y_{cf} \left(\nabla p_{gf} - \gamma_g \nabla D \right) \\ + \lambda_{wf} \xi_{wf} w_{cf} \left(\nabla p_{wf} - \gamma_w \nabla D \right) \end{bmatrix} \\ + \begin{bmatrix} \xi_{of} x_{cf} \hat{q}_{of} \\ + \xi_{gf} y_{cf} \hat{q}_{gf} \\ + \xi_{wf} w_{cf} \hat{q}_{wf} \end{bmatrix} \end{array} \right\} - \left(\tau_{t,c} \right)_{f/m} = \frac{\partial}{\partial t} \left[\phi z_c \left(\xi_o S_o + \xi_g S_g + \xi_w S_w \right) \right]_f \qquad ; c = 1, 2, \ldots nc + 1$$

$$= \frac{\partial}{\partial t} \left[\phi \left(\xi_o S_o x_c + \xi_g S_g y_c + \xi_w S_w w_c \right) \right]_f$$

Matrix:

$$\left(\tau_{t,c} \right)_{f/m} = \frac{\partial}{\partial t} \left[\phi z_c \left(\xi_o S_o + \xi_g S_g + \xi_w S_w \right) \right]_m$$

$$= \frac{\partial}{\partial t} \left[\phi \left(\xi_o S_o x_c + \xi_g S_g y_c + \xi_w S_w w_c \right) \right]_m$$

Dual-Porosity Implicit Model—This Work

Molar mass balance equation (Multi-component, multi-phase) in the fracture:

$$-\nabla\cdot\left(y_c\xi_g\vec{v}_g+x_c\xi_o\vec{v}_o+w_c\xi_w\vec{v}_w\right)_f-\tau_{f/m,c}+\hat{q}_{cf}=\frac{z_{c,f}}{v_{t,f}}\phi_f\left\{\begin{aligned}&\left(c_\phi+c_{v_t}\Big|_{T,\{z_c\}}\right)_f\frac{\partial p_f}{\partial t}\\&+\frac{1}{z_{c,f}}\sum_{d=1}^{nc}\left(\frac{\partial z_{c,f}}{\partial z_{d,f}}\frac{\partial z_{d,f}}{\partial t}\right)\\&-\frac{1}{v_{t,f}}\sum_{d=1}^{nc}\left(\overline{v}_{t,d}\frac{\partial z_d}{\partial t}\right)_f\end{aligned}\right\}$$

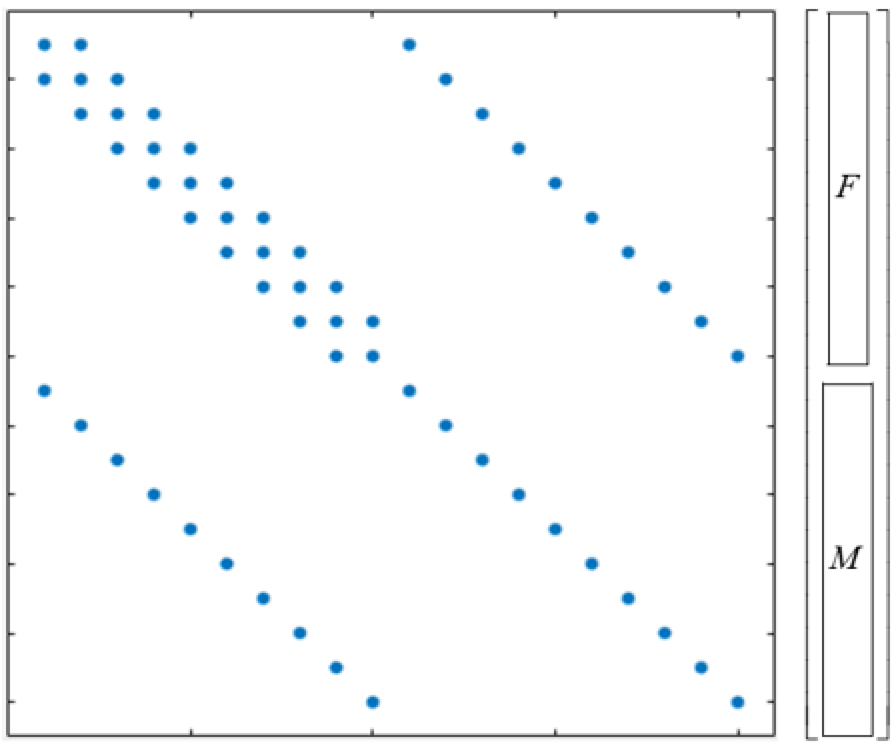
Dual-Porosity Implicit Model—This Work

Molar mass balance equation (Multi-component, multi-phase) in the **matrix:**

$$\tau_{f/m,c} = \frac{z_{c,m}}{v_{t,m}} \phi_m \left\{ \begin{array}{l} \left(c_\phi + c_{v_t}\Big|_{T,\{z_c\}} \right)_m \dfrac{\partial p_m}{\partial t} \\ + \dfrac{1}{z_{c,m}} \displaystyle\sum_{d=1}^{nc} \left(\dfrac{\partial z_{c,f}}{\partial z_{d,f}} \dfrac{\partial z_{d,f}}{\partial t} \right) \\ - \dfrac{1}{v_{t,m}} \displaystyle\sum_{d=1}^{nc} \left(\bar{v}_{t,d} \dfrac{\partial z_d}{\partial t} \right)_m \end{array} \right\}$$

Dual-Porosity Compositional Model

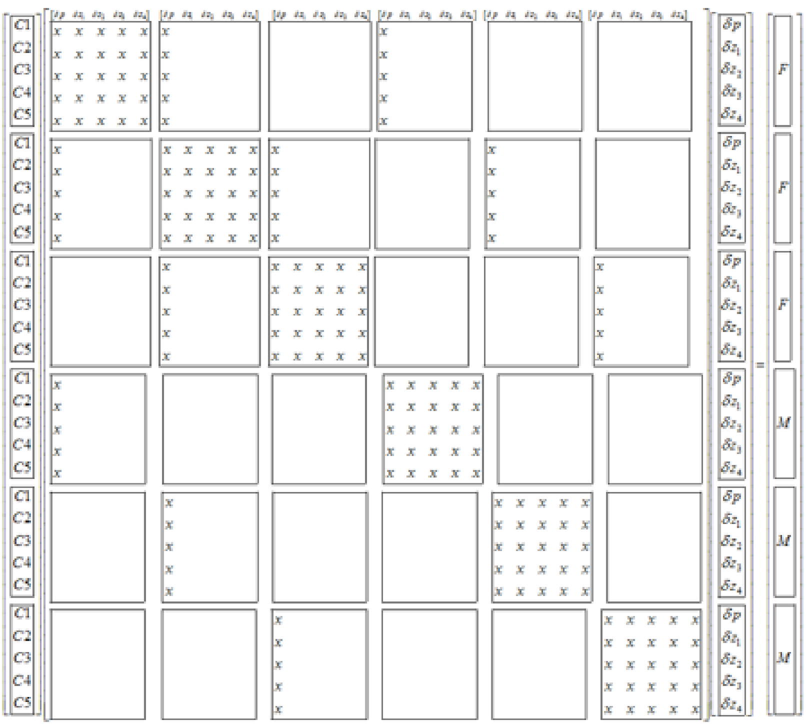
VOLUME BALANCE SOLUTION (Ramirez, CSM, 2010)



$$A\vec{p} = \vec{R} \; ; \; \vec{p} = \begin{bmatrix} \delta p_{of} \\ \delta p_{om} \end{bmatrix}$$

Dual-Porosity Compositional Model

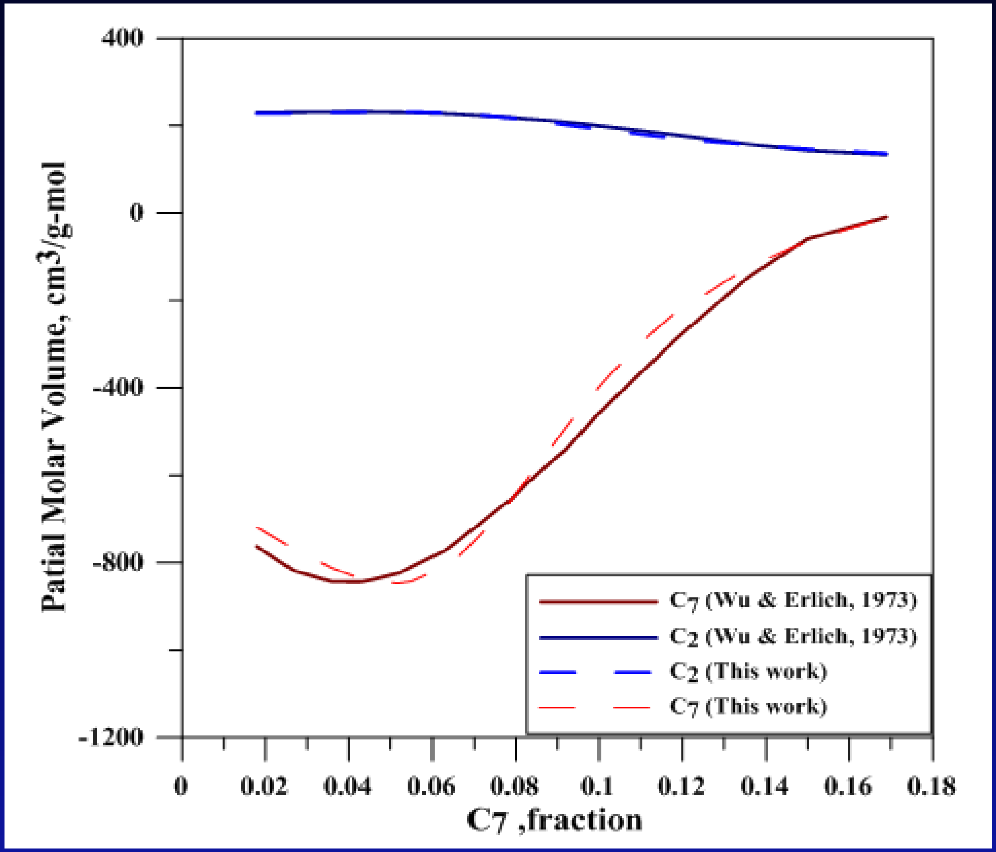
IMPLICIT SOLUTION—This Thesis



$$A\vec{p} = \vec{R}\ ;\quad \vec{p} = \begin{bmatrix} \delta p_{of} \\ \delta z_{1,f} \\ \vdots \\ \delta z_{nc,f} \\ \delta p_{om} \\ \delta z_{1,m} \\ \vdots \\ \delta z_{nc,m} \end{bmatrix}$$

$$\sum_{c=1}^{nc+1} z_c = 1 \qquad \sum_{c=1}^{nc} x_c = 1 \qquad \sum_{c=1}^{nc} y_c = 1 \qquad \sum_{c=1}^{nc} w_c = 1$$

Thermodynamic Validation



Dual-Porosity Compositional Model Including Molecular Diffusion Flux

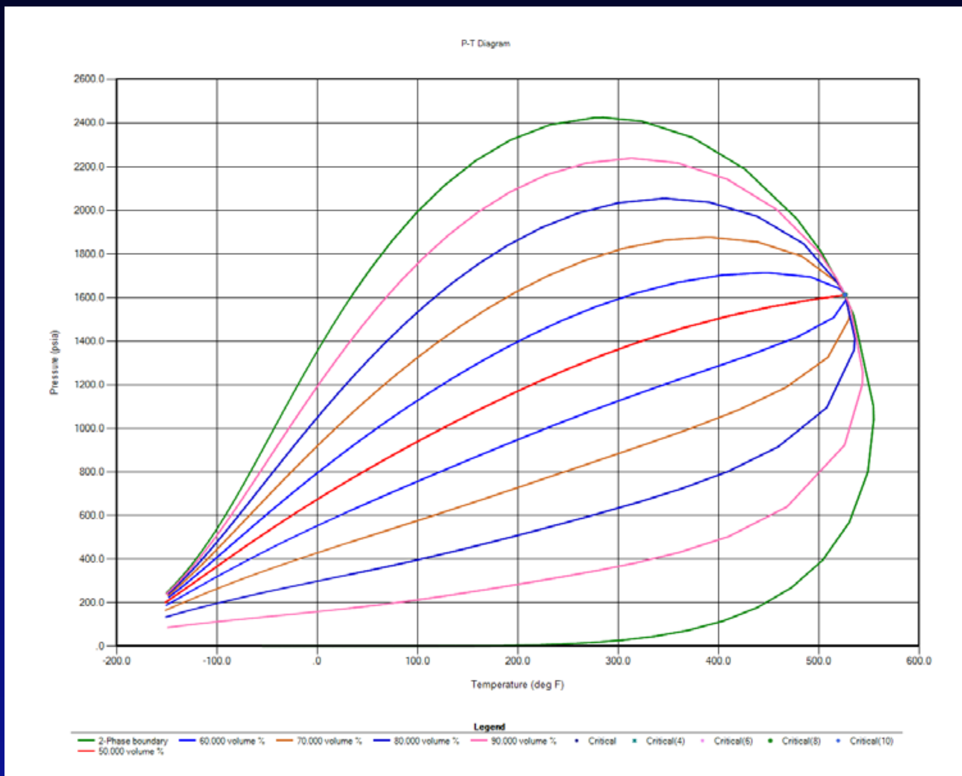
Molar mass balance equation (Multi-component, multi-phase) in the fracture:

$$\left\{-\nabla\cdot\left(\vec{J}_{mol,t,c}+\vec{J}_{adv,t,c}\right)_f-\tau_{f/m,mol,c}-\tau_{f/m,adv,c}\right\}+\hat{q}_{cf}=\frac{z_{c,f}}{v_{t,f}}\phi_f\left\{\begin{array}{l}\left(c_\phi+c_{v_t}\big|_{T,\{z_c\}}\right)_f\dfrac{\partial p_f}{\partial t}\\+\left[\dfrac{1}{z_{c,f}}\displaystyle\sum_{d=1}^{nc}\left(\dfrac{\partial z_{c,f}}{\partial z_{d,f}}\dfrac{\partial z_{d,f}}{\partial t}\right)-\dfrac{1}{v_{t,f}}\displaystyle\sum_{d=1}^{nc}\left(\bar{v}_{t,d}\dfrac{\partial z_d}{\partial t}\right)_f\right]\end{array}\right\}$$

Molar mass balance equation (Multi-component, multi-phase) in the matrix:

$$\tau_{f/m,mol,c}+\tau_{f/m,adv,c}=\frac{z_{c,m}}{v_{t,m}}\phi_m\left\{\begin{array}{l}\left(c_\phi+c_{v_t}\big|_{T,\{z_c\}}\right)_m\dfrac{\partial p_m}{\partial t}\\+\dfrac{1}{z_{c,m}}\displaystyle\sum_{d=1}^{nc}\left(\dfrac{\partial z_{c,f}}{\partial z_{d,f}}\dfrac{\partial z_{d,f}}{\partial t}\right)-\dfrac{1}{v_{t,m}}\displaystyle\sum_{d=1}^{nc}\left(\bar{v}_{t,d}\dfrac{\partial z_d}{\partial t}\right)_m\end{array}\right\}$$

Hydrocarbon Fluid System Used in the Model



$$T_{res} = 278\,°F$$

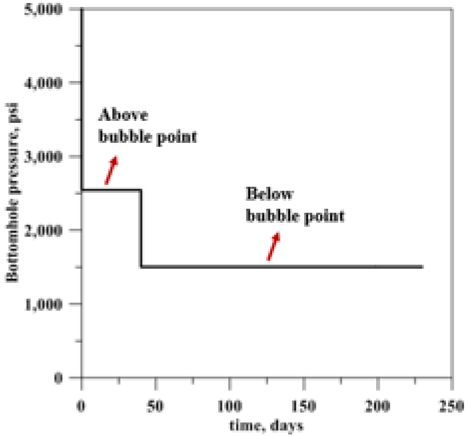
$$p_{sat} = 2395\ psi$$

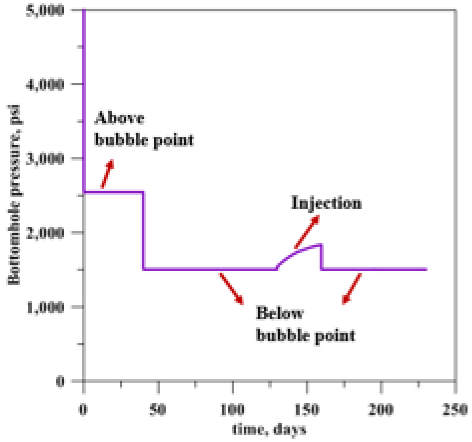
Hydrocarbon Fluid System

Component	Mole Fraction
CO2	0.01
C1	0.42
n-C4	0.21
n-C10	0.36
Total	1.00

Assessment of Cyclic Gas Injection Enhanced Oil Recovery

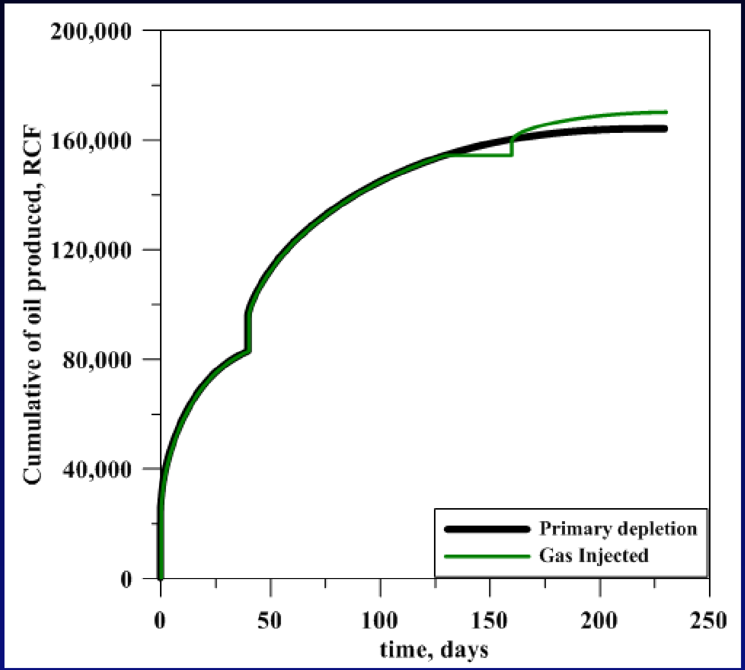
Injected Gas: $z_{nc} = \{C_1, CO_2, nC_4, nC_{10}\} = \{0.97, 0.01, 0.01, 0.01\}$

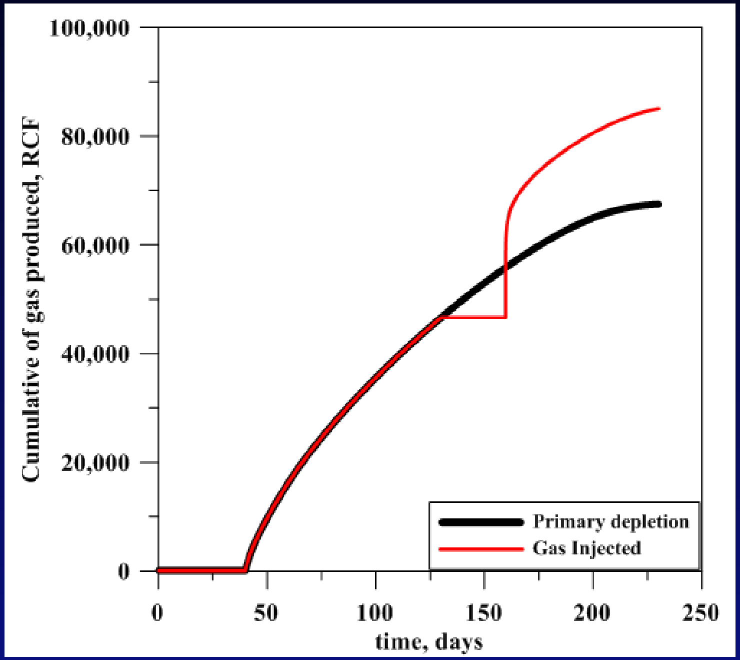




	Primary depletion (days)	Injection (days)	Soaking (days)	Production (days)
Case 1: Primary depletion	130	-	-	95
Case 2: Gas Injection	130	10	15	70

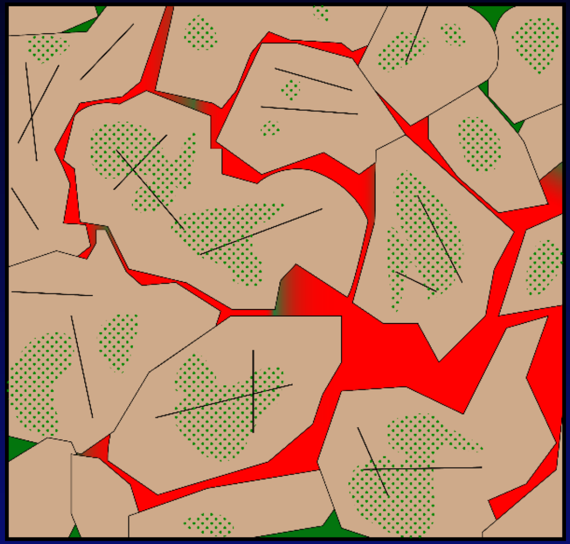
Assessment of Cyclic Gas Injection Enhance Oil Recovery



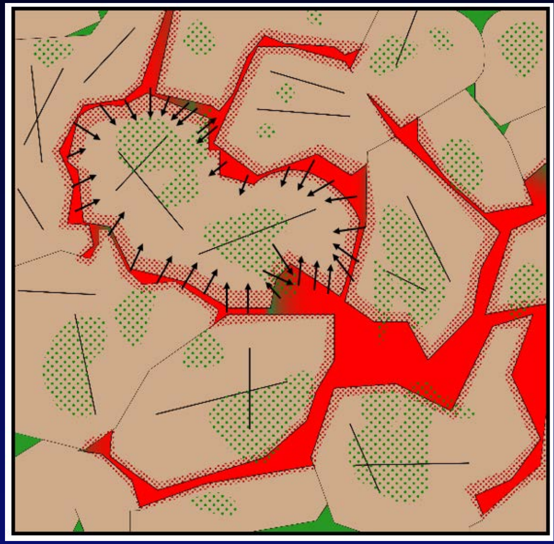


Increase in oil production: 3.36 %

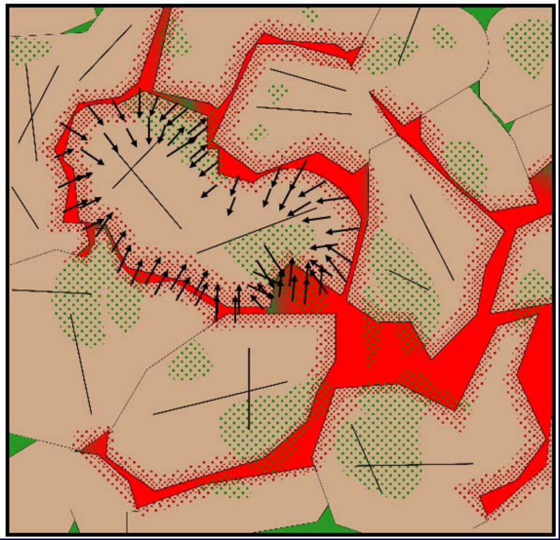
Cyclic Gas Injection Enhance Oil Recovery Physical Mechanism



INITIAL STATE
INJECTION OF GAS

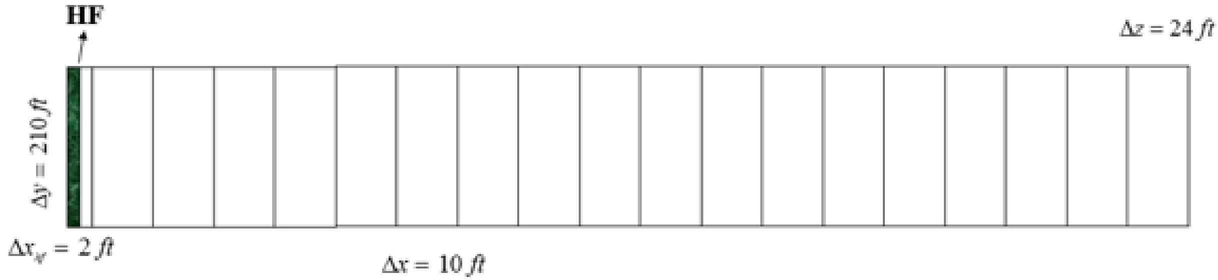


GAS PENETRATES VIA PRESSURE GRADIENT (ADVECTIVE FLOW)



GAS PENETRATES VIA CONCENTRATION GRADIENT (MOLECULAR DIFFUSION)

Assessment of Static Gas Dissolution into the Oil Column via Molecular Diffusion

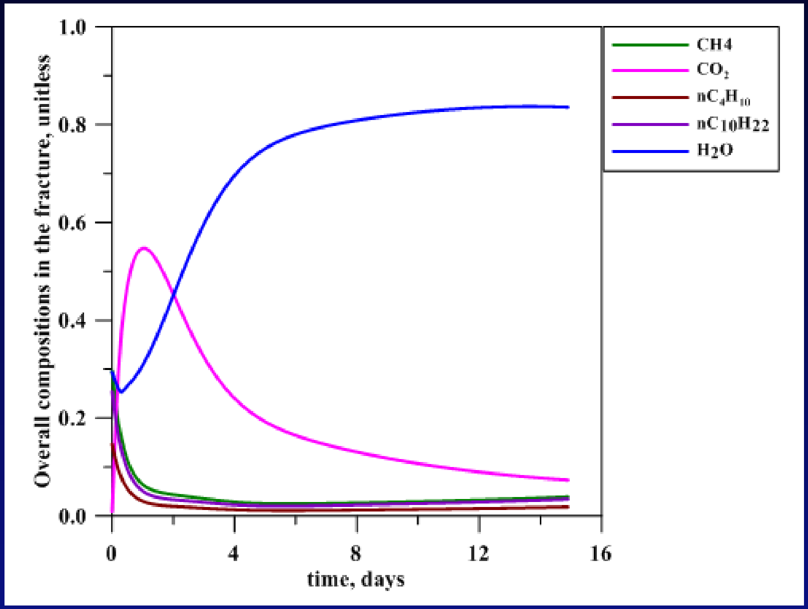


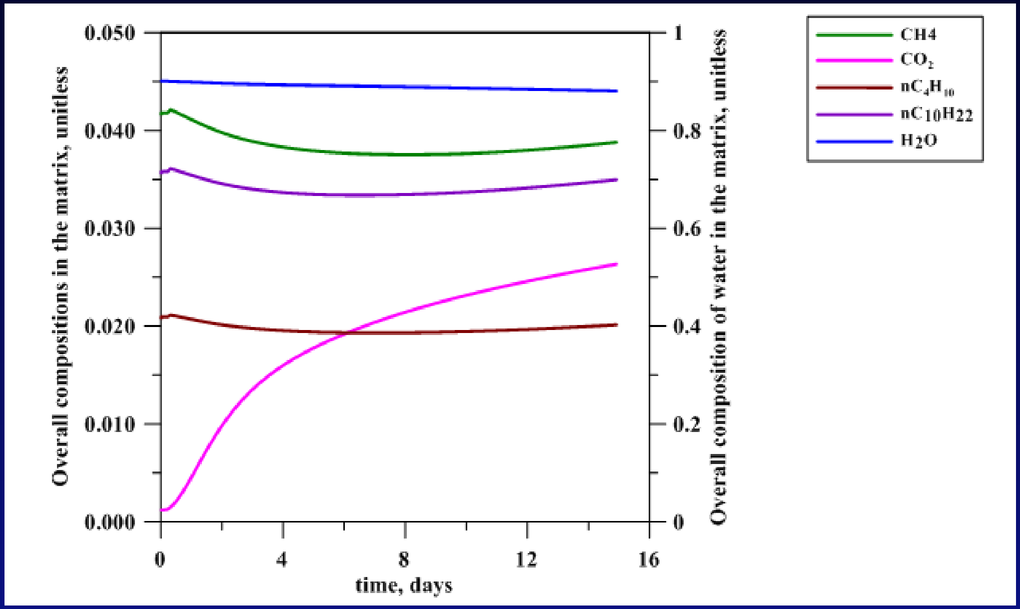
Hydraulic Fracture Node: $z_{nc} = \{C_1, CO_2, nC_4, nC_{10}\} = \{0.01, 0.97, 0.01, 0.01\}$

Reservoir Nodes: $z_{nc} = \{C_1, CO_2, nC_4, nC_{10}\} = \{0.42, 0.01, 0.21, 0.36\}$

2 ft away from the

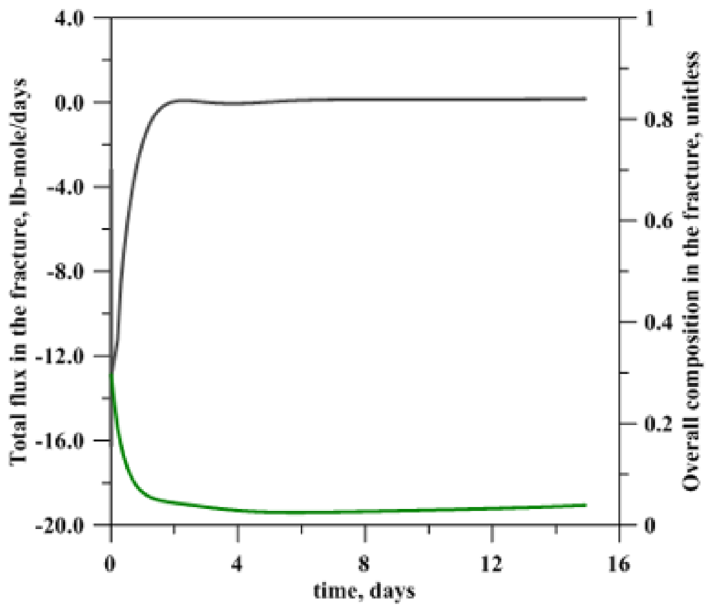
Assessment of Static Gas Dissolution into the Oil Column via Molecular Diffusion

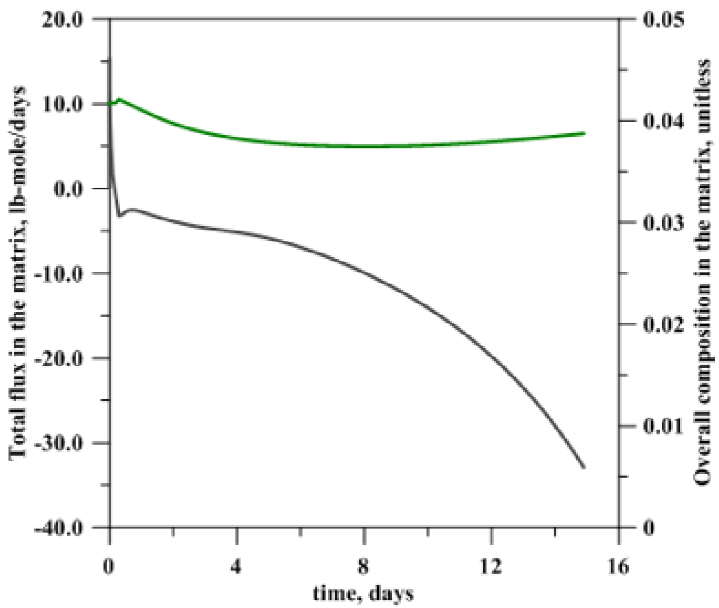




Assessment of Static Gas Dissolution into the Oil Column via Molecular Diffusion

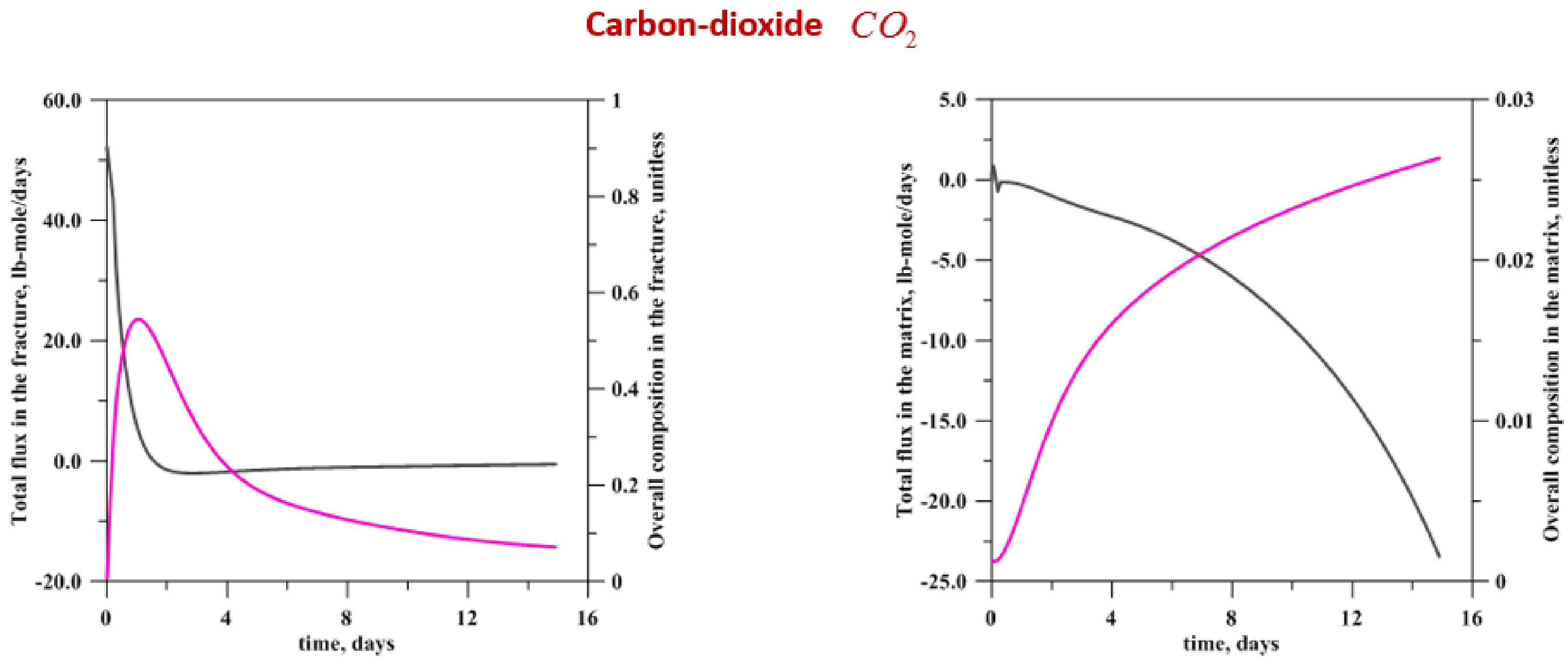
Methane CH_4





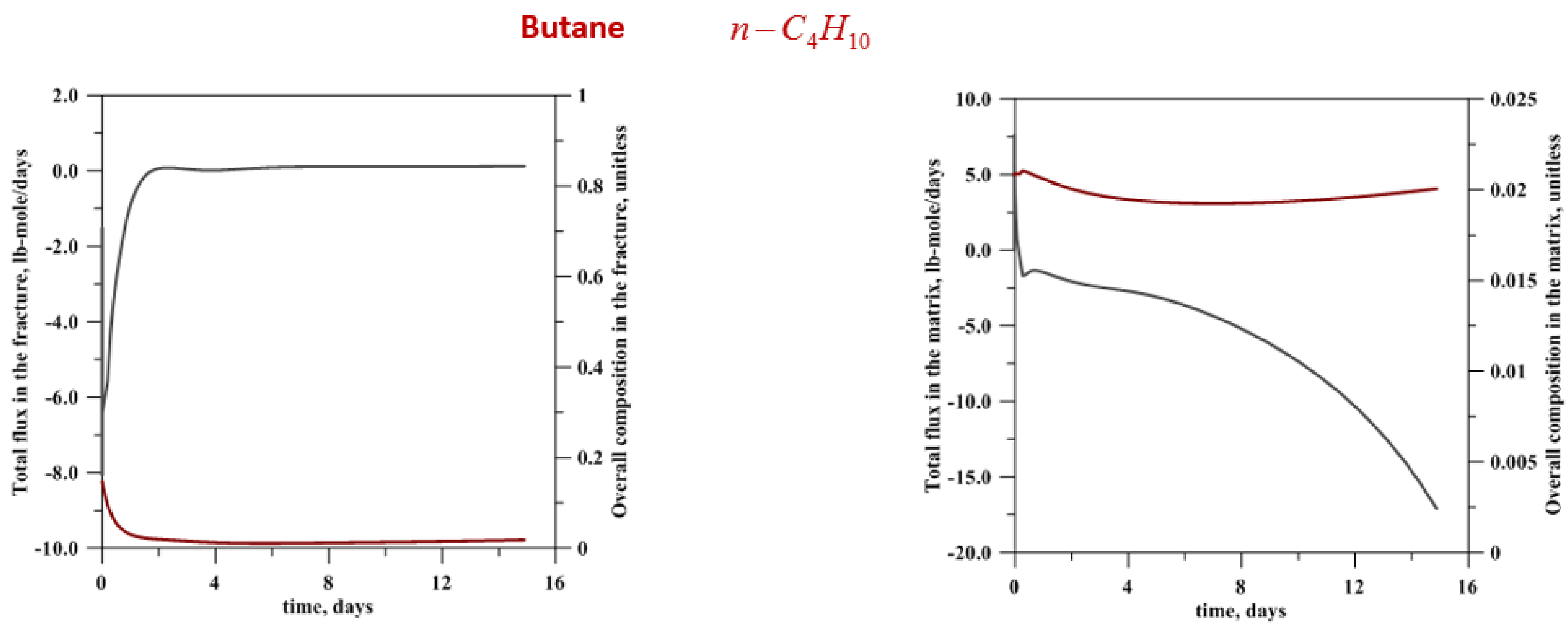
2 ft away from the hydraulic fracture

Assessment of Static Gas Dissolution into the Oil Column via Molecular Diffusion



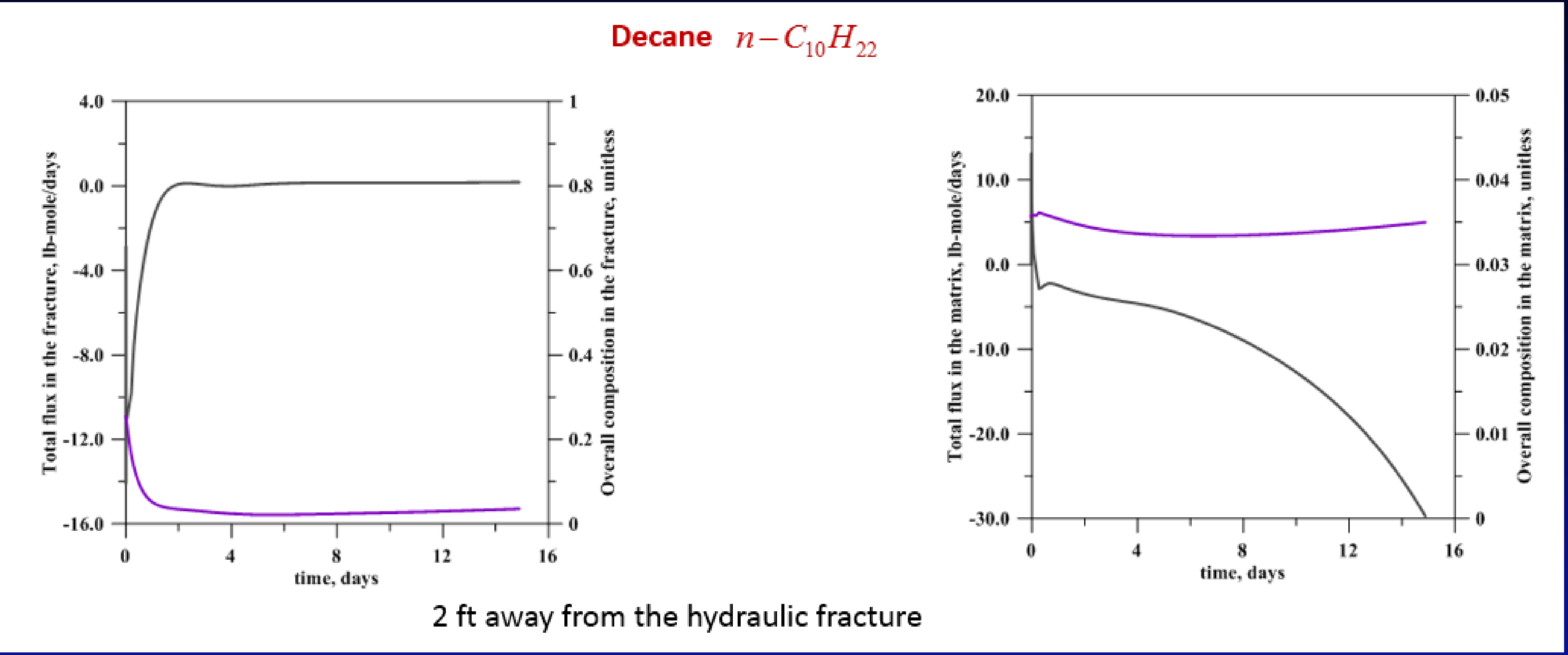
2 ft away from the hydraulic fracture

Assessment of Static Gas Dissolution into the Oil Column via Molecular Diffusion



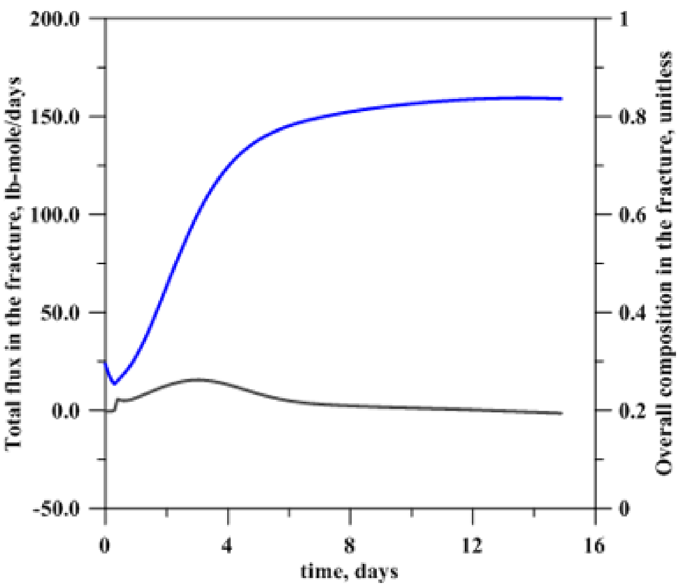
2 ft away from the hydraulic fracture

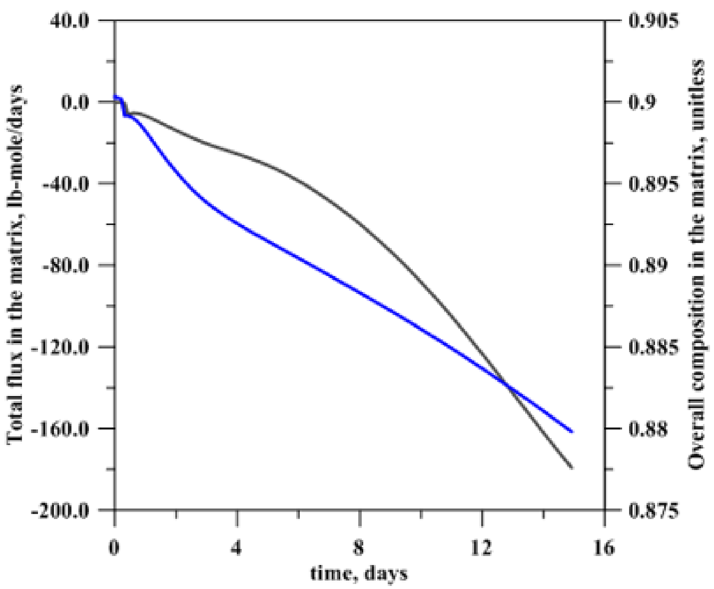
Assessment of Static Gas Dissolution into the Oil Column via Molecular Diffusion



Assessment of Static Gas Dissolution into the Oil Column via Molecular Diffusion

Water H_2O

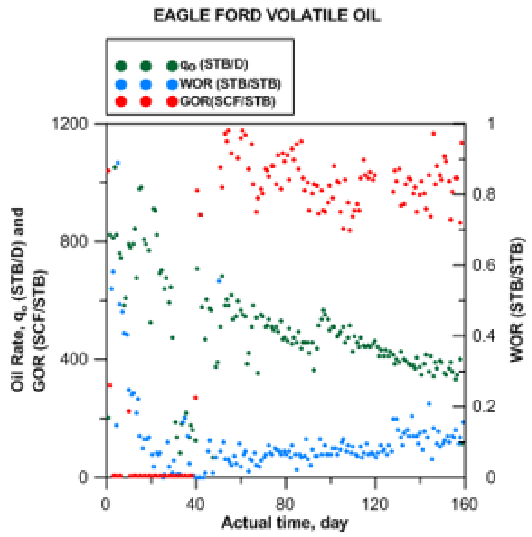


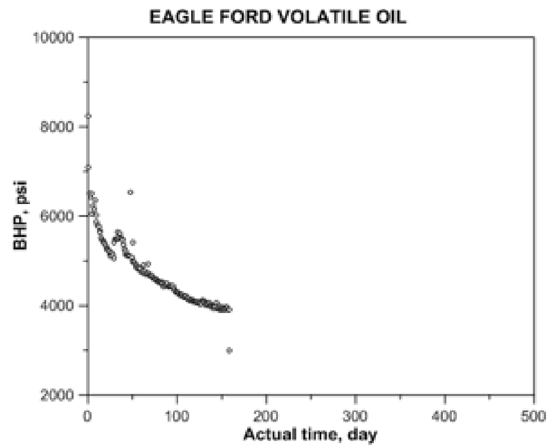


2 ft away from the hydraulic fracture

Multi-Phase Rate Transient Analysis

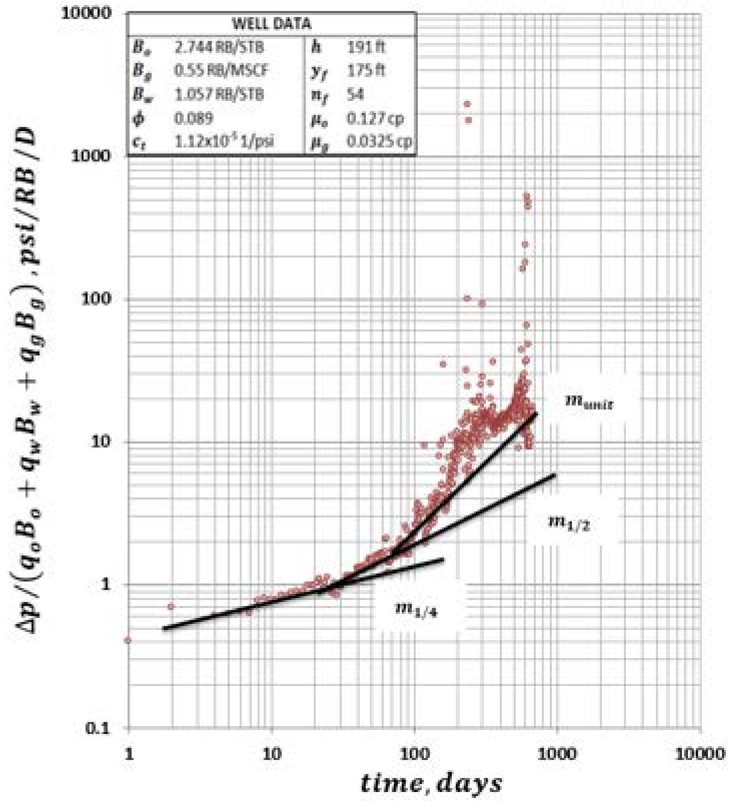
PRODUCTION AND PRESSURE HISTORY OF EAGLE FORD WELL





Multi-Phase Rate Transient Analysis

STEP 1 – DIAGNOSTIC PLOT FOR EAGLE FORD WELL



Flow Regimes

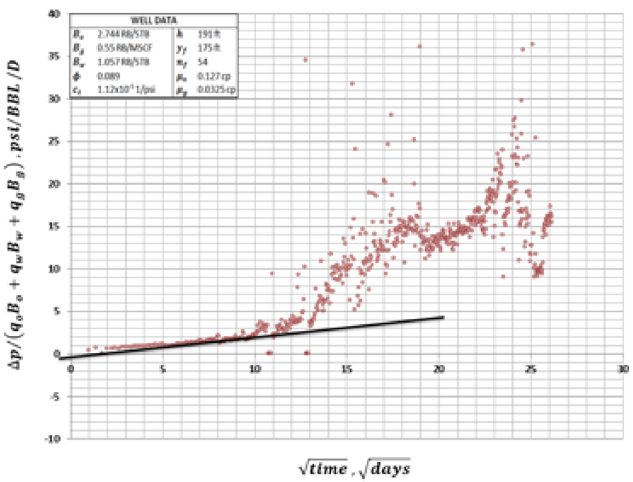
$m_{1/4}$: Bilinear Flow

$m_{1/2}$: Linear Flow

m_{unit} : Boundary-dominated flow

Multi-Phase Rate Transient Analysis

STEP 2 – LINEAR FLOW ANALYSIS



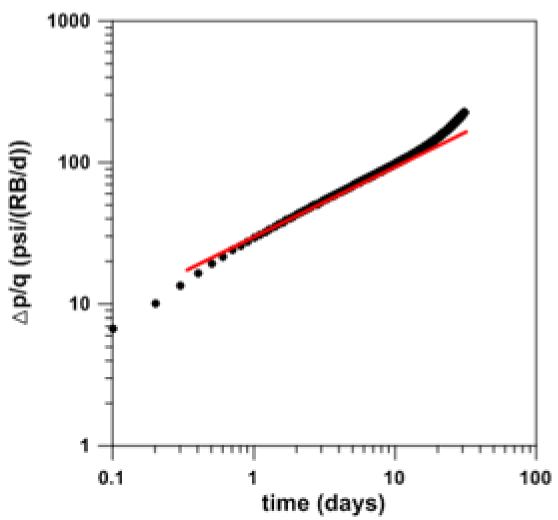
$$\frac{\Delta p_{wf}(t)}{q_{total}(t)} = \frac{4.064\sqrt{24}\left(\sqrt{\pi}\right)\lambda_t^{-1}}{\sqrt{k_{f,eff}}\left(h n_{hf} y_{hf}\right)}\left[\left(\frac{\lambda_t}{(\phi c_t)_{f+m}}\right)^{1/2}\right]\sqrt{t} + \frac{141.2\lambda_t^{-1}}{k_{f,eff}\, h n_{hf}} s_{hf}^{face}$$

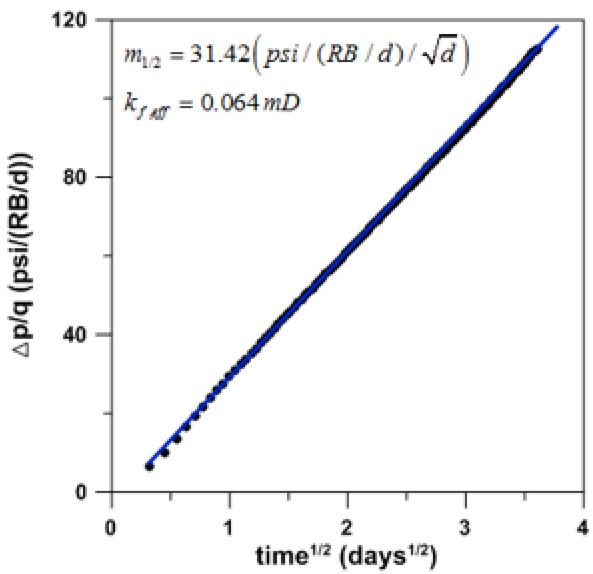
$$k_{f,eff}\,\lambda_t = 10^{-2}\, mD/cP \qquad s_{hf}^{face} = -0.18$$

$$k_{f,eff} = k_f \phi_f + k_m$$

Multi-Phase Rate Transient Analysis

Model Verification (Single-phase Flow):

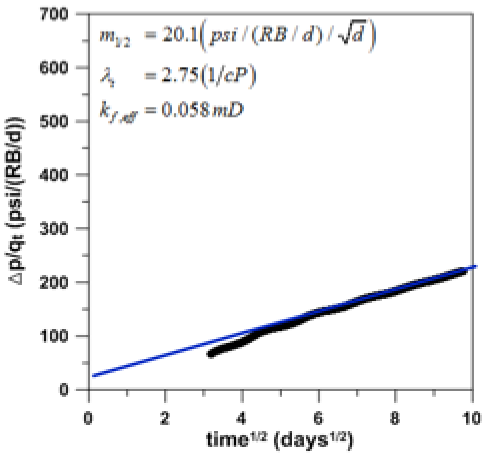


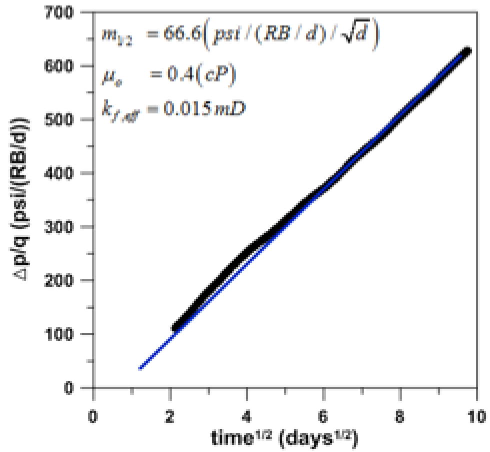


$$\left.\begin{array}{l} SIMULATION: k_{f,eff} = 0.064\,mD \\ INPUT: k_{f,eff} = 0.0659\,mD \end{array}\right\} \textit{Error } 2.85\%$$

Multi-Phase Rate Transient Analysis

Model Verification (Multi-phase Flow):





$$\left.\begin{array}{l} SIMULATION: k_{f,eff} = 0.058\,mD \\ INPUT: k_{f,eff} = 0.0659\,mD \end{array}\right\} \text{Error } 11\%$$

$$\left.\begin{array}{l} SIMULATION: k_{f,eff} = 0.015\,mD \\ INPUT: k_{f,eff} = 0.0659\,mD \end{array}\right\} \text{Error } 77\%$$

Conclusion

1. Developed a new numerical solution methodology consisting of simultaneous solution of pressure and overall composition. The formulation is very effective to model flow and interphase mass transfer in dual-porosity systems consisting of fracture and matrix.
2. The transport mechanism between the fracture and matrix consists of advective and molecular diffusion flux. Verified that when the pressure gradient between the nodes is diminished, the molecular diffusive flux, which is driven by the concentration differences, continues and became dominant.

Conclusion

3. My model results indicate that cyclic gas injection is an effective enhanced oil recovery mechanism in shale reservoirs. Specifically, the numerical experiments in this model indicates a three percent incremental oil production in the research model of the Eagle Ford fluid system. The model fluid system was a four-component pseudo system; however, the phase envelop of the model system mimicked the Eagle Ford system closely.

4. I successfully extended the single-phase rate transient analysis to multi-phase rate transient analysis, and obtained the model input effective permeability of the system.

Thank You