[PS]A Dynamic Reserve Estimation Method for Both Methane and Water in Coal Reservoirs*

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Abstract

Coalbeds in situ contain significant amounts of water, and ideally this water is removed by pumping prior to the primary recovery of coalbed methane (CBM) to lower pressure and stimulate methane desorption. Such a prior water production can be challenging because desorption depends on the occurrence state of methane and water in situ. The objectives are to: (1) quantify both the occurrence state of methane and water of different coals for a range of coalbed properties and conditions, (2) specifically quantify the impact of coal moisture on methane desorption.

In this study, ultimate and proximate analysis and methane adsorption tests were first conducted on several coal samples from different basins. Simplified local density (SLD) theory was then tailored and applied to describe the adsorption characteristics of specific methane/water mixtures for each coal. Then, a fluid mixing rule was introduced to characterize the competitive adsorption processes and a minimum potential energy method was applied to distinguish primary and secondary water adsorptions. Analysis of all resulting data included a regression analysis to obtain best fit parameters. Finally, an analytical reserve estimation method for methane and water was developed to quantify the original reserves and their change, and results of the method were compared to forecasts by conventional simulators.
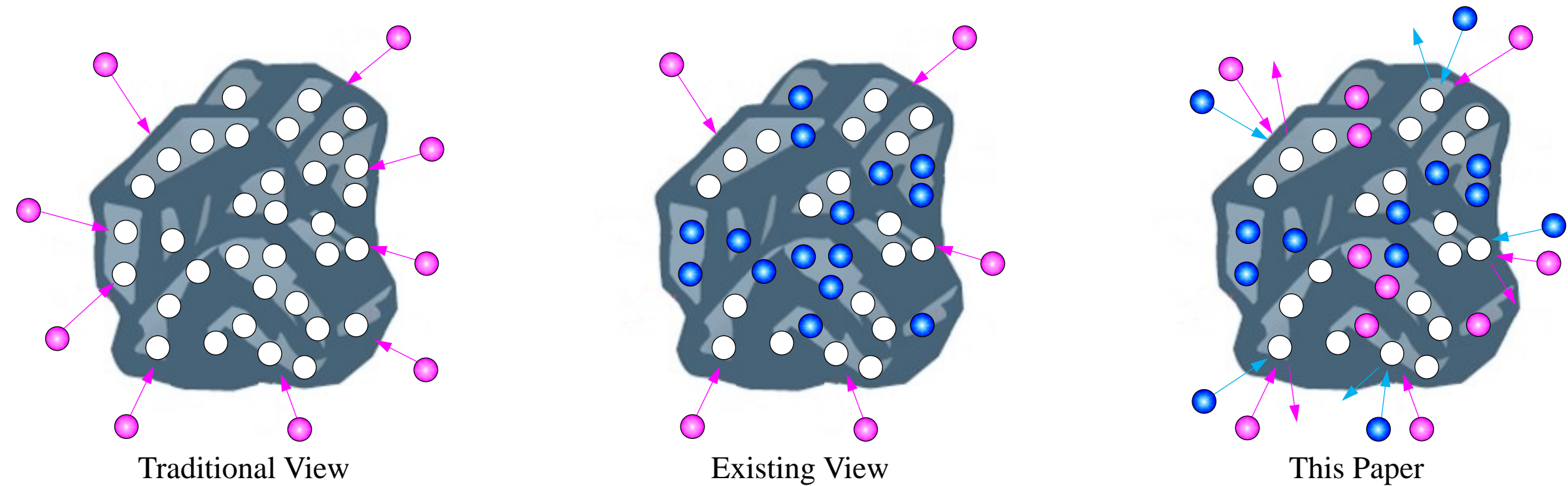
Combined results of all analyses suggest that both methane and water adsorptions decrease with temperature. While water adsorption decreases monotonically with pressure, methane adsorption first increases then decrease with pressure. Maximum methane adsorption occurs at approximately 10 MPa pressure. Fixed carbon is the effective components adsorbing methane while equilibrium moisture isn't, on the contrary, water will compete with methane for adsorption sites, thus degrading the effective methane adsorption capacity of coal. Both methane and water adsorptions on coals can be effectively described by a competitive adsorption model, but the impact of moisture on methane desorption varies with temperatures and pressures. With water divided into adsorbed and free states and with methane occurring in adsorbed, free, and dissolved forms, the proposed reserve estimation method predicted approximately the same original reserves as existing simulators predict, and also quantifies how reserves change during CBM recovery.
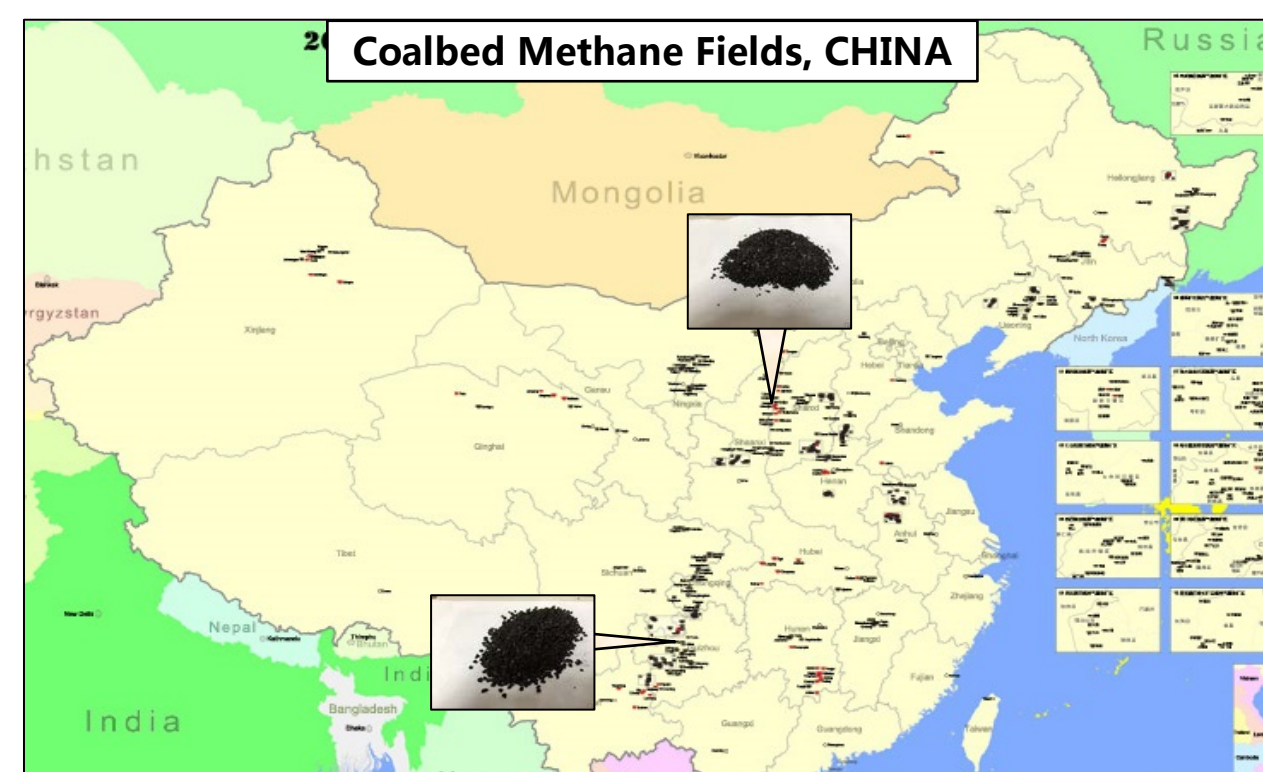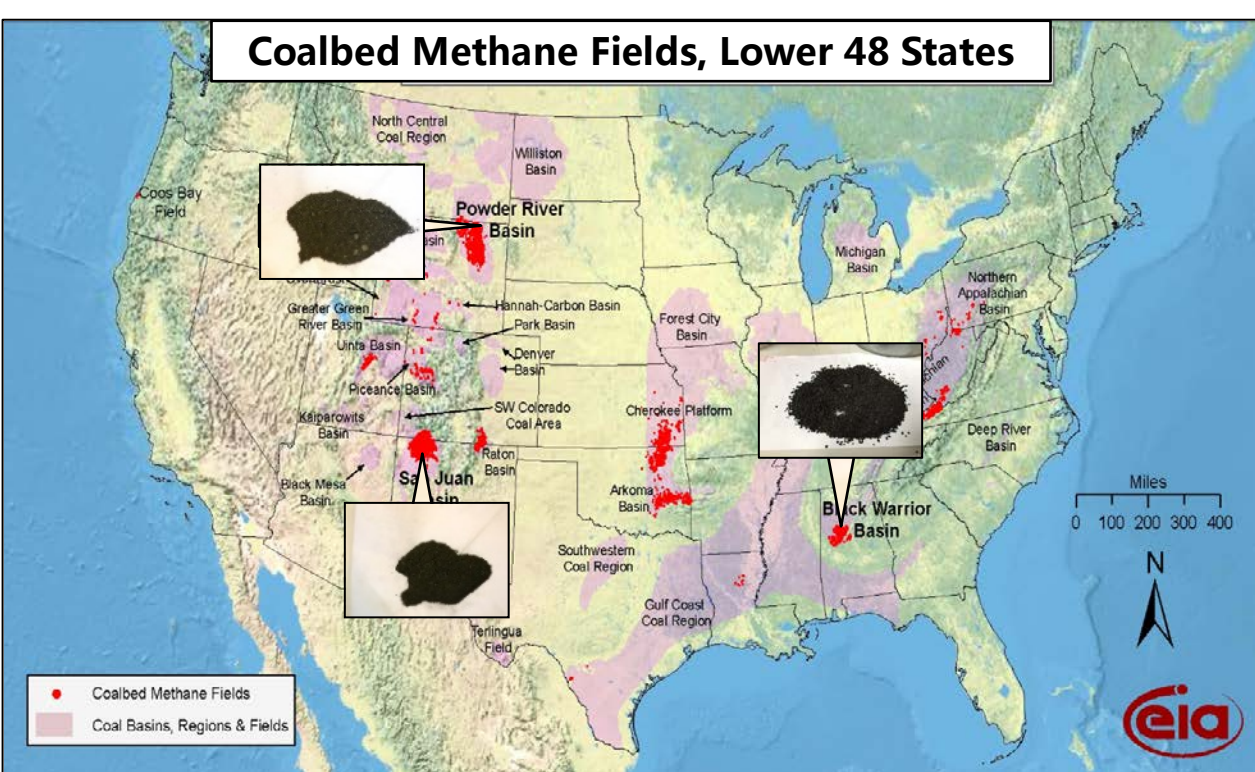
A dynamic reserve estimation method for both methane and water in coal reservoirs

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Introduction

Since coalbeds in situ usually contain significant amounts of water, understanding the occurrence characteristics of water and its impact on methane adsorption/desorption can improve quantitative forecasts of original reserves and well performance.


Traditional View   Existing View   This Paper

Experiment

Coalbed Methane Fields, Lower 48 States

Coalbed Methane Fields, CHINA

Coal samples used for adsorption capacity assessment

Adsorbent		BWBC Coal	SJF Coal	PRW Coal	O4 Coal	EYWG 3 Coal
Ultimate Analysis	C, %	80.55	59.11	53.28	67.02	84.20
	H, %	4.86	5.09	6.04	4.23	3.09
	O, %	3.23	17.37	34.08	21.99	5.68
	N, %	1.70	1.36	0.74	0.87	1.03
	S, %	0.92	0.90	0.39	0.66	0.54
Proximate Analysis	M$_{EMC}$, %	1.94	6.10	23.78	11.03	1.80
	M$_{FC}$, %	56.39	40.79	37.48	44.02	78.48
	M$_V$, %	32.93	36.94	33.27	39.72	5.23
	M$_A$, %	8.74	16.17	5.47	5.23	5.46

Ultimate and proximate analysis of coal samples tested

P: 0~20MPa
T: 35~75℃
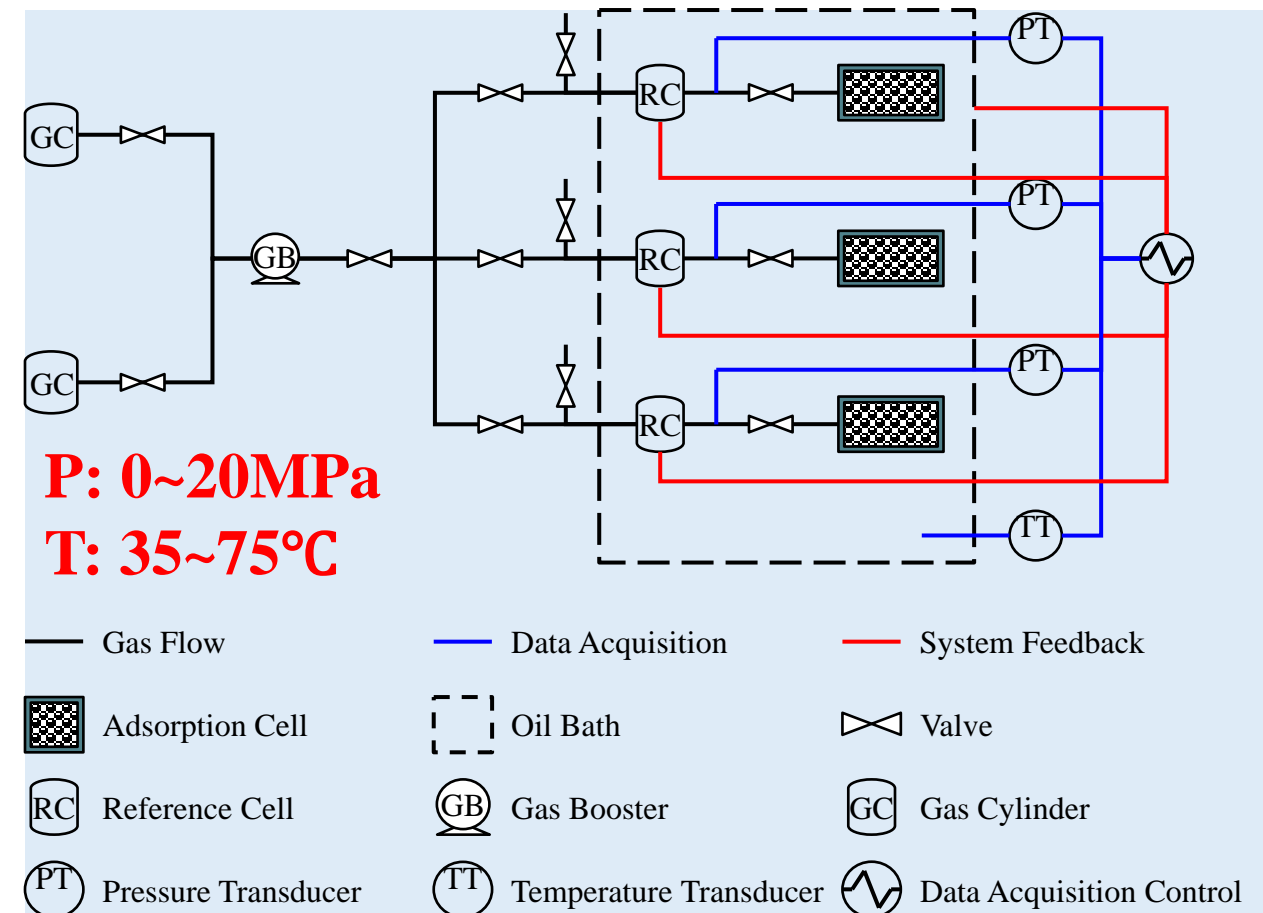
Schematic diagram of experimental apparatus

$$N_{CH_4}^{inj}(k)=\frac{p_{CH_4}^{ref}(k)V_{ref}}{Z_{CH_4}^{ref}(k)RT}-\frac{p_{CH_4}^{ref}(k-1)V_{ref}}{Z_{CH_4}^{ref}(k-1)RT}$$
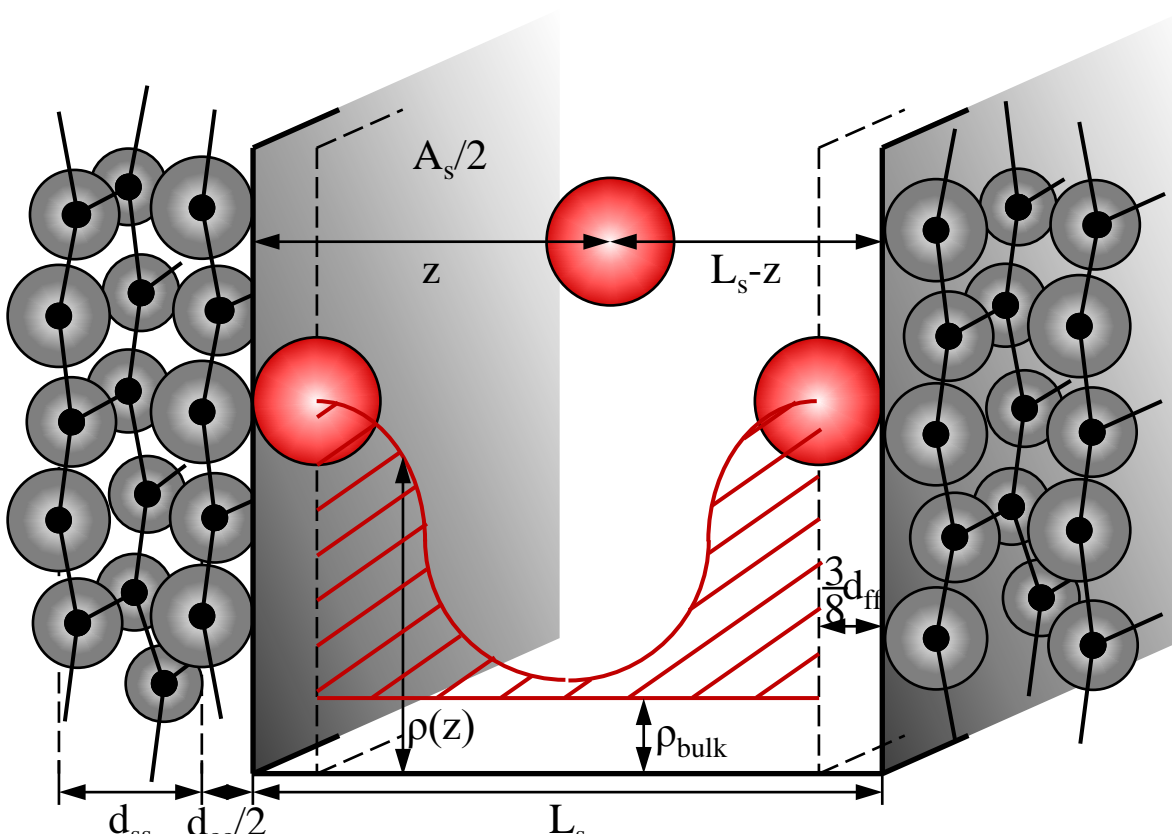
$$N_{CH_4}^{free}(k)=\frac{p_{CH_4}^{equ}(k)\left(V_{ref}+V_{void}\right)}{Z_{CH_4}^{equ}(k)RT}$$

$$N_{CH_4}^{ads}(k)=\sum_{i=1}^{k}N_{CH_4}^{inj}(i)-N_{CH_4}^{free}(k)$$

(1) Place 80-100 grams prepared ground sample inside the adsorption cell, and heat to experimental temperature;
(2) Check system air tightness, then vacuum the system, and calibrate reference and adsorption cell volumes with helium injection;
(3) Vacuum the system, re-inject methane into the system, and calculate the amount of injected, free, and adsorbed methane;
(4) Inject more methane into the reference cell to increase pressure, and re-calculate the injection, free, and adsorbed amounts;
(5) Divide the adsorption amount with adsorbent mass, plot the adsorption isotherm;
(6) Change system temperature, repeat from Step (3);
(7) Change the coal samples, repeat from Step (1).

Modeling

Simplified local density (SLD) theory was tailored and applied to describe the adsorption characteristics of specific methane/water mixtures for each coal.
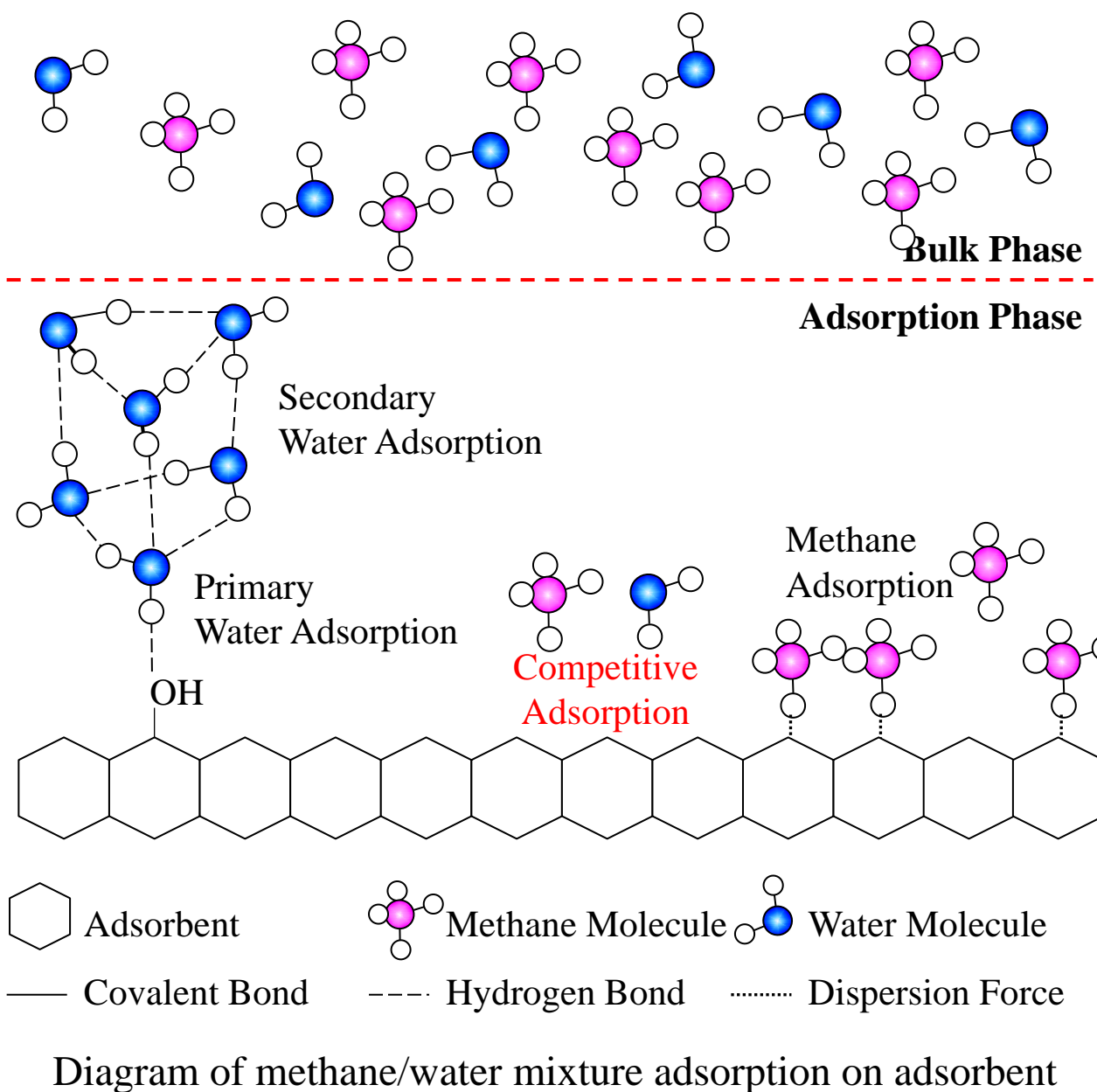

Slit pore characterization in SLD theory

$$\Psi_{fs}(z)=4\pi\rho_{atoms}\varepsilon_{fs}d_{fs}^2\left\{\frac{1}{5}\left(\frac{d_{fs}}{z}\right)^{10}-\frac{1}{2}\sum_{i=1}^{4}\left[\frac{d_{fs}}{z^*+(i-1)d_{ss}}\right]^4\right\}+\Psi_{HB}$$

$$\frac{p}{R\theta\rho}=\frac{1}{1-b\rho}-\frac{a\rho}{R\theta\left[1+(b+c)\rho-bc\rho^2\right]}$$

$$\ln\frac{f_{bulk}}{p}=\frac{p}{R\theta\rho_{bulk}}-1-\ln\left(\frac{p}{R\theta\rho_{bulk}}-\frac{pb}{R\theta}\right)+\frac{a_{bulk}/(R\theta)}{\sqrt{b_{bulk}^2+6b_{bulk}c_{bulk}+c_{bulk}^2}}$$

$$\times\ln\left[\frac{2+\rho_{bulk}\left(b_{bulk}+c_{bulk}-\sqrt{b_{bulk}^2+6b_{bulk}c_{bulk}+c_{bulk}^2}\right)}{2+\rho_{bulk}\left(b_{bulk}+c_{bulk}+\sqrt{b_{bulk}^2+6b_{bulk}c_{bulk}+c_{bulk}^2}\right)}\right]$$

$$\mu_{bulk}=\mu_0+RT\ln\left(f_{bulk}/f_0\right)$$

$$a_{bulk}=\sum_i\sum_j x_i x_j a_{ij}^{bulk} \qquad a_{ads}(z)=\sum_i\sum_j y_i(z)y_j(z)a_{ij}^{ads}(z)$$

$$b_{bulk}=\sum_i x_i b_i^{bulk} \qquad b_{ads}=\sum_i y_i(z)b_i^{ads}$$

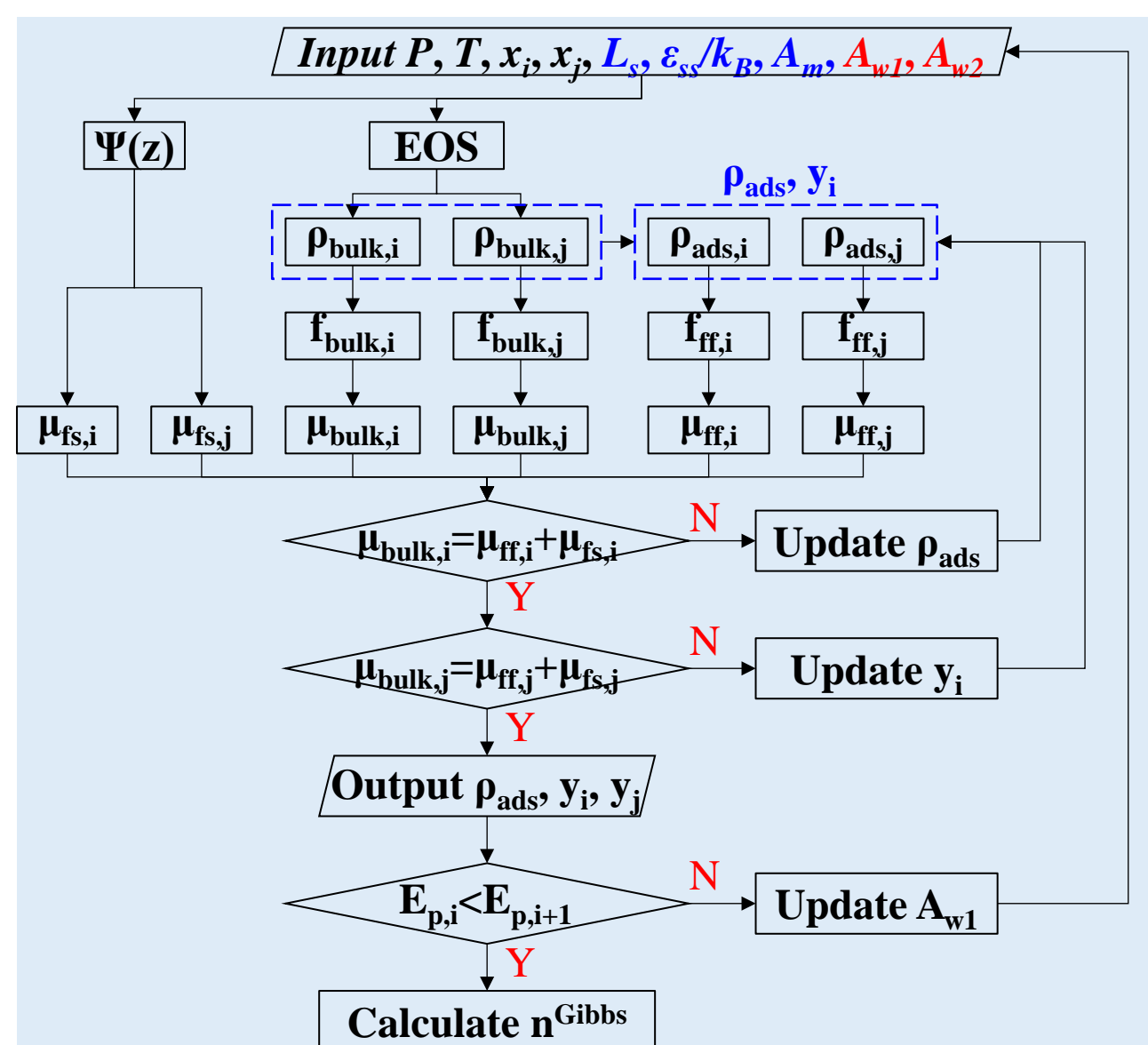$$c_{bulk}=\sum_i x_i c_i^{bulk} \qquad c_{ads}=\sum_i y_i(z)c_i^{ads}$$

$$E_p=2\times\mu_{water}^1\left(\frac{3d_{ff}}{8}\right)\rho\left(\frac{3d_{ff}}{8}\right)A_{water}^1+\frac{t_c}{\frac{3d_{ff}}{8}}\int_{\frac{3d_{ff}}{8}}^{L_s-\frac{3d_{ff}}{8}}\mu_{water}^{fs}(z)\rho(z)A_{water}^{*2}dz$$

$$f_i^{ads}(z)=f_i^{bulk}\exp\left[-\frac{\Psi_i^{fs}(z)+\Psi_i^{ff}(L_s-z)}{k_BT}\right]$$

$$\sum x_i=1 \qquad \sum y_i=1$$

$$n_{CH_4}^{Gibbs}=\frac{A_s^s c_{H_4}}{2}\int_{\frac{3d_{ff}}{8}}^{L_s-\frac{3d_{ff}}{8}}\left[\rho_{ads}(z)y_{CH_4}(z)-\rho_{bulk}x_{CH_4}\right]dz$$

$$n_{water}^{Gibbs}=\frac{A_s^s1}{2}\rho_{water}\left(\frac{3d_{ff}}{8}\right)y_{water}\left(\frac{3d_{ff}}{8}\right)-\rho_{bulk}x_{water}$$

$$+\frac{A_{water2}^s}{2}\int_{\frac{3d_{ff}}{8}}^{L_s-\frac{3d_{ff}}{8}}\left[\rho_{ads}(z)y_{water}(z)-\rho_{bulk}x_{water}\right]dz$$

ASSUMPTIONS

(1) The chemical potential of any point above adsorbent surface is equal to the bulk phase chemical potential;
(2) The chemical potential of any point above adsorbent surface is the sum of adsorbate-adsorbate and adsorbate-adsorbent interactions;
(3) The adsorbate-adsorbent interaction of any point above adsorbent surface is independent of the temperature and the number of molecules;
(4) Coal pores are considered as perfect slits with temperature and pressure distributed uniformly;
(5) All adsorbate and adsorbent molecules are spherical, except for the adsorbate molecules touching slit walls.

A fluid mixing rule was further introduced to characterize the competitive adsorption processes while a minimum potential energy method was applied to distinguish primary and secondary water adsorptions.

Diagram of methane/water mixture adsorption on adsorbent

Solution procedure for methane-water competitive adsorption

Results

Both experimental and modeling results of methane and water adsorption on coals with varying temperatures and pressures are shown below. The deviations between the predicted and experimental results are all within 1% for methane and within 5% for water.

BWBC coal   SJF coal   PRW coal   O4 coal   EYWG3 coal
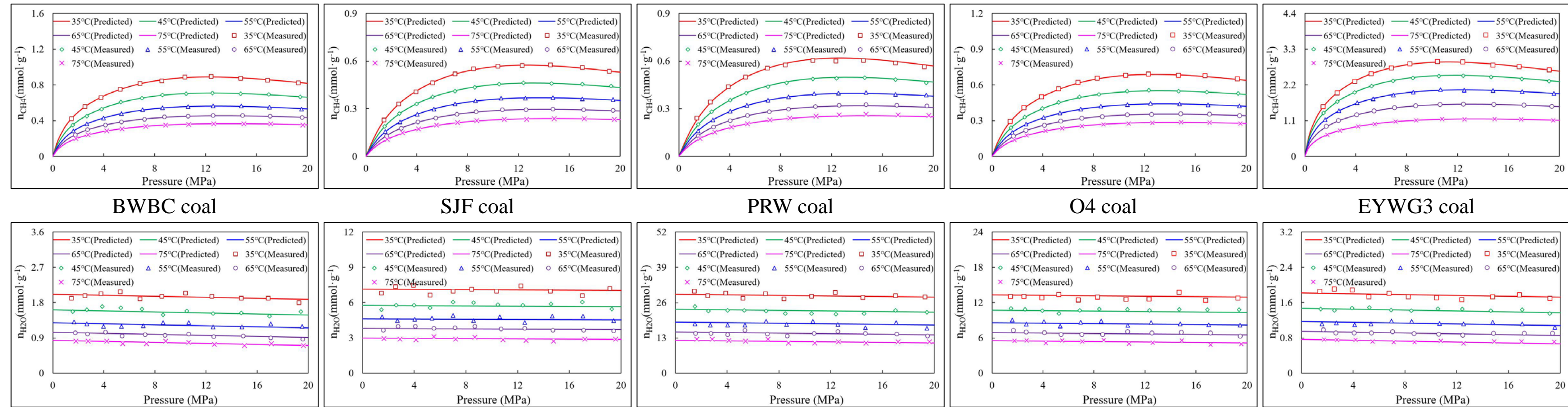
Methane and water adsorption on coal with varying temperatures and pressures

Discussion & Case Study

The performance of proposed reserve estimation method was validated against a CBM case, and compared to estimates by coalbed simulators and by a volumetric method.

Coal seam properties for case studied

Parameter	A$_c$ m²	t$_c$ m	Φ$_f$	T ℃	P$_{pi}$ MPa	ρ$_c$ kg/m³	ρ$_{water}$ kg/m³	S$_{water}$	S$_{CH4}$	M$_A$	M$_{EMC}$	P$_L$ MPa	V$_L$ m³/t	L$_s$ nm	e$_{ss}$/k$_B$ K	A$_{CH4}$ m²/g	A$_{water1}$ m²/g	A$_{water2}$ m²/g
Value	647497.0	9	0.001	45	7.65	1434	990	0.592	0.408	0.156	0.0672	4.6885	15.2	1.96	16.0	60.6	112.3	29.7

Initial methane and water in place predicted

	G$_{CH4}$ 10⁷sm³	G$_{CH4}$(ads) 10⁷sm³	G$_{CH4}$(free) 10⁷sm³	G$_{CH4}$(dis) 10⁷sm³	G$_{water}$ 10⁸kg	G$_{water}$(ads) 10⁸kg	G$_{water}$(free) 10⁸kg
GEM	6.1681						
ECLIPSE	6.1233						
COMET2	6.1290						
SIMED II	6.1340						
GCOMP	6.0315						
Seidle	6.1165	6.0995	0.0169		13.0363		
This Study	6.1170	6.0995	0.0169	0.0005	9.5426	9.5083	0.0343

$$G_{CH_4}^{Gibbs}=A_t t_c \rho_c n_{CH_4}^{Gibbs} \qquad G_{CH_4}^{free}=\frac{pA_t t_c\phi S_{CH4}}{Z_{CH4}(p,T)RT} \qquad G_{CH_4}^{dis}=A_t t_c\phi S_{water}\rho_{water}(p,T)s_{CH4}(p,T)$$

$$G_{water}^{Gibbs}=A_t t_c \rho_c n_{water}^{Gibbs} \qquad G_{water}^{free}=\frac{A_t t_c\phi S_{water}\rho_{water}(p,T)}{Mr_{water}}$$

Results suggest that the methane reserve estimation forecasted by this study approximates the forecast by all simulators considered and that by Seidle, while the water reserve estimation is consistent with results by Seidle. With water divided into adsorbed and free states, and methane divided into adsorbed, free, and dissolved forms, the approach detailed here provides the occurrence states of methane and water in situ and a robust reserve estimation method for coal seam.

Conclusions

(1) The adsorption characteristics of methane/water mixture on coals can be described by the proposed competitive adsorption model, and the deviation between predicted and experimental results are within 1% for methane and 5% for water.
(2) Both methane and water adsorptions decrease with temperature. While water adsorption decreases monotonically with pressure, methane adsorption first increases then decreases with pressure, and the maximum occurs at pressure ~10 MPa.
(3) Fixed carbon is the effective component that adsorbs methane while equilibrium moisture does not; on the contrary, water will compete with methane for adsorption sites, thus degrading the adsorption capacity of coal.
(4) The proposed reserve estimation method reveals the occurrence states of methane and water in situ, as well as a robust reserve estimation for a variety of coal seam.

Acknowledgments