COMSOL
CONFERENCE
2014 BOSTON

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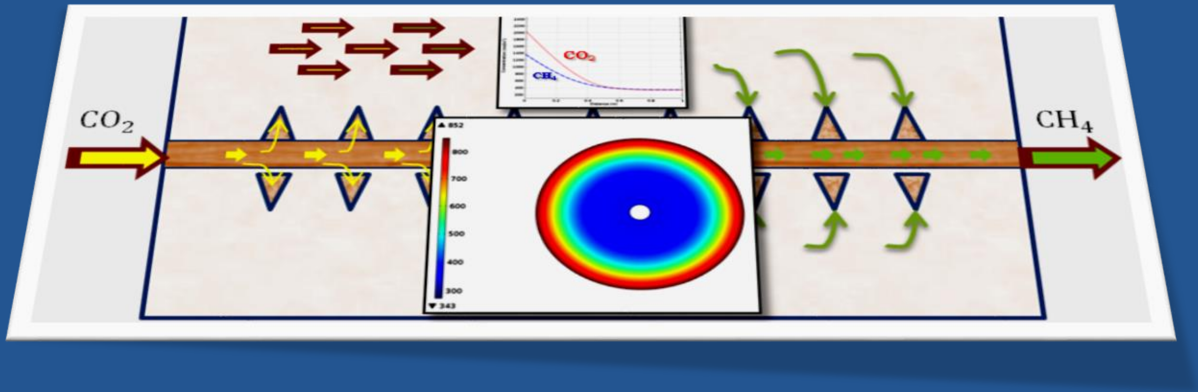
Numerical Study of Flux Models for CO_2 : Enhanced Natural Gas Recovery and Potential CO_2 Storage in Shale Gas Reservoirs

Session : Flow in Porous Media



Nilay J. Prajapati & Patrick L. Mills
Dept. of Chemical and Natural Gas Engineering
Texas A&M University - Kingsville

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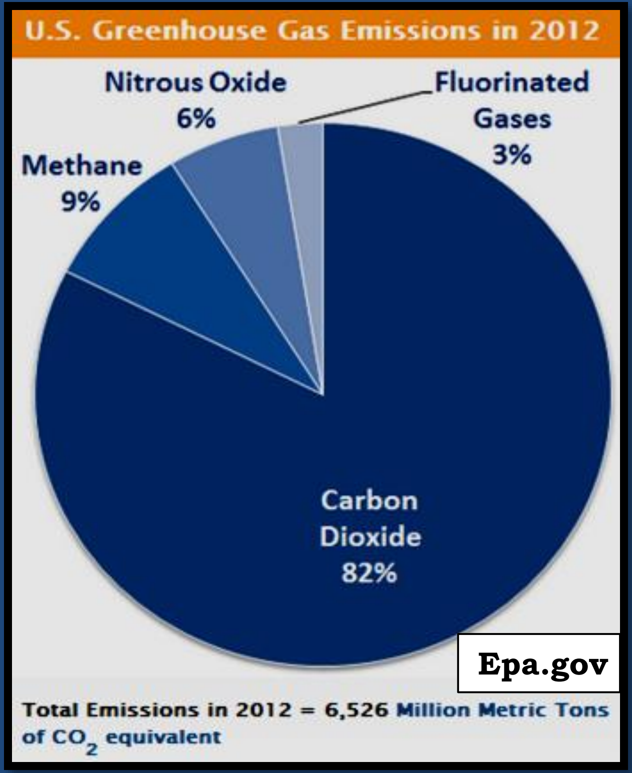
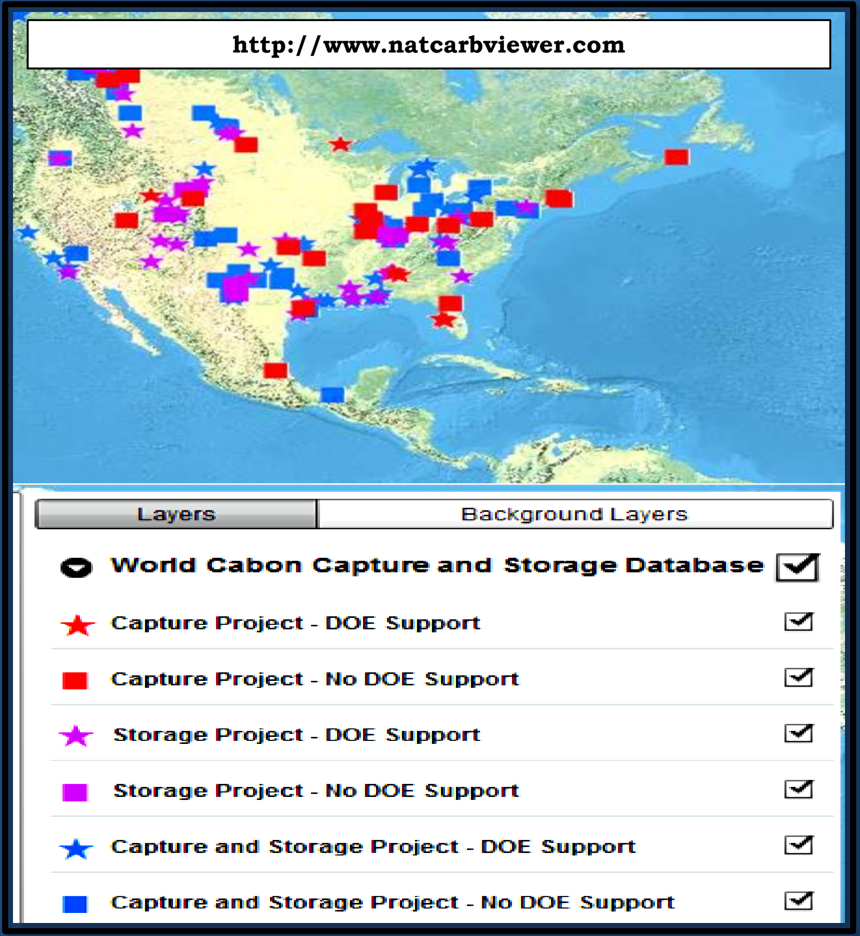
Boston, MA

Introduction

CO_2 is identified by the EPA as a ***Primary Greenhouse Gas*** and is largely responsible for current global warming trends.





http://www.natcarbviewer.com

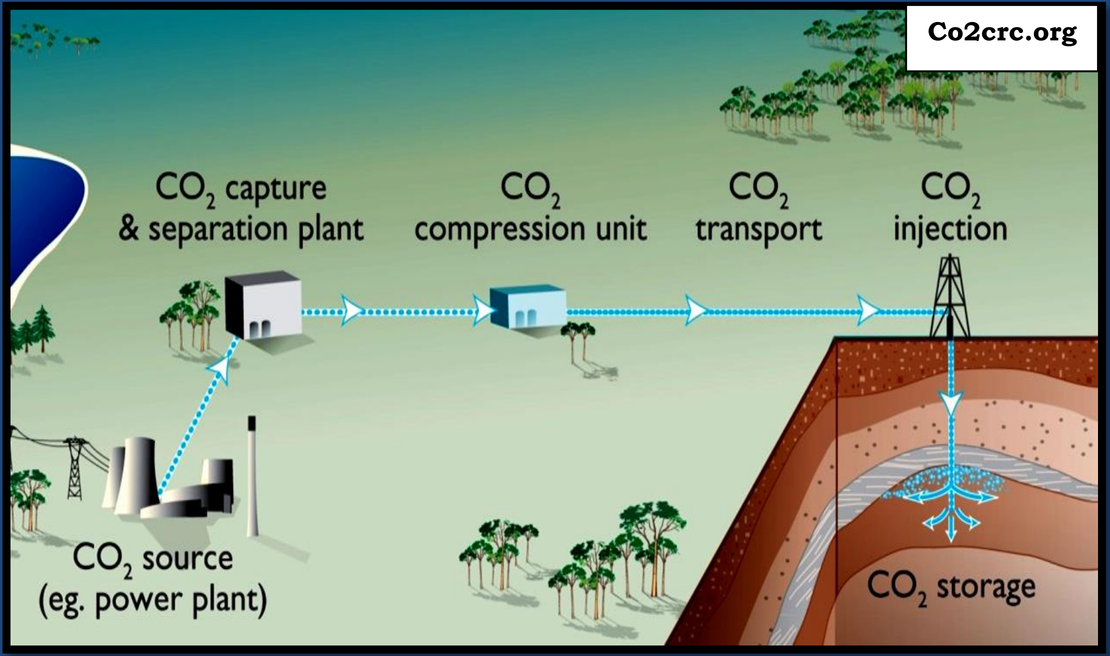
- World Cabon Capture and Storage Database ☑
- ★ Capture Project - DOE Support ☑
- 🟥 Capture Project - No DOE Support ☑
- ★ Storage Project - DOE Support ☑
- 🟪 Storage Project - No DOE Support ☑
- ★ Capture and Storage Project - DOE Support ☑
- 🟦 Capture and Storage Project - No DOE Support ☑

Various USA groups are actively involved in developing technologies for reducing CO_2 emissions by using ***capture and storage*** methods.

Geological CO_2 Storage Methods

Technologies being developed for geologic storage are focused on five different approaches:

1. Oil and gas reservoirs
2. Saline formations
3. Coal seams
4. Basalts
5. **Organic-rich shales**



Challenges

- Very low inter-pore communication
- Shale characterization
- High drilling and completion costs

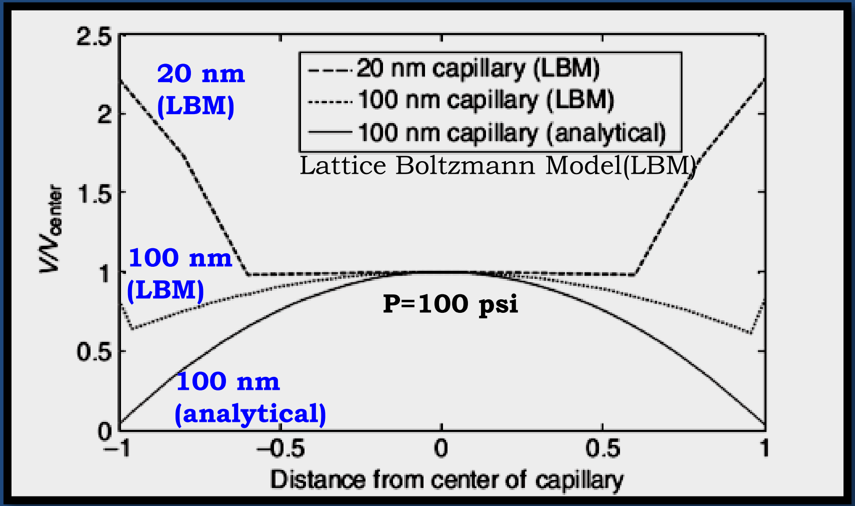
Motivation

- Shale gas reservoirs would benefit by enhanced recovery methods owing to low recovery factors
- Methane production is primarily limited by shale gas reservoir nano-pores
- No detailed comparison of flux models used for gas transport has been performed
- Performance of various flux models need to be delineated for developing better understanding of gas transport in nano-pores & hence development of higher recovery factors

Shale Gas Reservoir

Unique Features

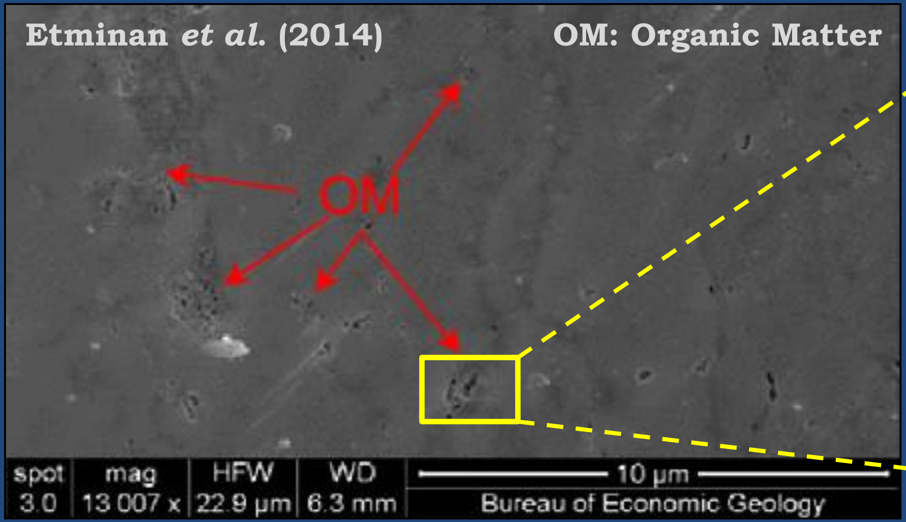
- Low voidage (0.08-0.12) & ultra-low permeability (10^{-10}-10^{-12} Darcy)
- Significant gas production through adsorption and desorption

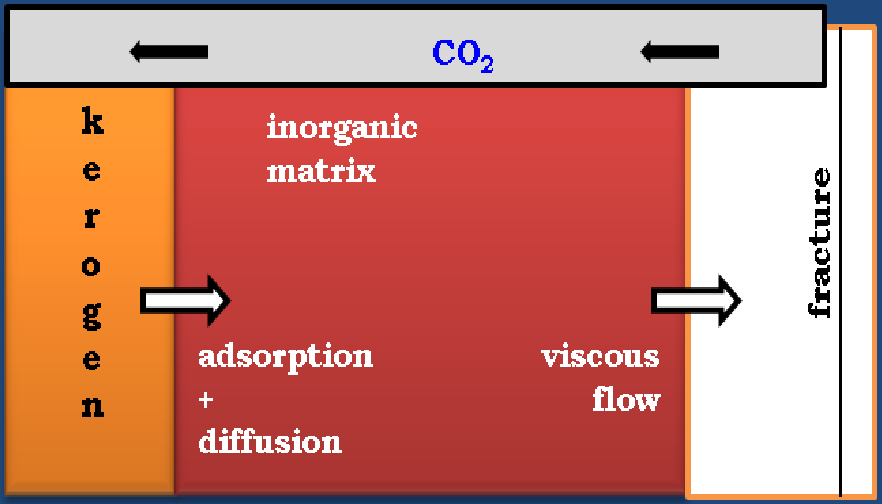


Fathi and Akkutlu (2013)

- Desorption occurs as pressure decreases during production and becomes part of the free gas in the natural fractures.
- Javadpour (2009), Fathi and Akkutlu (2011), Kang *et al.* (2011) proved the existence of nano-pores in shales.
- This resulted in the introduction of Knudsen diffusion and slit flow to describe species transport in nano-pores.

Gas Flow in Shale Nano-pores





- In thermodynamic equilibrium, gas molecules are found in three layers:
  1. **Adsorption layer**
  2. **Transition layer**
  3. **Free gas layer**
- Application of ᴅP (drilling & production)
  - **Slippage** (transition region) and
  - **Surface diffusion** (adsorbed layer)

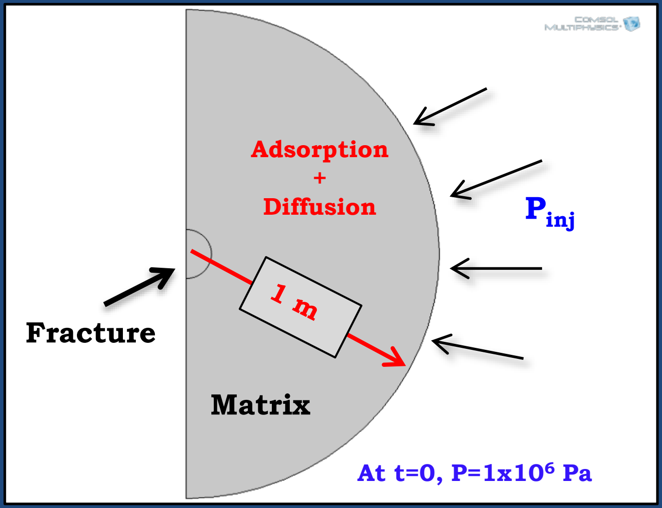
Nano-pore (10 nm)

Model Description

Assumptions

1. Ideal gas behavior
2. Constant reservoir temperature
3. Single-phase gas flow
4. Constant rock compressibility
5. Isotropic & homogeneous matrix
6. Constant matrix & fracture voidage

- **Physics: COMSOL PDE Module**
- **Solver: Time Dependent PARDISO Solver**
- **Tolerance Factor: 0.1**
- **Maximum Iterative Steps: 5**



COMSOL model geometry with initial boundary conditions

Reservoir Parameters

Molar mass of CH_4, kg/mol	0.016
Molar mass of CO_2, kg/mol	0.044
Permeability, m^2	1.0 x 10^{-19}
Voidage	8.0 %
Rock density, kg/m^3	2560
Absolute temperature, K	353
Compressibility factor (Z_s)	1.0
Rock compressibility, Pa^{-1}	1 x 10^{-5}
Langmuir pressure of CH_4*, Pa	3.05 x 10^6
Langmuir pressure of CO_2*, Pa	1.68 x 10^6
Langmuir volume of CH_4*, std.m^3/kg	9.80 x 10^{-4}
Langmuir volume of CO_2*, std.m^3/kg	1.91 x 10^{-3}

***Sun *et al.* (2014)**

Governing Multiphysics Equations

Kerogen-Matrix Species Mass Balance

$$\frac{\partial(\rho\phi_m + \rho_q(1-\phi_m))_i}{\partial t} + \nabla\cdot(\rho u)_{m,i} = 0$$

where, i = 1 (Methane, CH_4)
i = 2 (Carbon Dioxide, CO_2)

$$\rho_i = \frac{P_i M_i}{Z_i R T} \quad \& \quad P_i = x_i P$$

Adsorbed Gas Density

$$\rho_{q,i} = \frac{\rho_s M_i}{V_{std}} \times q_{ads,i}$$

Extended Langmuir Adsorption Isotherm

$$q_{ads,i} = \frac{V_{L,i} B_i P_i}{1 + \sum_{j=1}^{n} B_j P_j}$$

Binary Diffusion Coefficient : **Chapman-Enskog Theory**

Knudsen Diffusion Coefficient : **Sun *et al.* (2014)**

Flux Models

Wilke Model

$$N_i = \left(-D_{ei,m}\nabla C_i\right), \quad D_{ei,m} = \frac{1}{\left(\sum_{j=1,j\neq i}^{n}\left(x_j / D_{ij}^{e}\right)\right)}$$

Wilke-Bosanquet Model

$$N_i = \left(-D_{i,eff}\nabla C_i\right), \quad \frac{1}{D_{i,eff}} = \frac{1}{D_{ei,m}} + \frac{1}{D_{ei,k}}$$

Maxwell-Stefan Model

$$N_i = \frac{-\nabla C_i + \sum_{j=1,j\neq i}^{n} \frac{x_i N_j}{D_{ij}^{e}}}{\sum_{j=1,j\neq i}^{n} \frac{x_j}{D_{ij}^{e}}}$$

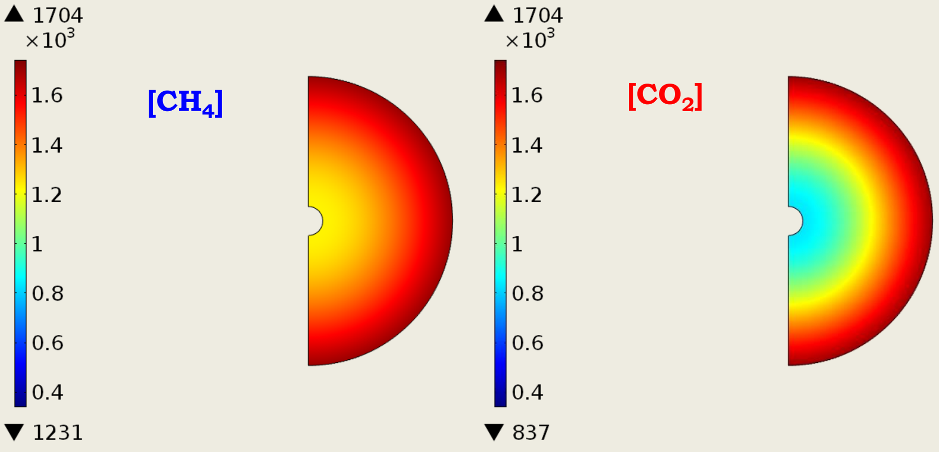
Dusty Gas Model

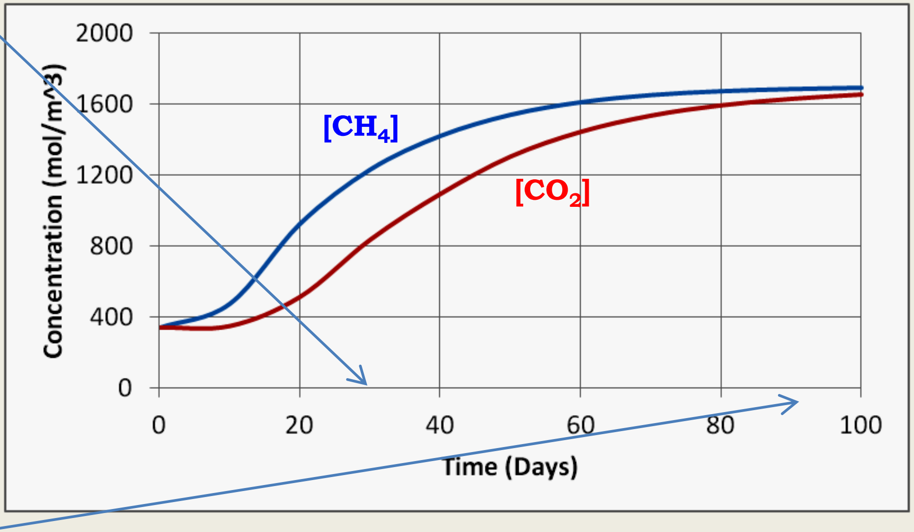
$$N_i = \frac{\sum_{j=1,j\neq i}^{n} \frac{x_i N_j}{D_{ij}^{e}} - \frac{C_i v^*}{D_{ei,k}} - \nabla C_i}{\sum_{j=1,j\neq i}^{n} \frac{x_j}{D_{ij}^{e}} + \frac{1}{D_{ei,k}}}, \quad V^* = -\frac{\varepsilon\, d_{pore}^{2}}{32\,\tau\,\mu}\nabla P$$

Key Results

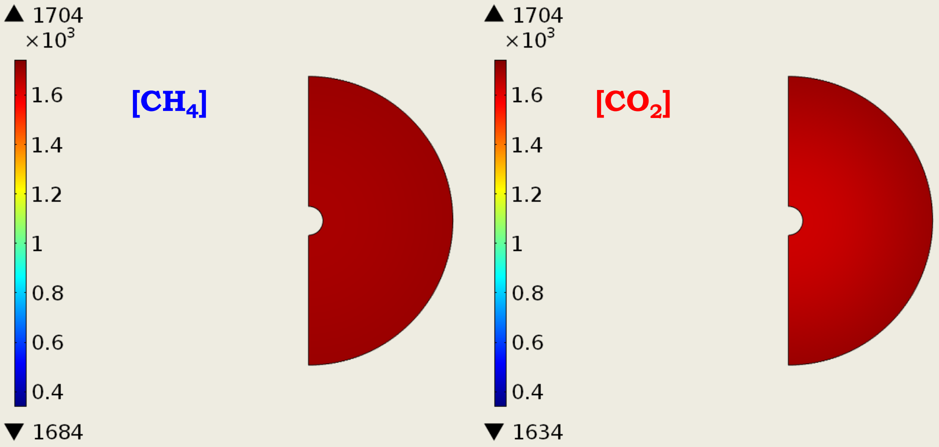
Wilke Flux Model: $N_i = \left(-D_{ei,m}\,\nabla C_i\right),\quad D_{\mathrm{ei,m}} = \left(\sum_{j=1,\,j\neq i}^{n}\left(x_j / D^{e}_{ij}\right)\right)^{-1}$

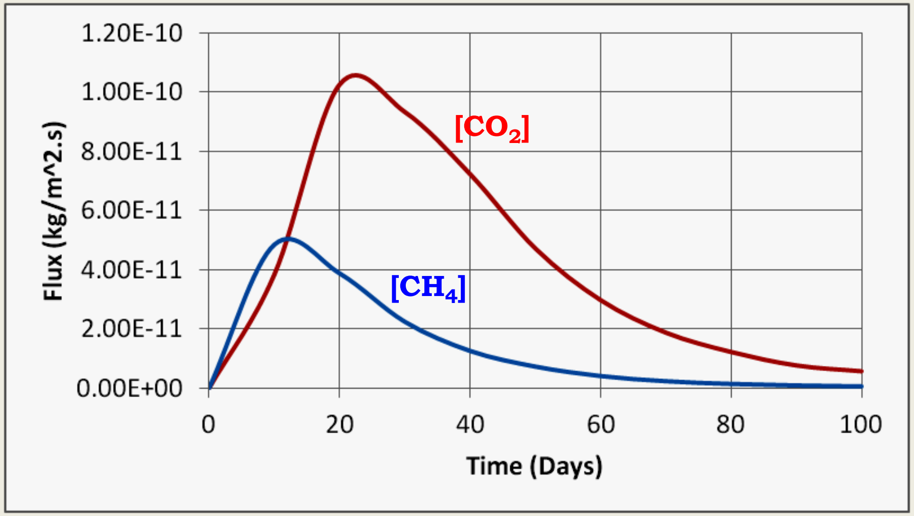
Production Time = 30 Days





Production Time = 90 Days

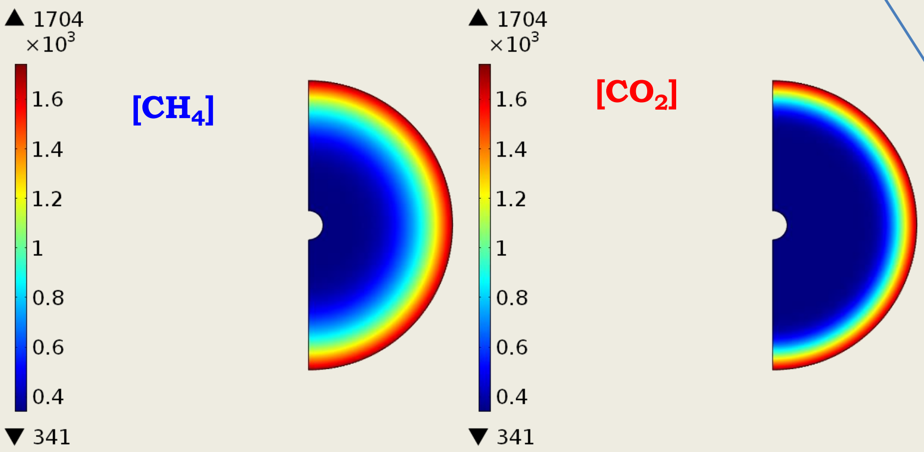


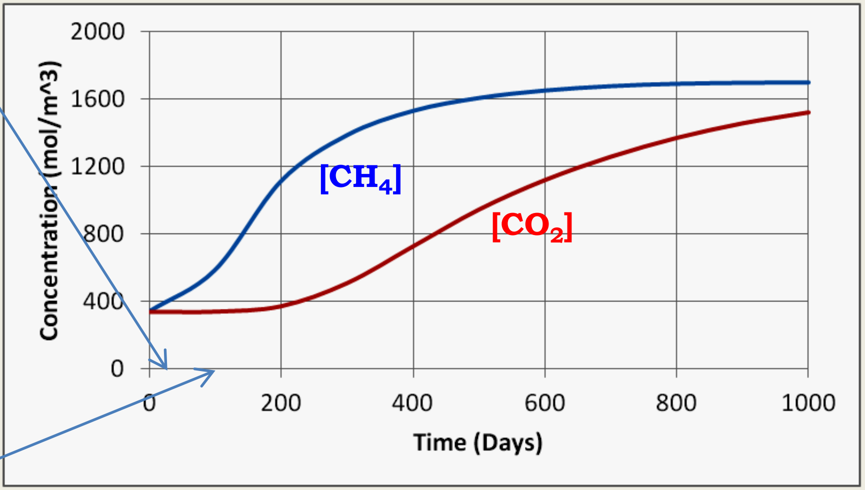


Wilke-Bosanquet Flux Model: $N_i = \left(-D_{i,eff}\, \nabla C_i\right),\quad \frac{1}{D_{i,eff}} = \frac{1}{D_{ei,m}} + \frac{1}{D_{ei,k}}$

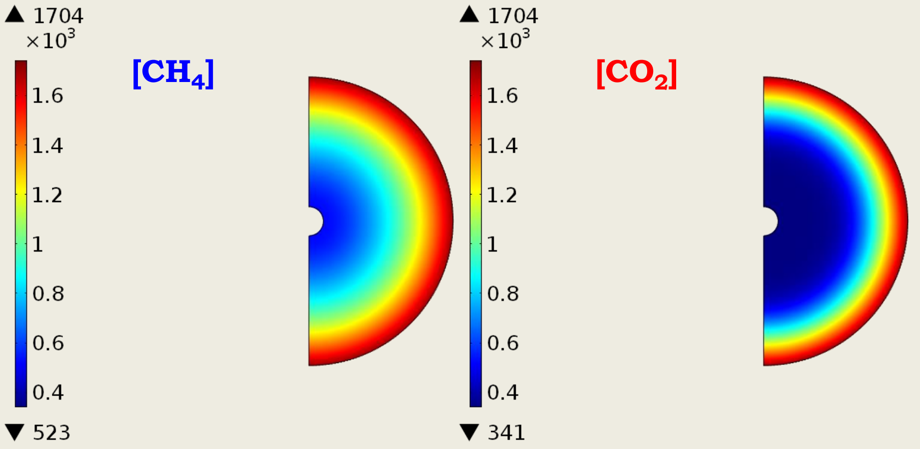
Production Time = 30 Days

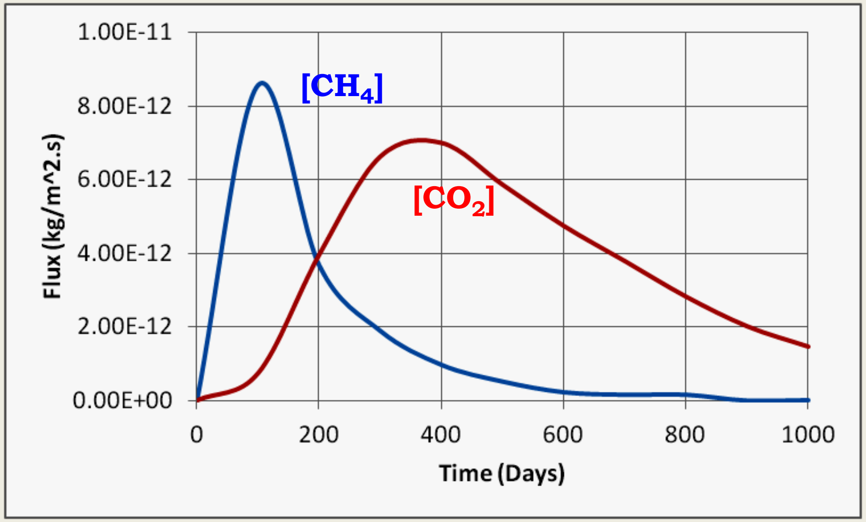
Simulation Time = 1000 Days





Production Time = 90 Days

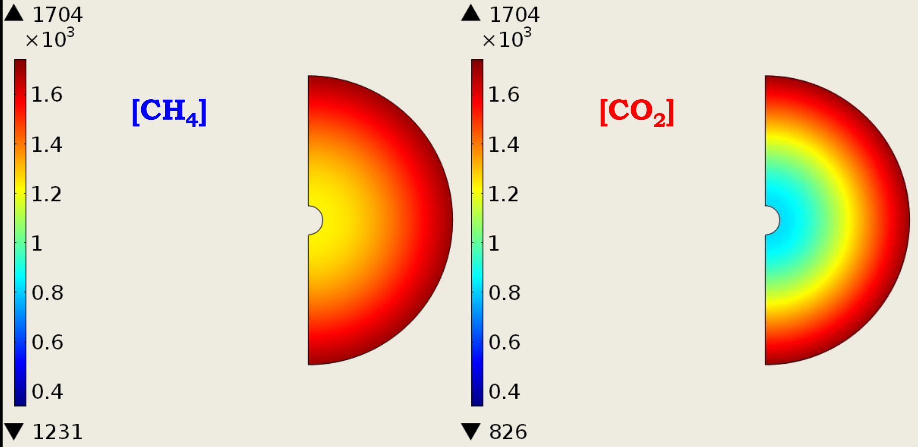




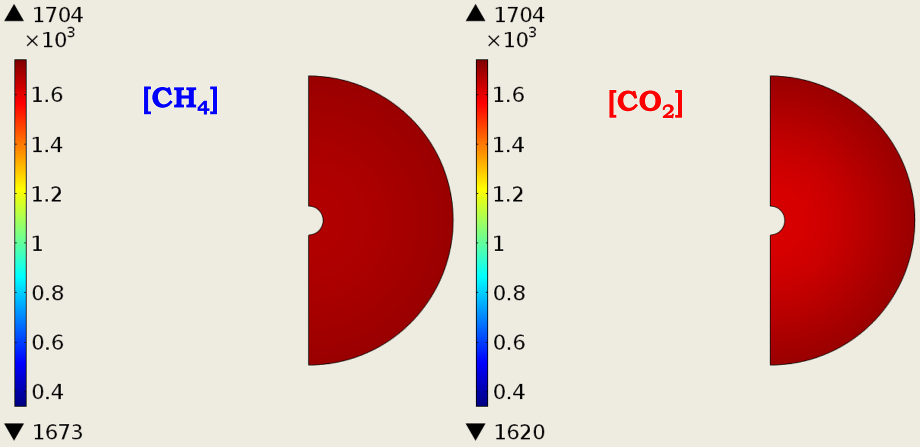
Maxwell-Stefan Flux Model:

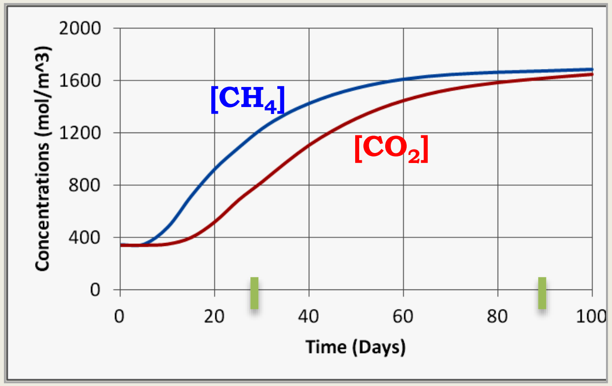
$$N_i = \left(-\nabla C_i + \sum_{j=1, j\neq i}^{n} \frac{x_i N_j}{D_{ij}^{e}}\right) \times \left(\sum_{j=1, j\neq i}^{n} \frac{x_j}{D_{ij}^{e}}\right)^{-1}$$

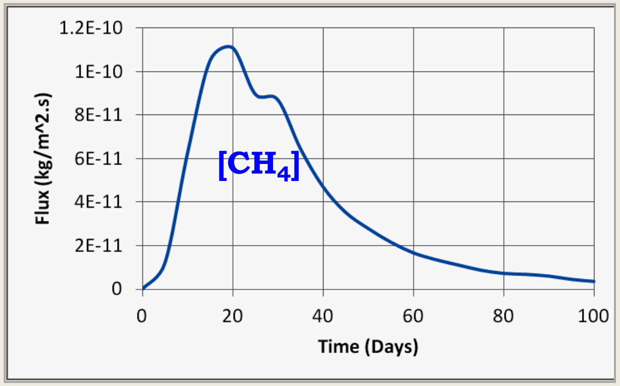
Production Time = 30 Days

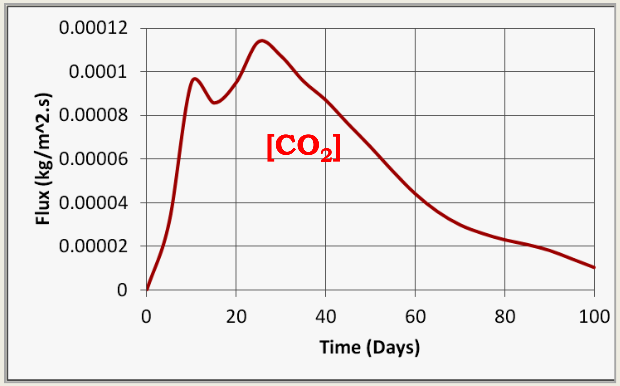


Production Time = 90 Days



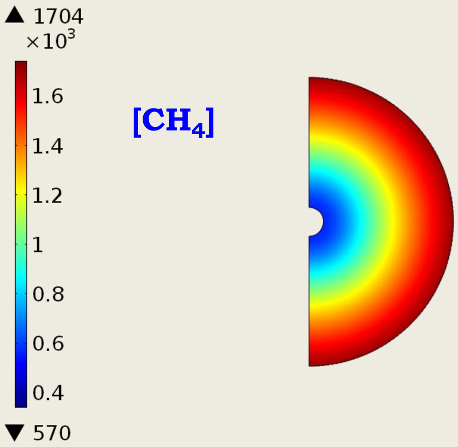


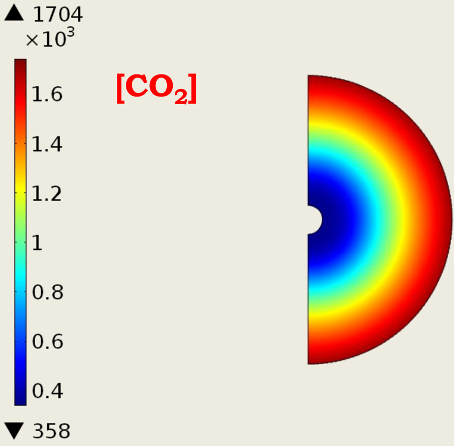


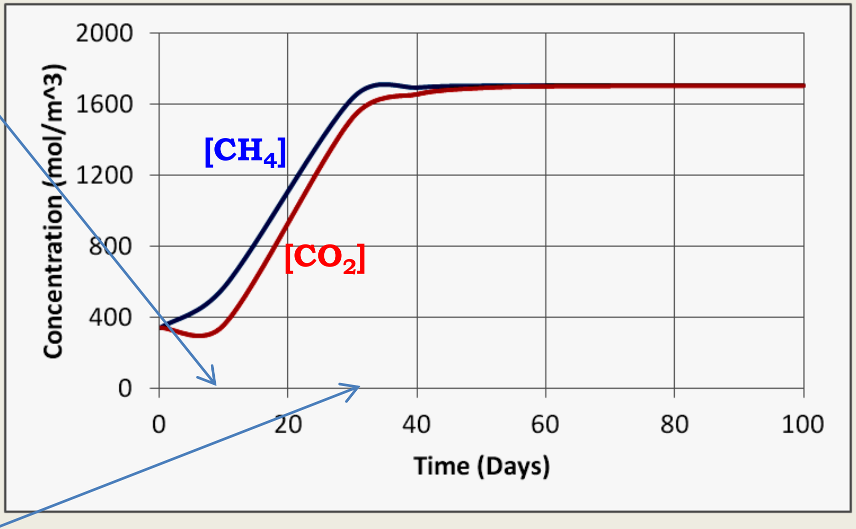


Dusty Gas Flux Model: $$N_i = \left(\sum_{j=1, j\neq i}^{n} \frac{x_i N_j}{D_{ij}^e} - \frac{C_i v^*}{D_{eik}} - \nabla C_i \right) \times \left(\sum_{j=1, j\neq i}^{n} \frac{x_j}{D_{ij}^e} + \frac{1}{D_{eik}} \right)^{-1}$$

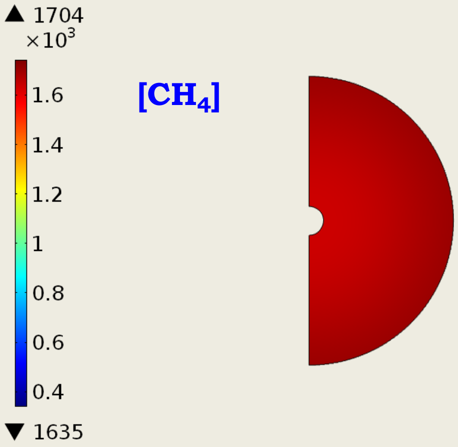
Production Time = 10 Days

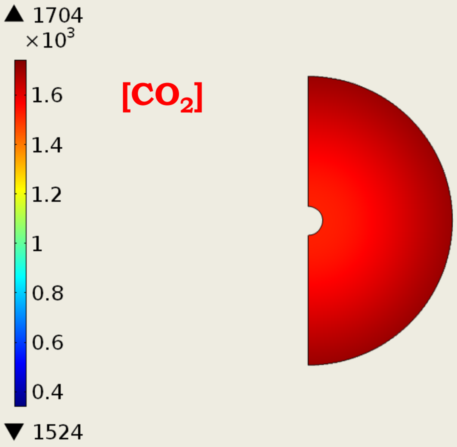


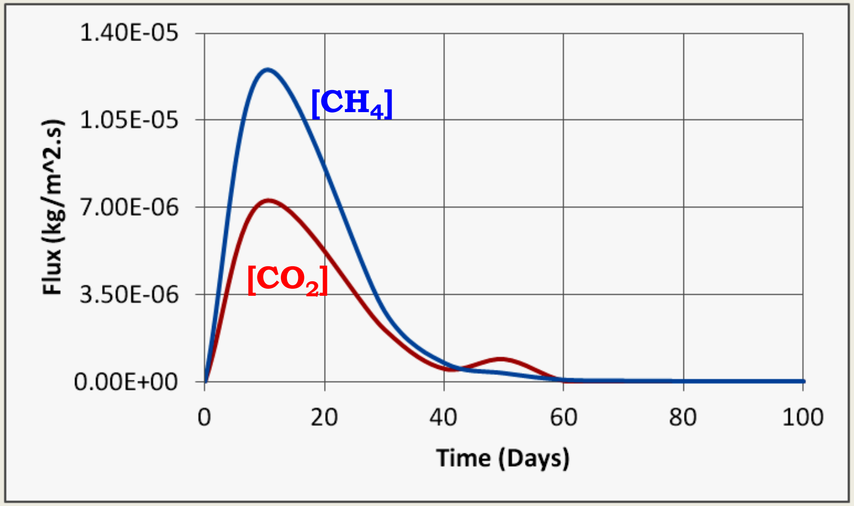




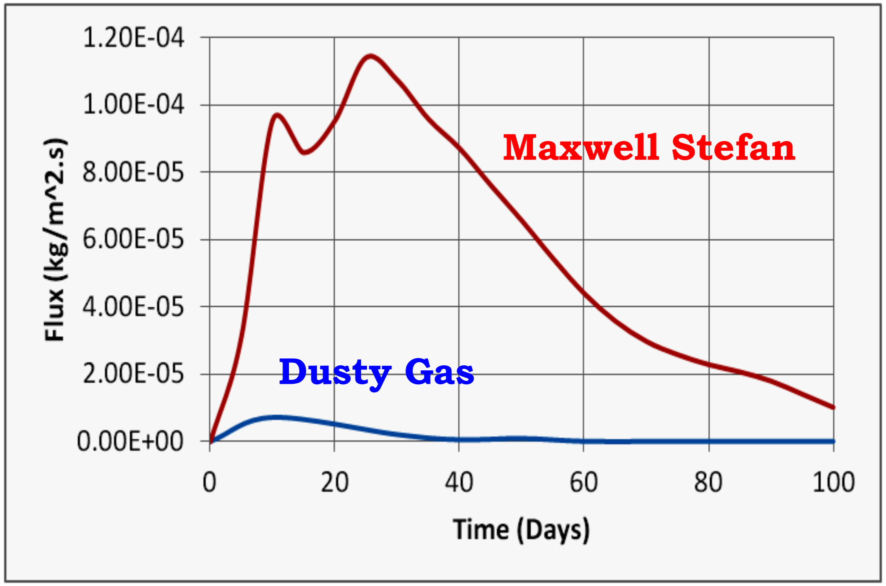
Production Time = 30 Days

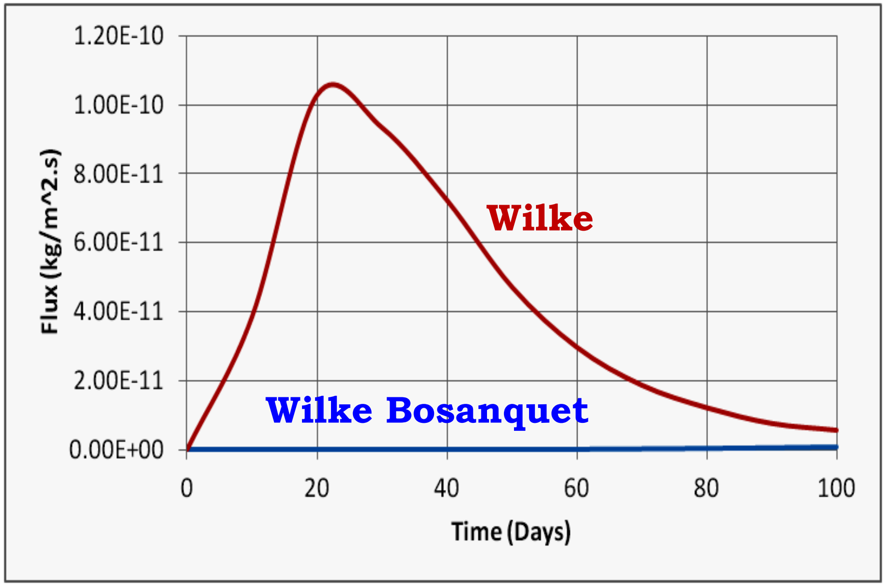




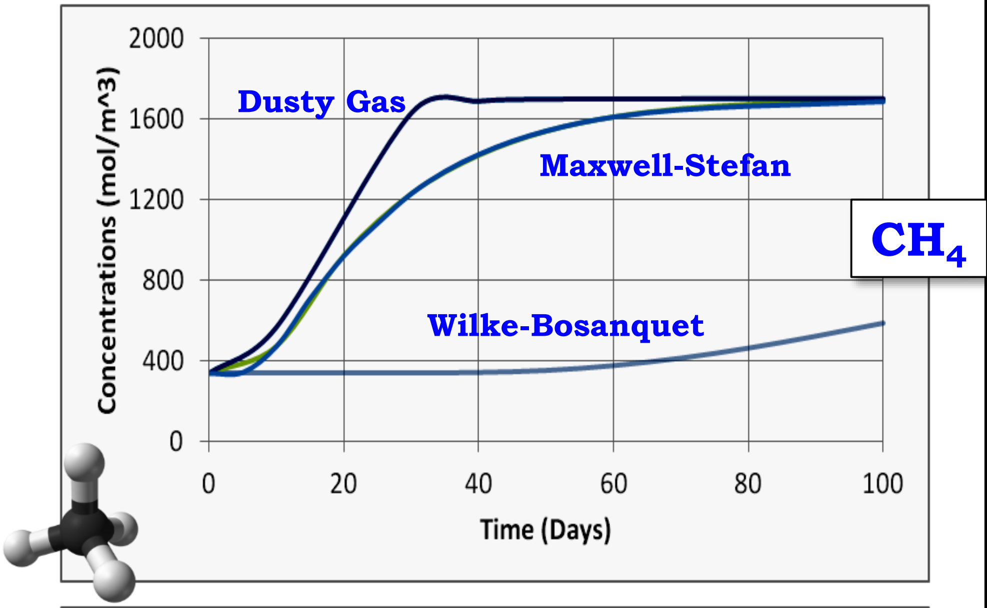


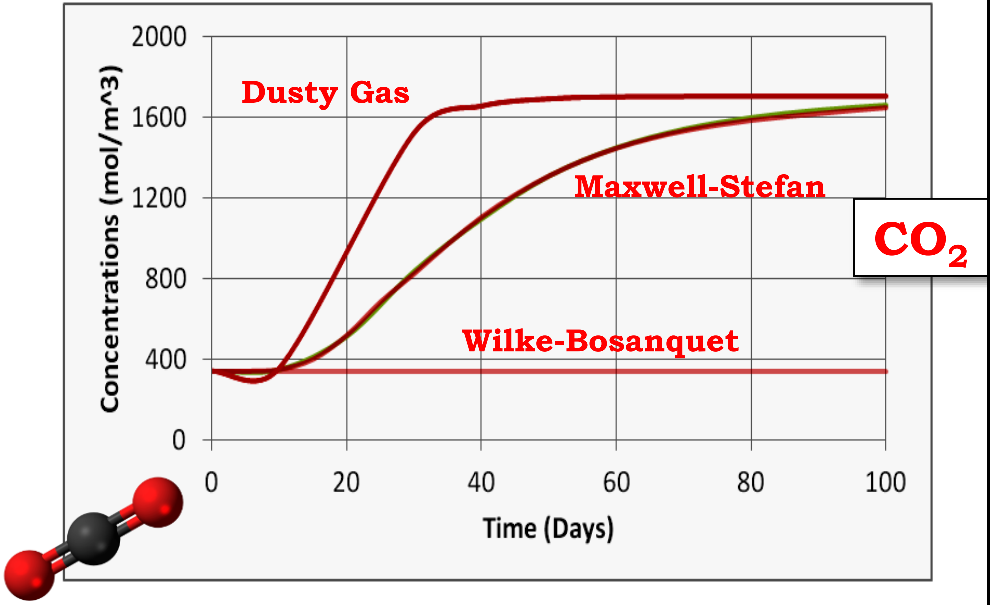
FLUX COMPARISION





CONC. COMPARISION





Key Adaptations

- Initial difficulties encountered in 2D with Dusty gas and Maxwell-Stefan flux models:
  - Non-smooth conc^{n} & flux profiles with increasing time range
  - Convergence errors occurred when t > 50 mins

Adaptation :

- Reduced DOF by use of 2D-axisymmetric geometry

- Equations for both the above models are highly non-linear
  - Operator : (Pz<=0)*(Pz>=0) for efficient computation

Conclusions & Future Work

- Shale characterization is very important for optimum development of the reservoir. COMSOL has served as a very strong computation engine for solving the non-linear equations associated with shale nano-pores.

- Comparison of various flux models shows that Knudsen diffusion (D_k) plays very important role for defining fluid flow in shale nano-pores specially in a fluid mixture with CO_2.

- Higher adsorption of CO_2 is noticed, causing preferential flow of CH_4 molecules. CO_2 will stay adsorbed until a threshold pressure is reached.

- Dusty gas model gives the best fit for the considered system as it incorporates pore structure as part of equation along with D_k and D_m.

- This model can be extended by including other physical phenomena, such as fracture flow mechanics, other gas species and multi-phase flow due to variable pressure, temperature and water concentration.

Thank you
for your
Attention

QUESTIONS??