Simulation of CO_2-ECBM and Influences on Coal Structure of CO_2 Storage

CO_2—ECBM模拟及CO_2储存对煤结构影响

Lai Zhou (周 来)

Run Chen(陈 润)

Jiangsu Key CCS Laboratory(CUMT)

江苏煤基CO_2捕集与地质储存重点实验室(中国矿业大学)

cags China Australia Geological Storage of CO_2

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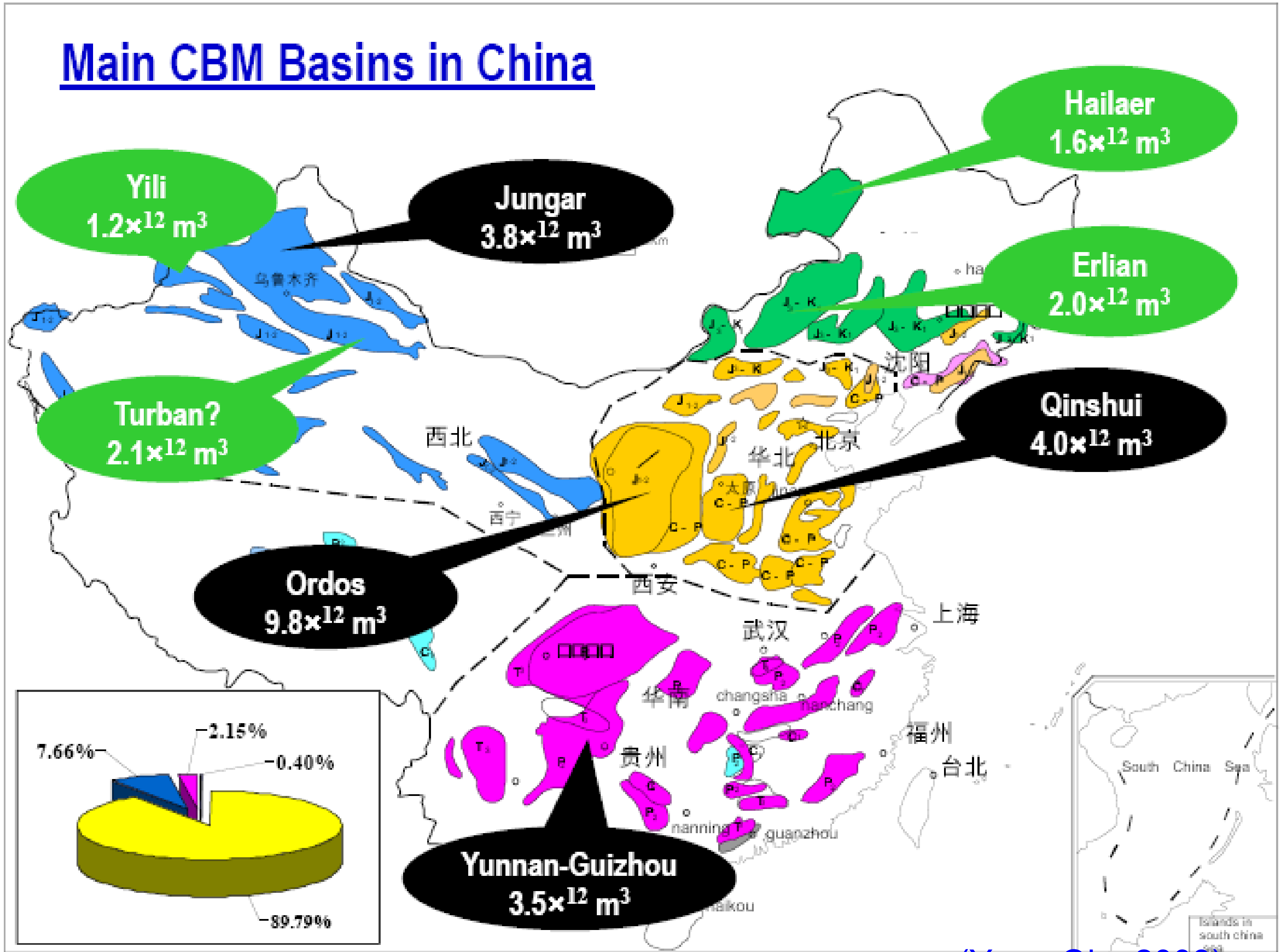
Outline

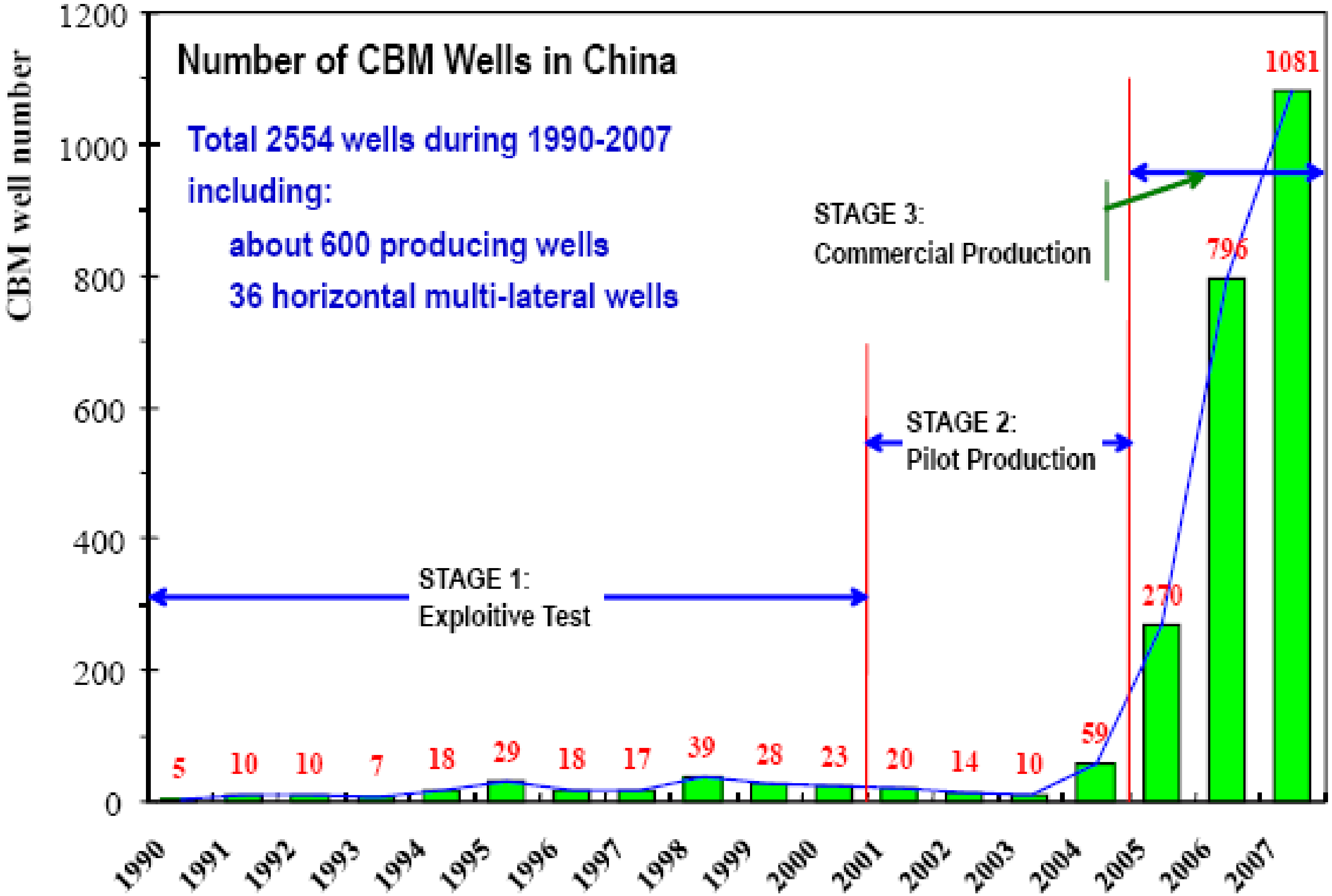
1. CO_2 Storage and ECBM
2. Modeling and Numerical simulation of CO_2-ECBM
3. Influences on Coal Structure of CO_2 Storage
4. Conclusions and Puzzles

1. CO_2 Storage and ECBM



(Yong Qin, 2008)

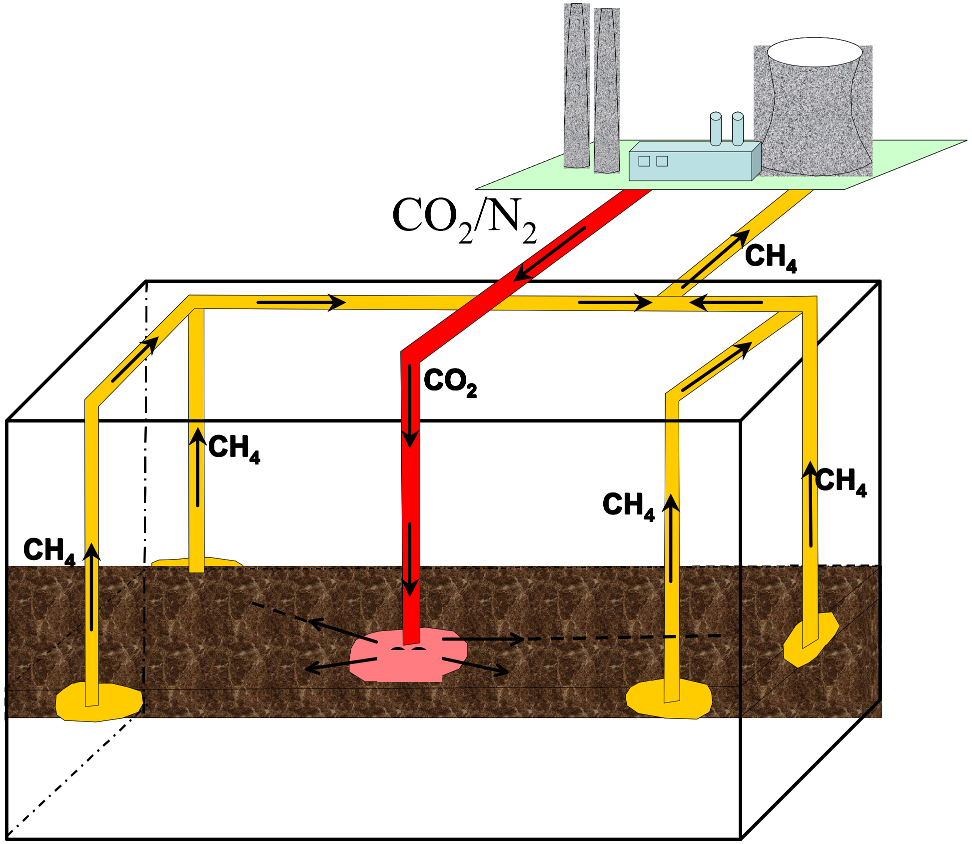
CBM exploration & mining

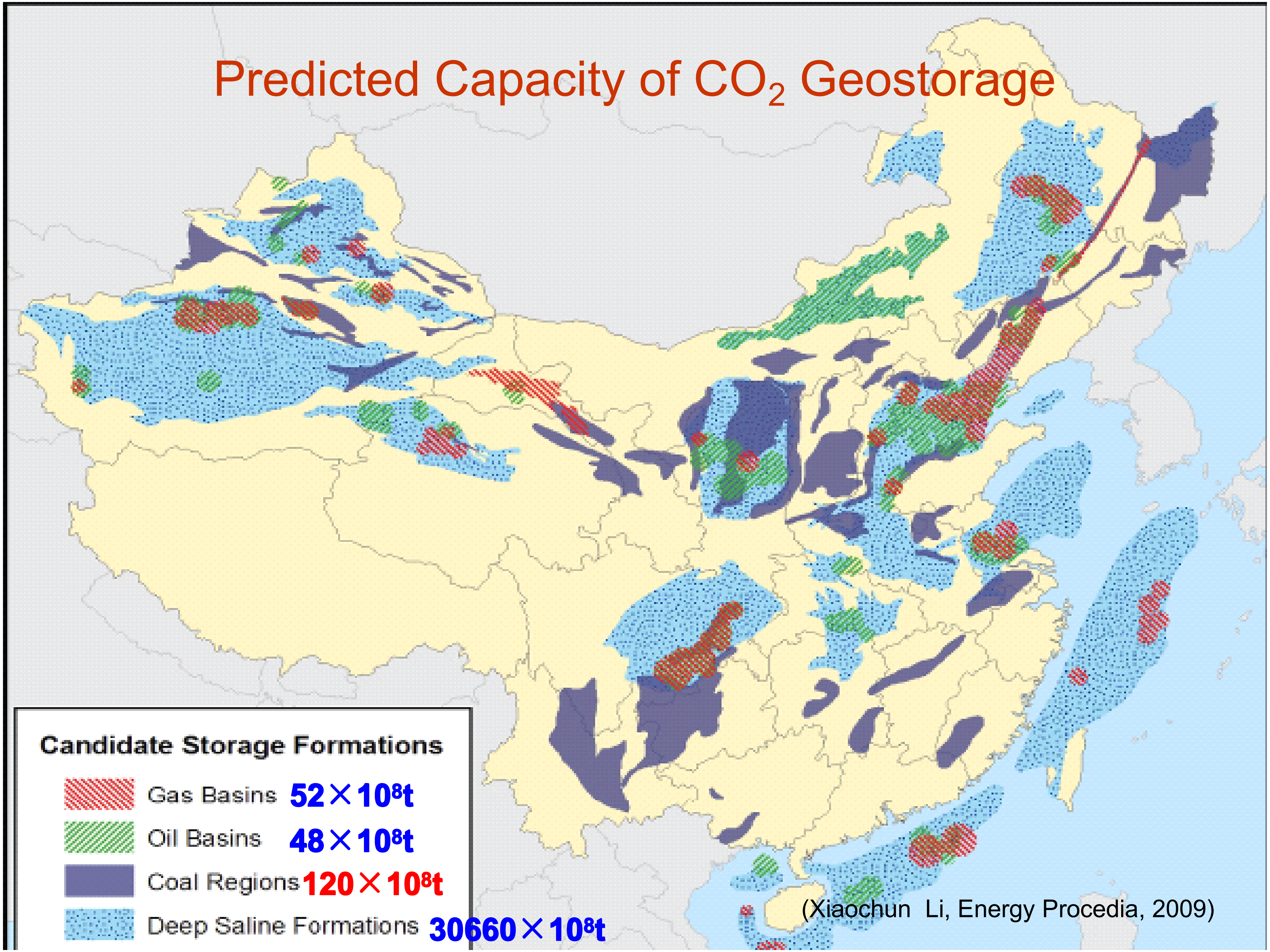


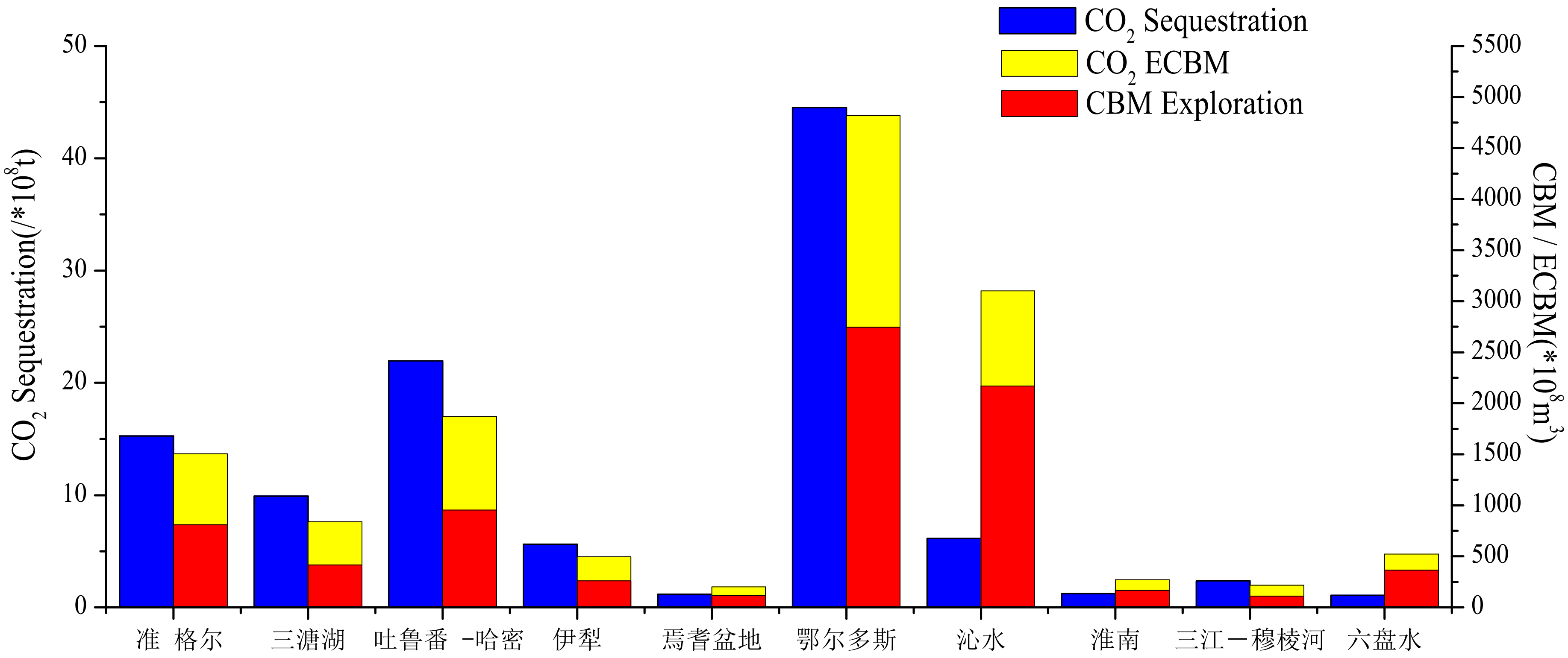
(Yong Qin, 2008)

CO_2 ECBM/ CCS

Injection of CO_2 into deep coal seams is one of the potential approaches for enhancing coalbed methane (CBM) Recovery and CO_2 storage. The feasibility of this technology has been investigated in China since the 1990s




Predicted Capacity of CO_2 Geostorage
Candidate Storage Formations
Gas Basins 52×10⁸t
Oil Basins 48×10⁸t
Coal Regions 120×10⁸t
Deep Saline Formations 30660×10⁸t
(Xiaochun Li, Energy Procedia, 2009)



（Yanfeng Liu，2005）

✓About 98％ of CO_2-ECBM is allocated in northern part of China.

✓CO_2 Storage in unmineable coal seams of Ordos, Turpan-Hami and Junggar basins accounts for 65.49% of national storage.

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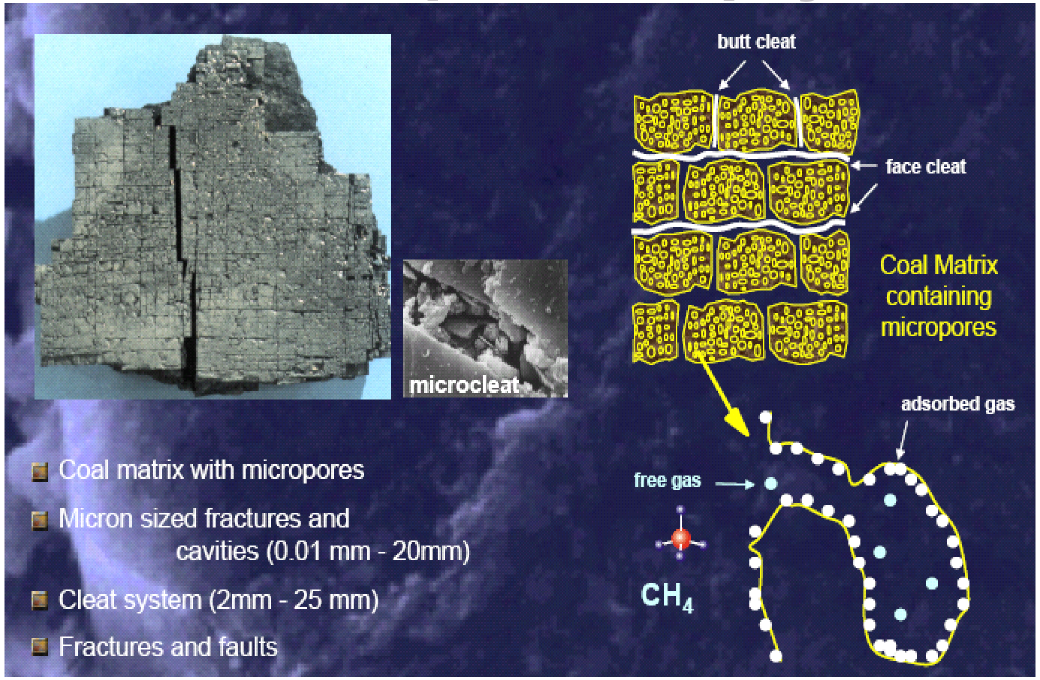
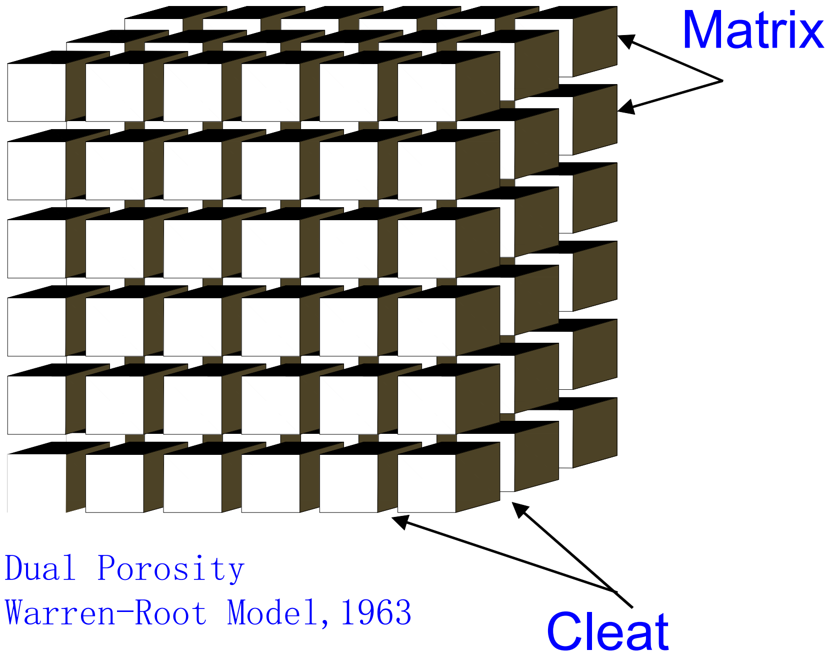
2. Modeling and Numerical simulation of CO_2-ECBM

Coupled Multiphysics of CO_2 ECBM





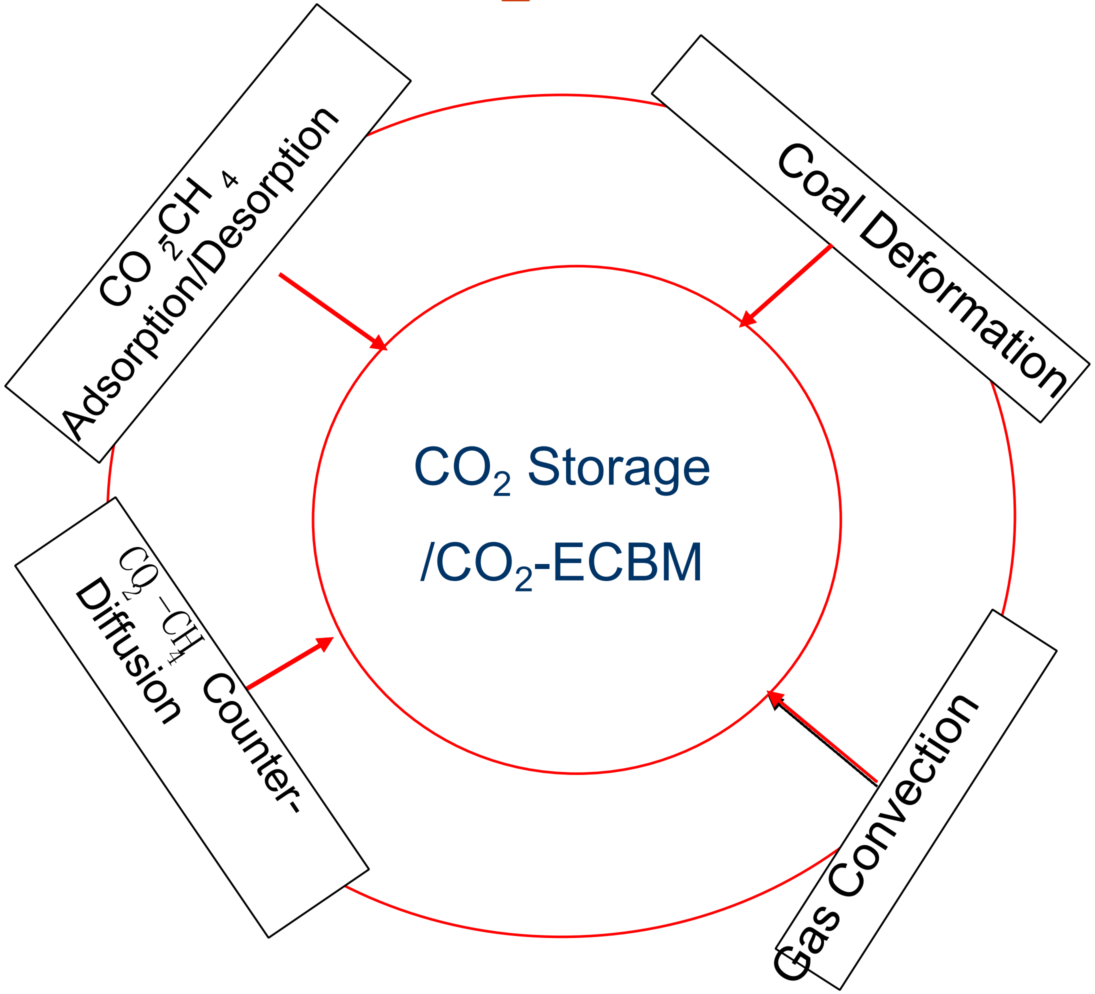
Dual Porosity
Warren-Root Model, 1963

Gas transport and storage in the coal

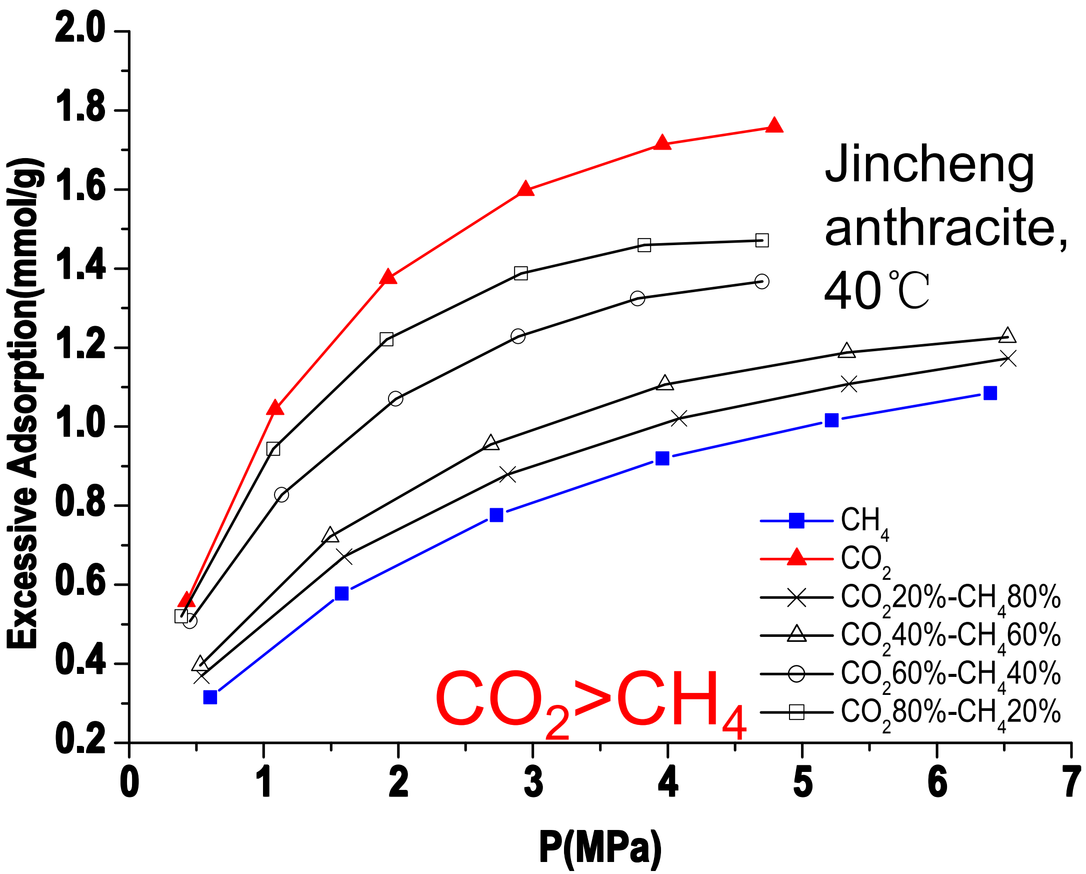
- Flow through the cleat network
- Diffusion through the micropores
- Adsorption onto the internal coal surface

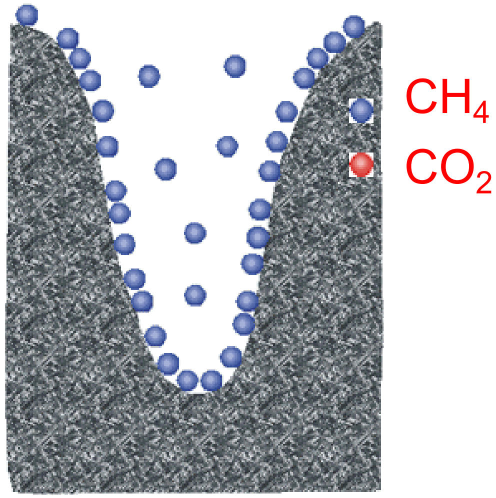
Key Scientific Issues for CO_2-ECBM

- **Gas sorption strain Vs. Effective stress strain**
- **CO_2 sorption Vs. CH_4 sorption**
- **Binary gas sorption induced differential swelling**



Experimental Evidence of Gas Competitive Adsorption

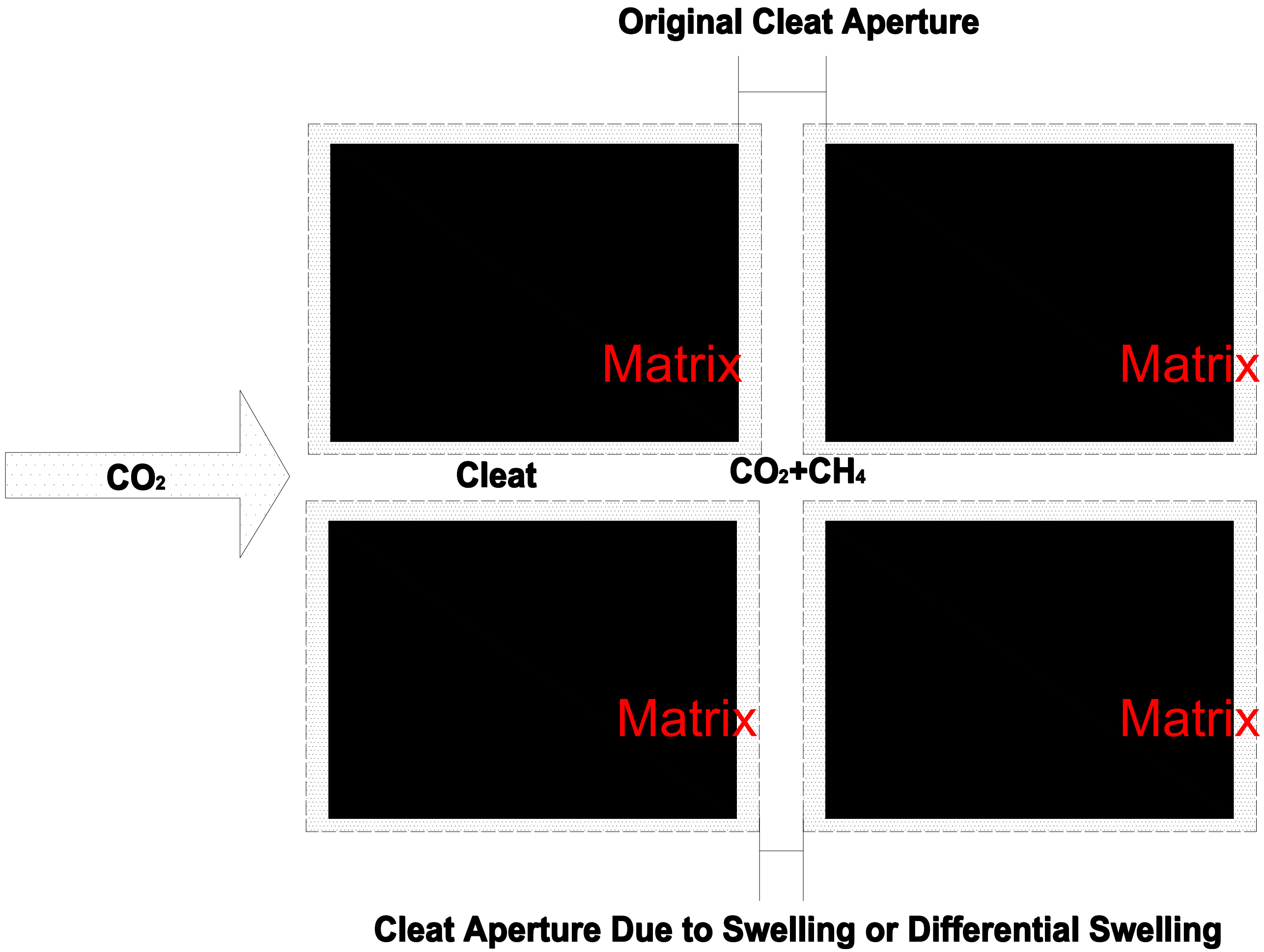




CO_2-ECBM (Enhance Coal Bed Methane Recovery)

- ☜ Competitive sorption against methane
- ☜ Lowering the partial pressure of methane in the free gas

CO_2 adsorption induced coal matrix swelling

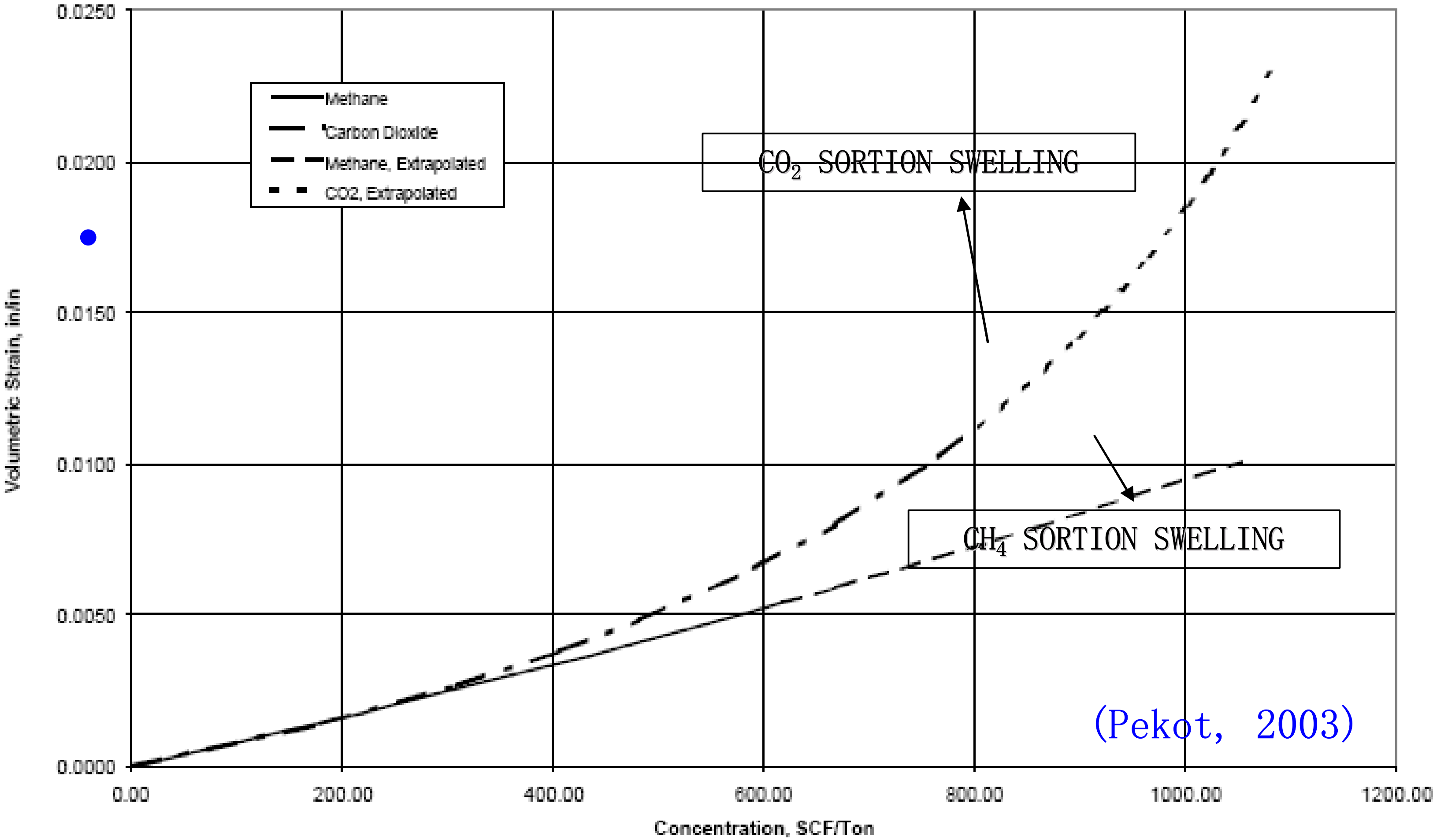


CO_2 sorption → Coal matrix swelling → Cleat aperture reducing → Permeability reducing

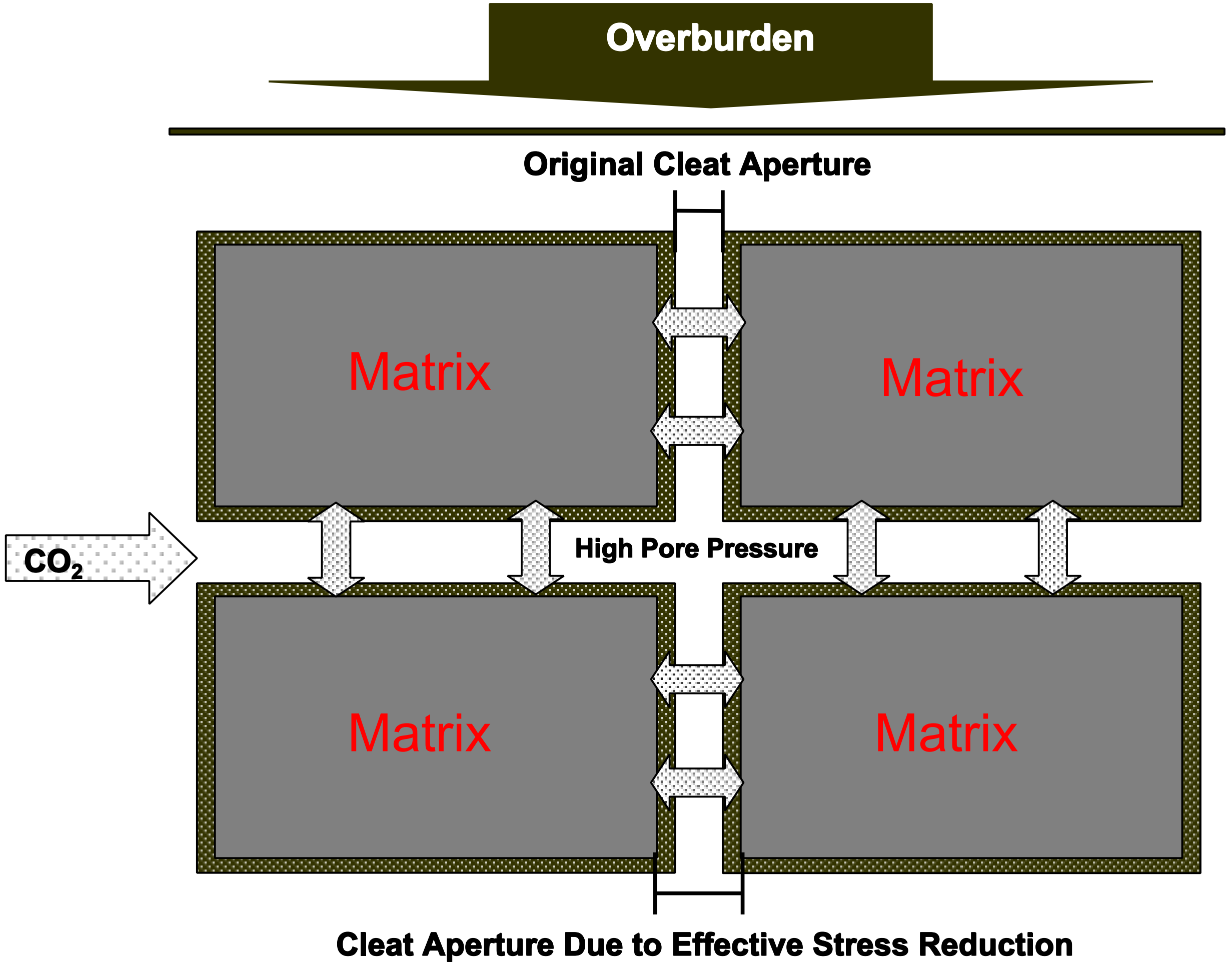
Differential Swelling

CO_2 causes more swelling of coal matrix in response to CO_2 displacing CH_4

The volumetric strain from CO_2 sorption is at least 1.5 times than from CH_4 (Chikatamarla, et al, 2004).



Effective stress causing cleat aperture increase



$$\sigma_t = \sigma_{eff} + \alpha p$$

$$d\sigma_t = d\sigma_{eff} + \alpha dp$$

$$d\sigma_{eff} = d\sigma_t - \alpha dp$$

$$\varepsilon_{eff} = f(d\sigma_{eff})$$

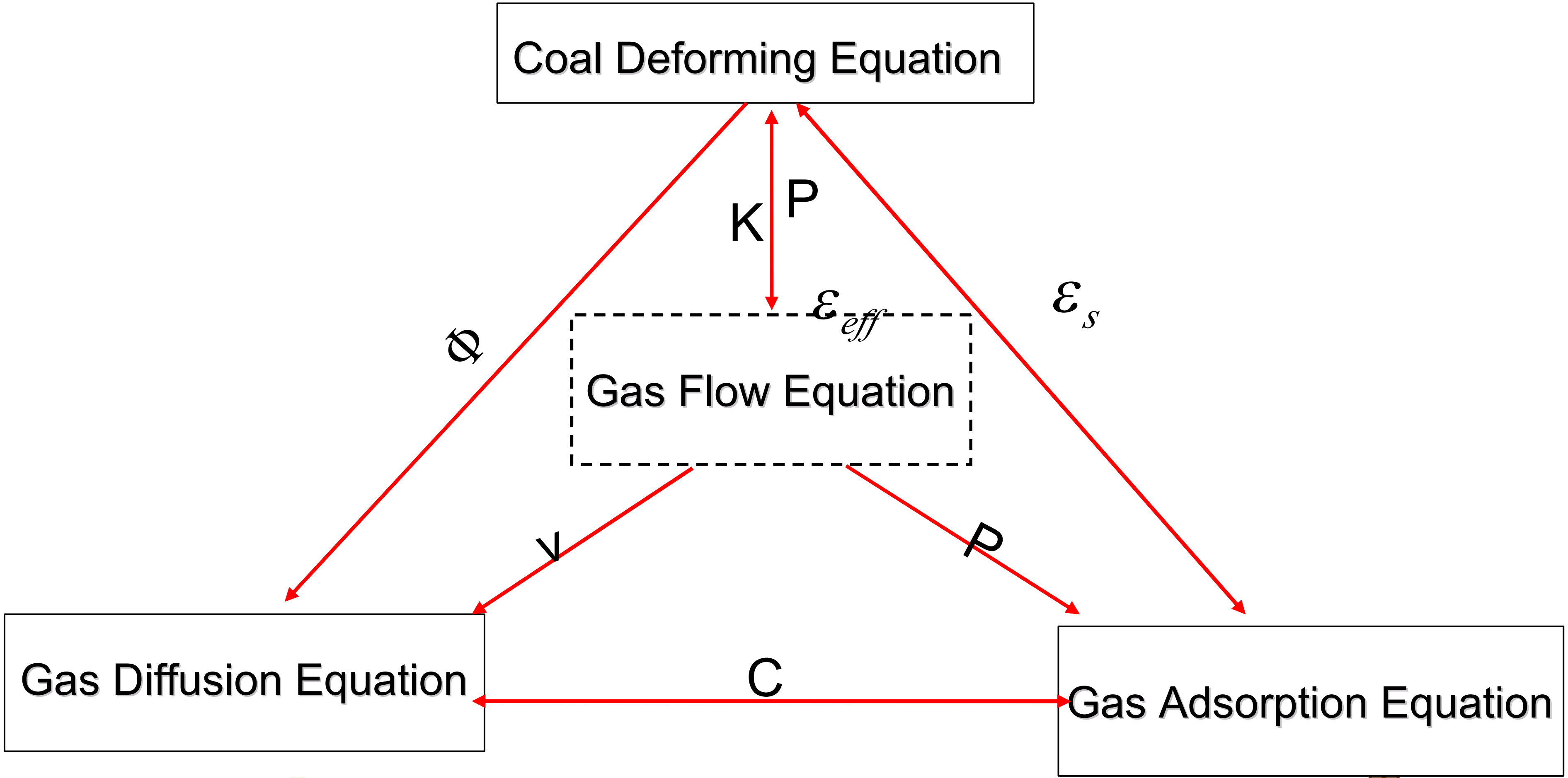
$$\phi = \phi(\varepsilon) = \phi(\varepsilon_s, \varepsilon_e)$$

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3$$

CO_2 injection→ High pore pressure→Cleat aperture Increasing→Permeability increasing

Modeling of CO_2 ECBM

Governing Equations



Assumptions

① Coal is homogeneous, isotropic and elastic continuum, and the system is isothermal.

② Strains are much smaller than the length scale.

③ Gas contained within the pores is ideal, and its viscosity is constant under isothermal conditions.

④ Gas flow through the coal matrix is assumed to be viscous flow obeying Darcy ’ s law (water phase is not included in the model).

☞Isothermal adsorption ----Extended Langmuir Equation:

$$V_i = \frac{V_{Li} b_i P_i}{1 + \sum b_i P_i}$$

☞Adsorption-induced strain/pressure relationships fits with Langmuir like equation:

$$\varepsilon_s = \varepsilon_L \frac{p}{P_{\varepsilon L} + p} \qquad \varepsilon_s = \sum_{i=1}^{2} \varepsilon_i = \sum_{i=1}^{2} \varepsilon_{Li} \frac{RTb_i C_i}{1 + \sum_{j=1}^{2} RTb_j C_j}$$

(Harpalani and Schraufnagel, 1990; Cui and Bustin,2005)

Coal deformation (Constitute Equation)

$$Gu_{i,kk} + \frac{G}{1-2\nu} u_{k,ki} - \alpha p_{,i} - K\varepsilon_{s,i} + f_i = 0$$

$\alpha p_{,i}$ → Pressure deformation

$K\varepsilon_{s,i}$ → Sorption induced deformation

Coal porosity and permeability

$$\phi = \frac{1}{1+S}[(1+S_0)\phi_0 + \alpha(S - S_0)]$$

$$\frac{k}{k_0} = \left(\frac{1}{1+S}[(1+S_0) + \frac{\alpha}{\phi_0}(S - S_0)]\right)^3$$

$$S = \varepsilon_v + \frac{p}{K_s} - \varepsilon_s = \varepsilon_v + \frac{p}{K_s} - \sum_{i=1}^{2} \varepsilon_{Li} \frac{RTb_iC_i}{1+\sum_{j=1}^{2} RTb_jC_j}$$

Binary gas diffusion and convection (Mass Balance Equation)

$$\frac{\partial m}{\partial t} + \nabla \cdot (\rho_g \cdot q_g) = \nabla \cdot (D \cdot \phi \nabla C_f) + Q_s$$

CO_2

$$M_1 C_1 \frac{\alpha - \phi}{1+S}\left[\frac{\partial \varepsilon_v}{\partial t} + \frac{RT}{K_s}\left(\frac{\partial C_1}{\partial t} + \frac{\partial C_2}{\partial t}\right) - \frac{\partial \varepsilon_s}{\partial t}\right] + \phi \cdot M_1 \frac{\partial C_1}{\partial t} + \rho_c M_1 \frac{\partial V_1}{\partial t} +$$

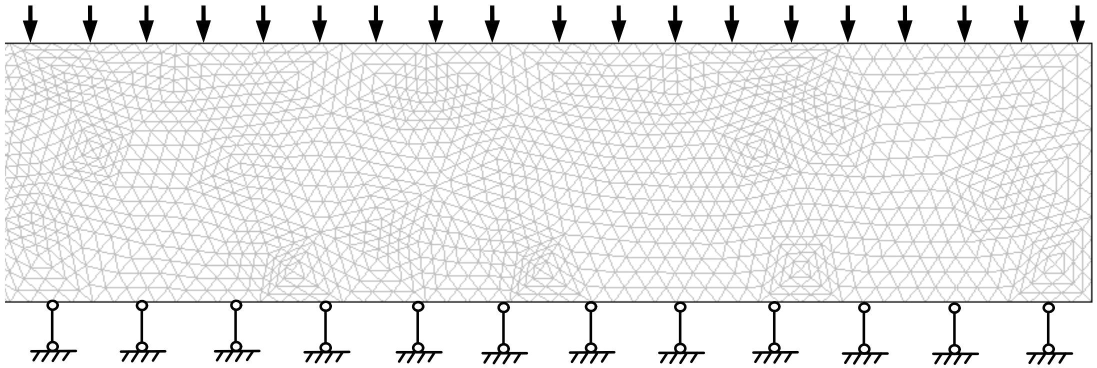
$$\nabla \cdot \left[M_1 C_1 \cdot \left(-\frac{kRT}{\mu}\nabla C_1\right)\right] + \nabla \cdot [-D\phi \cdot \nabla (M_1 C_1)] = 0$$

CH_4

$$M_2 C_2 \frac{\alpha - \phi}{1+S}\left[\frac{\partial \varepsilon_v}{\partial t} + \frac{RT}{K_s}\left(\frac{\partial C_1}{\partial t} + \frac{\partial C_2}{\partial t}\right) - \frac{\partial \varepsilon_s}{\partial t}\right] + \phi \cdot M_2 \frac{\partial C_2}{\partial t} + \rho_c M_2 \frac{\partial V_2}{\partial t} +$$

$$\nabla \cdot \left[M_2 C_2 \cdot \left(-\frac{kRT}{\mu}\nabla C_1\right)\right] + \nabla \cdot [-D\phi \cdot \nabla (M_2 C_2)] = 0$$

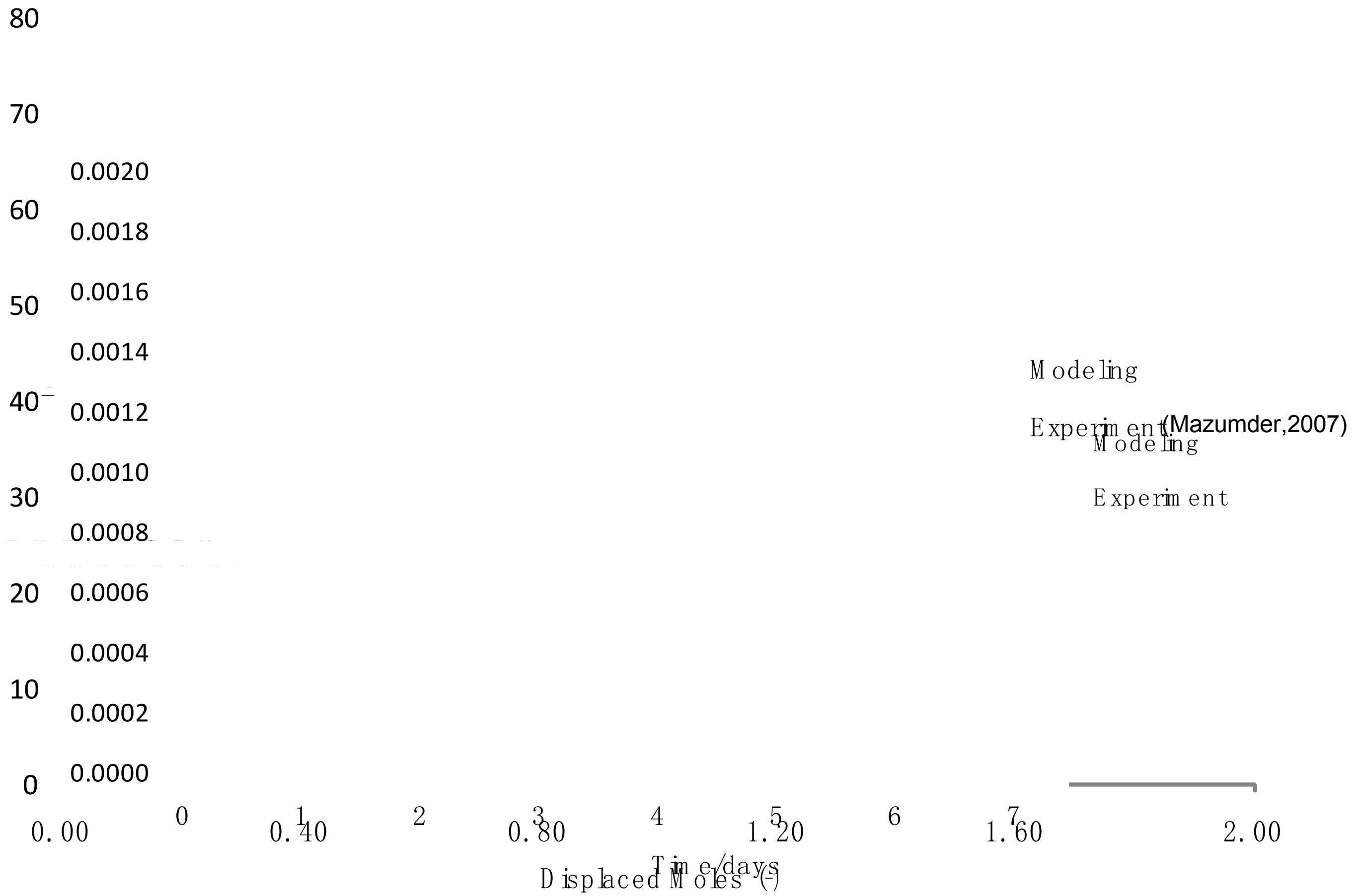
Validation and Verification of Modeling



Experiments provided by Mazumder et al, 2007

- Sample was 334mm long and 69.50mm in diameter
- Pore pressure was 4.3MPa
- The difference between the annular pressure and the pore pressure was 3.61MPa
- CO_2 was injected from the left side and flowed out from the right side.
- The injection rate is 6.0ml/h.

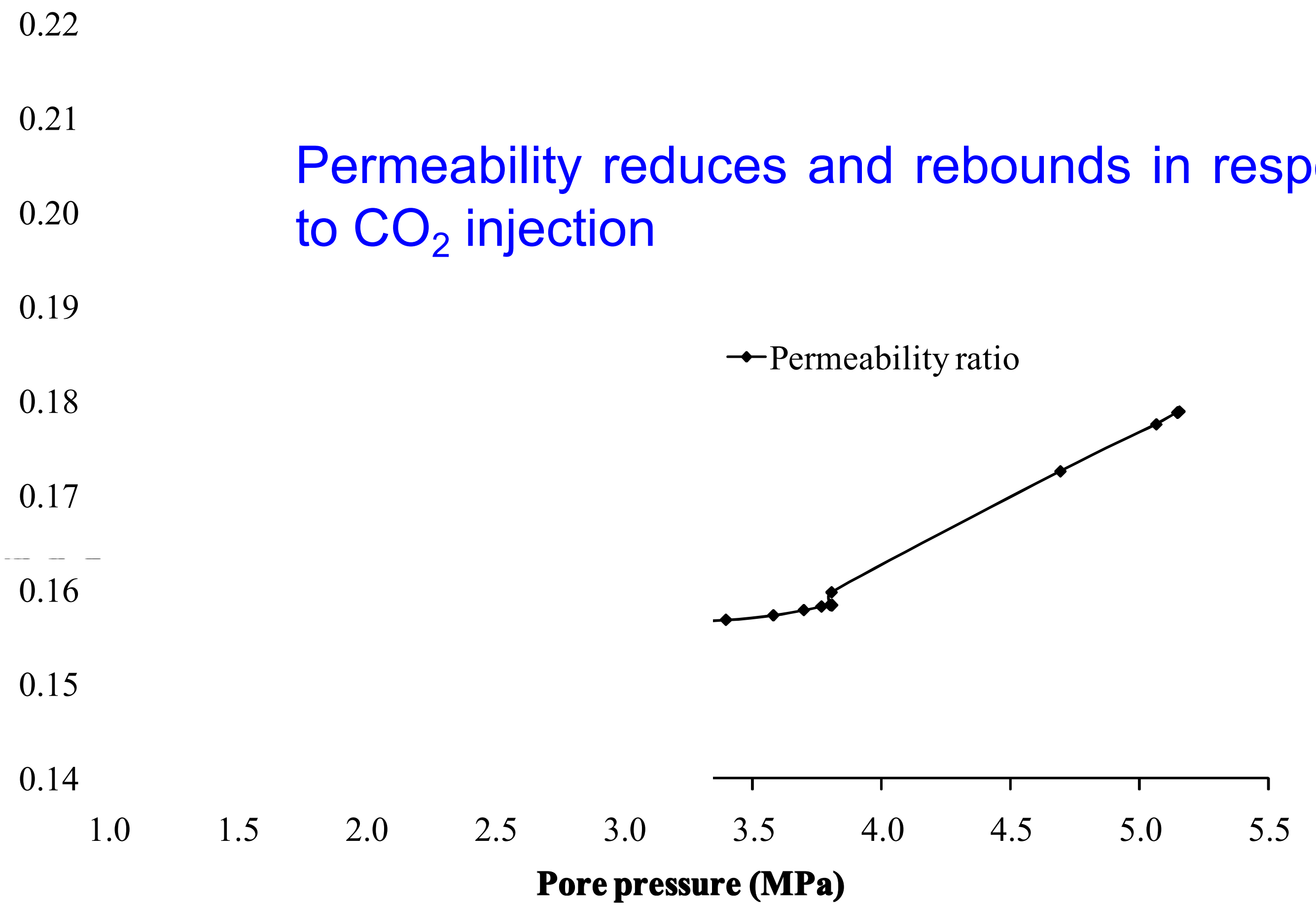
Move to COMSOL Multiphysics Lab……



$$\text{Sweep efficiency} = \frac{\text{moles of } CH_4 \text{ produced} \times 100\%}{\text{moles of } CH_4 \text{ initially in place}}$$

$$\text{Displaced volume} = \frac{\text{moles of } CO_2 \text{ injected}}{\text{moles of } CH_4 \text{ initially in place}}$$

Permeability reduces and rebounds in response to CO_2 injection



CO_2-ECBM Technology

Pilot test at Well TL-003, Zhaoyuan, Jincheng

Jointly made by China CBM Corp. & Alberta Research Council

120 tons of CO_2 Injection

Modeling of Pilot test in Jincheng Coal Gas Reservoir

291.167m

PW-2

37.35m

PW-1

Simulation Area

13.631m

IW

354.867m

82.942m

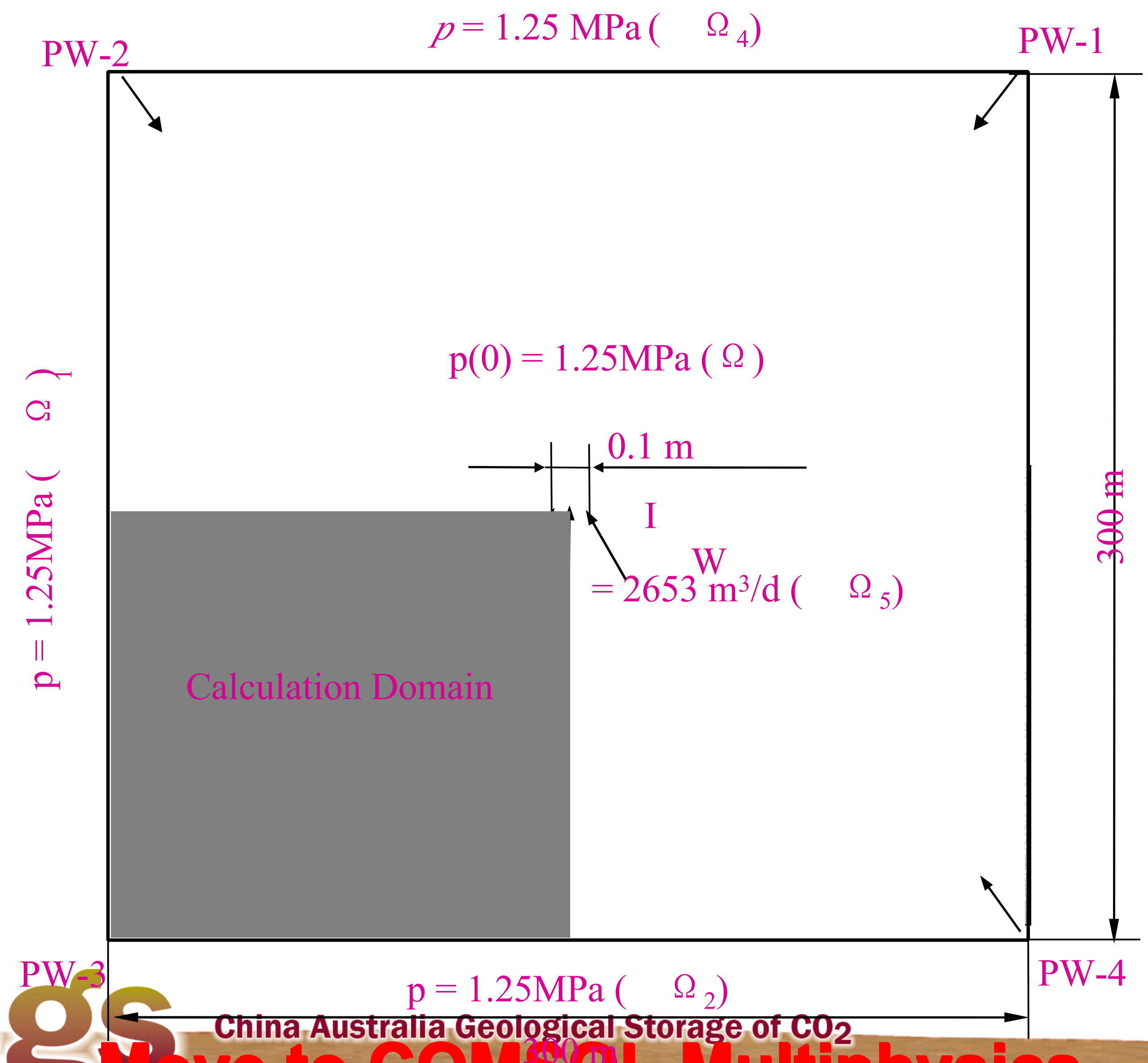
PW-3

PW-4

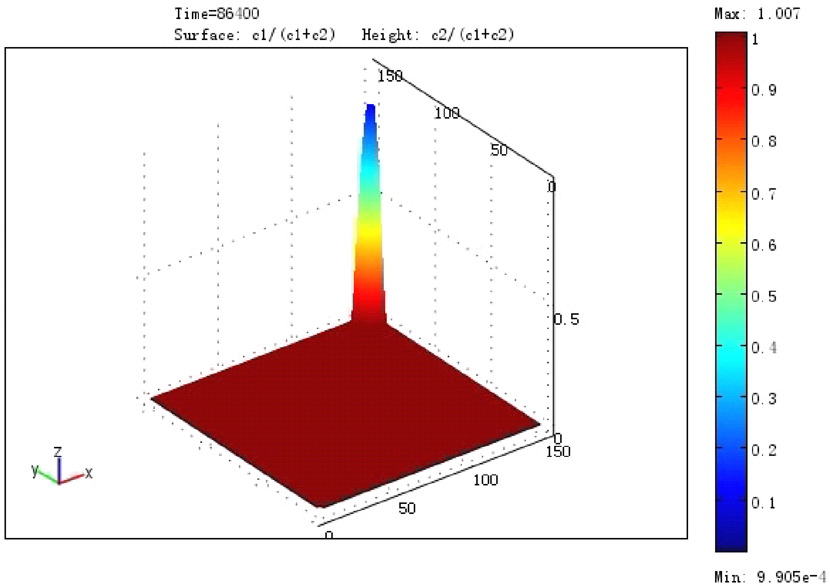
278.67m

（Wong，2007）

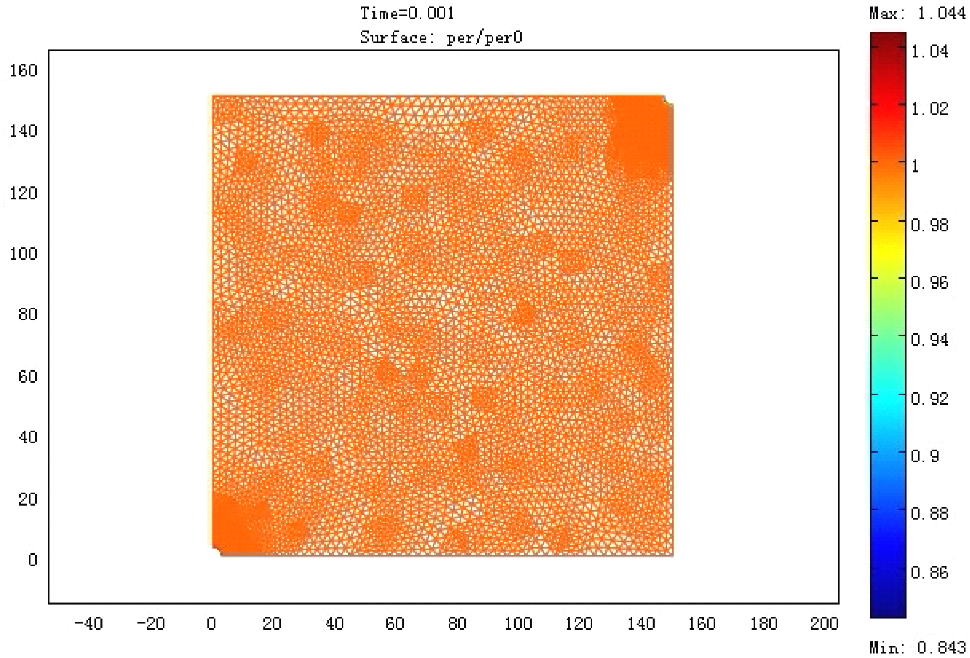
Finite Element Model



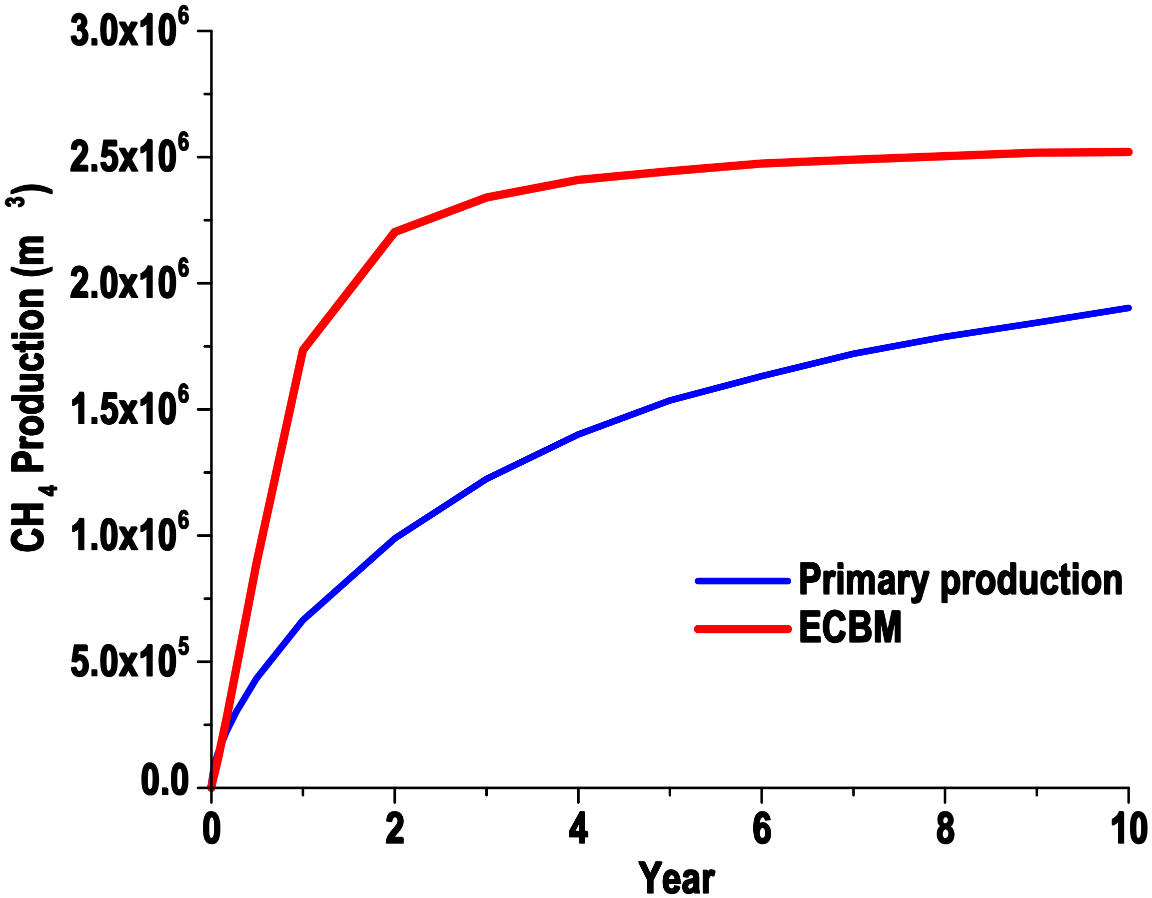
CO_2 Sweeping CH_4



Binary gas component exchange



Change of coal seam permeability



- After six months of injection, the CBM production is dramatically enhanced.
- CO_2-ECBM helps to extract 1.44 times more methane than the primary production
- 1.75×10^4t of CO_2 is sequestrated in the 300*300 m^2 area within 10 years

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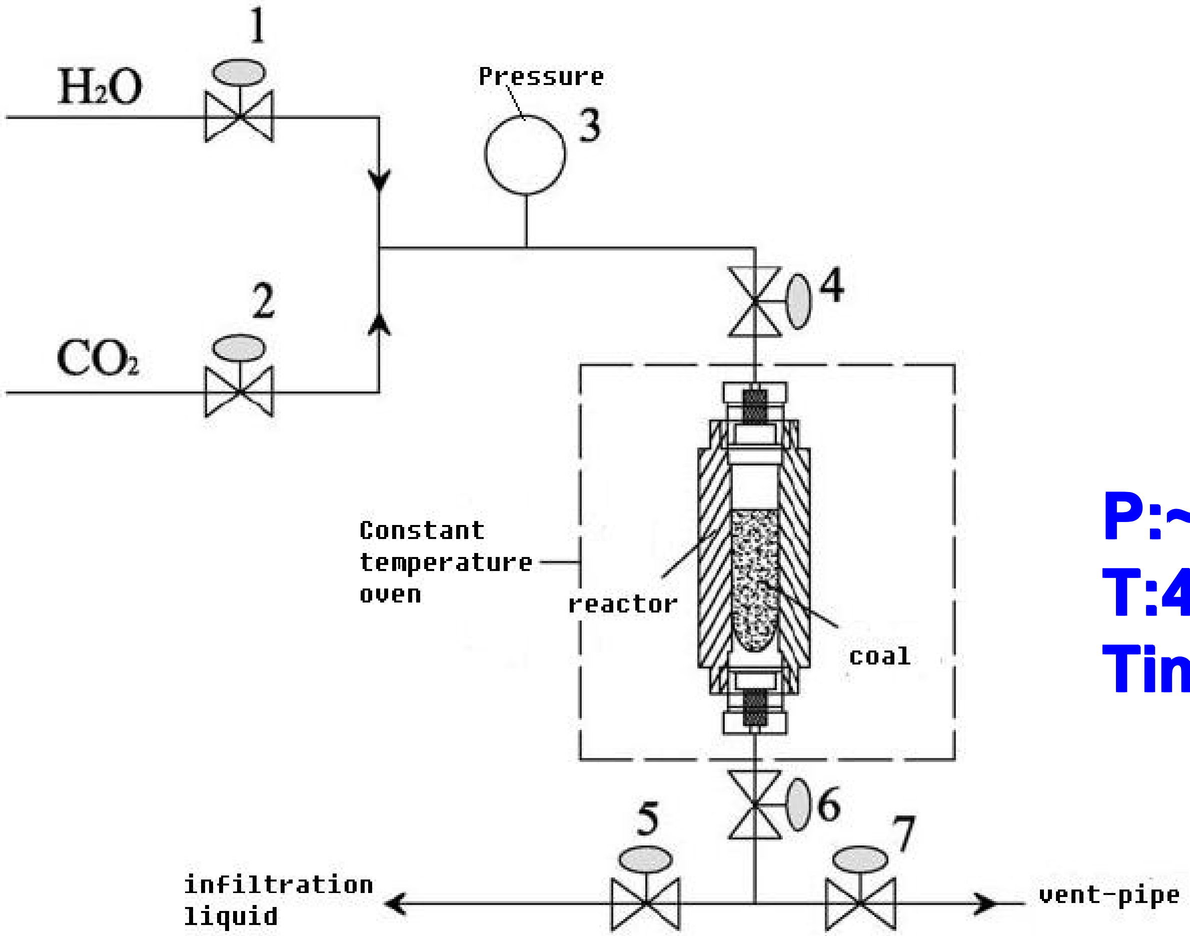
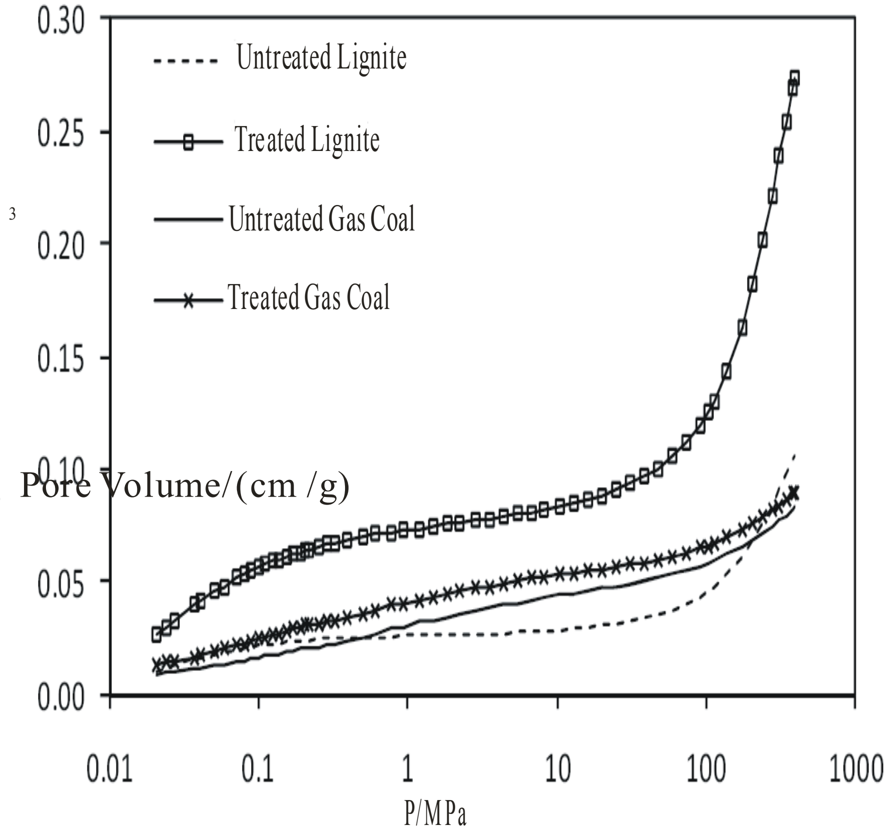
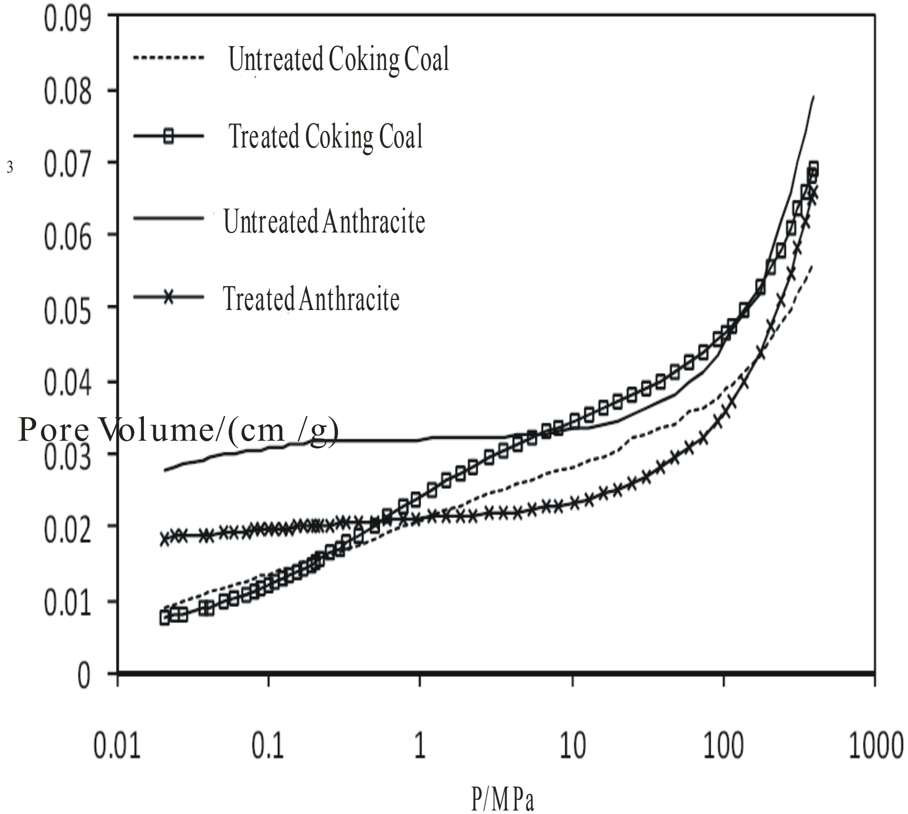
Sketch of Reactor



P:~10MPa
T:40℃
Time：72 h

Cumulative pore volume of different rank coal (mercury injection)





Permeability changed during the process

- Firstly, decrease in the initial stage;
- Secondly,briefly stability ;
- Thirdly, increase in the middle stage;
- Lastly, stability

Outline

4 Conclusions and Puzzled

Conclusions:

- A fully coupled coal deformation, gas transport and gas adsorption/desorption finite element (FE) model is introduced to achieve a better understanding of gas-coal interactions, implications for ECBM and CO2 sequestration in coal seams.
- COMSOL FE simulator is extended to simulate the CO2 injection performance in Qinshui Basin under field scale and conditions, to address in-situ spatial-temporal binary gas composition exchange and evolutions of coal permeability.
- CO2 storage in coal seam can improving the coal structure and influencing Permeability.

Puzzled:

- Which is more important to Permeability changed， adsorption swelling or reaction between H_2O-CO_2 and minerals？

Thank you for your attentions!