Gas and Water Production Forecasting Using Semi-analytical Method in Coalbed Methane Reservoirs*

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Abstract

This paper presents a method for forecasting gas and water production in coalbed methane (CBM) reservoirs. In this paper, the author developed a semi-analytical method for predicting gas and water production without numerical simulation. This method combined all of reservoir equations such as Langmuir Sorption Isotherm, Material Balance, Darcy's equation and relative permeability correlation. Iterative method has been developed to predict reservoir pressure throughout production life. The results of this method were compared with numerical simulation results to validate the equation. The proposed method can be applied as sensibility and comparison of reservoir simulation results and reservoir comprehensions of CBM.

Introduction

Coalbed methane is classified as unconventional gas reservoir. The difference between CBM and conventional gas reservoir is related to gas storage mechanism. In conventional gas reservoir, the gas is stored as free gas in porous media. In coalbed, gas is stored as adsorbed gas on coal surface (micropores) and in fracture (cleat) as free gas[7]. But, amount of gas within cleat is very low and in some cases, it can be neglected.

Gas transport for coalbed starts from desorbed gas from coal surface. This desorption process has been described by Langmuir Isotherm. During dewatering process, reservoir pressure decreases with time and when reservoir pressure reaches critical desorption pressure, adsorbed gas is released from coal surface and moves through matrix following diffusion law that caused by concentration gradient. Thereafter, the gas moves to cleat and flows through fracture following Darcian flow and finally can be produced to surface from wellbore. Production rate profile of gas in coalbed is unique. At early production, produced gas increases to peak rate. This process called negative decline rate or dewatering period. After reaching peak rate, produced gas decreases with time and follows production trend of conventional gas reservoirs. Figure 1 shows production profile of gas and water for coalbed.

Analyzing and predicting production profile in coalbed reservoirs are a challenge. It caused by the complication to predict production pattern especially for early production time, thus common decline curve is difficult to be applied. The best method to predict production profile in coalbed is numerical simulation. This method considers fluid mechanisms that occur in reservoir completely. But, knowing and understanding numerical simulation methods are not easy thus need other method which is simpler in predicting production performance. Using assumptions on parameters can be used to simplify the calculations. Futhermore, applying this method is useful to easily predict and analyze production profile.

Literature Review

Coal is a material which is rich on carbon compound and generated from organic materials such as plants and vegetables. Organic materials are buried, sedimented, compressed and heated. The generation processes of coal start from plants to peat, lignite, sub-bituminous, bituminous to anthracite. These steps are called coalification. During these processes, produced methane gas increases with time and the gas will be adsorbed on coal surface because pressure and temperature effects.

Pore Structure. The dual porosity characteristic of coal where there are primary porosity in matrix and secondary porosity in fracture. The diameter range of micropores is 5 to 10 angstroms and macropores diameter is larger than 500 angstroms. Figure 2 describes pore structure for coal.

Storage Mechanism. There are two storage mechanisms in coalbed. First, gas is stored within matrix as adsorbed gas. Second, gas is stored in cleat as free gas[2]. However, the amount of gas within cleat is very low and for certain cases is ignored. Most gas is adsorbed on coal surface. The adsorption process is directly affected by pressure and temperature. Coal rank and methane capacity on coal surfaces increase with increasing pressure, temperature and coal depth. The other fluid within cleat is water. Water migrates into cleat during coalification and saturates the cleat almost 100%.

Gas Transport Mechanism. The gas is desorbed from coal surface with decreasing pressure. Desorbed gas moves through matrix to cleat as diffusion process. The gas flow through cleat follows Darcian flow. Figure 3 shows gas transport mechanisms for coalbed methane.

Langmuir Sorption Isotherm Model. Adsorption Isotherm is defined as amount of gas that is adsorbed on solid surface as a function of pressure at constant temperature. There are several Sorption Isotherm theories which have been developed such as Freundlichs's, Langmuir's, Henry's and Brunauer's theory. Among these theories, Langmuir's theory is the most frequently used for coalbed methane (Figure 4). The assumptions for this theory are

1.   One gas molecule is adsorbed at a single adsorption site;
2.   An adsorbed molecule does not effect the molecule on the neighboring site;
3.   Site are indistinguishable by the gas molecules;

4. Adsorption is on an open surface and there is no resistance to gas access to adsorption sites.

The equation for adsorption can be described as:

$$V_E(P_g) = \frac{V_L P_g}{P_L + P_g} \tag{1}$$

Gas Transport Through Matrix. The gas moves through matrix to cleat as a diffusion process. Diffusion is a movement of molecules from high concentration to low concentration. The famous diffusion equation is known as Fick's Law. Thereafter, this equation has been developed by King and Ertekin,[4,6] which is similar to Warren and Root approach. The equation is in the following:

$$\frac{dV_i}{dt} = -\frac{1}{\tau}[V_i - V_E(P_g)] \tag{2}$$

where τ is sorption time constant. It is defined as time that is needed to desorb or release 63% of gas per total adsorbed methane from coal sample at reservoir temperature and reservoir pressure until reaching atmospheric pressure. But, in this paper, to simplify the calculation, the gas is assumed moving rapidly to cleat and neglecting diffusion process (equilibrium).

Gas Transport Through Cleat. The gas which is released from matrix moves into cleat and flows through the cleat. Darcy equation is used to describe the fluid transport through cleat and equals to conventional gas flow at pseudo steady state where pressure transient effect has reached the boundary without any flow from outer boundary. Generally, Radial Darcy's equation for gas uses pseudo pressure approach. In certain cases, P² approach used for reservoir pressure is lower than 2000 psi:

$$q_g = \frac{k_a k_{rg} h (P^2 - P_{wf}^2)}{1422.5 T \mu_g Z[\ln(\frac{r_e}{r_w}) - 0.75 + S]} \tag{3}$$

Other fluid within cleat is water. During production life, water flows through cleat to wellbore. The flowing equation for water is Darcy's Equation. It can be written as:

$$q_w = \frac{k_a k_{rw} h (P - P_{wf})}{141.2 \mu_w B_w[\ln(\frac{r_e}{r_w}) - 0.75 + S]} \tag{4}$$

Relative Permeability and Saturation. Relative permeability and saturation for coalbed are different from conventional gas. For CBM, the cleat is almost 100% saturated by water and relative permeability to water close to 1 at early time. In addition, the gas is adsorbed on coal

matrix surface thus the relative permeability to gas within the cleat close to zero. As pressure decreases throughout production, adsorbed gas is released and moves into cleat thus gas saturation and gas relative permeability increases. On the other hand, water saturation and water relative permeability decrease with time. Increasing relative permeability to gas is stopped at S_{wc} where the gas cannot push water anymore. This depends on surface tension of rock. Commonly, in naturally fractured, K_r and S_w profiles are straight line due to wettability effect and rock permeability which is very high. Relative permeability and water saturation relationship are determined by experiment in laboratory using Special Core Analysis (SCAL). But, if there is no data available, it can use correlations such as Corey's and Honarpour's correlation. Corey's correlation for gas and water are sequentially described:

$$\frac{k_{rg}}{k_{rg}^*} = \left(\frac{S_g - S_{gc}}{1 - S_{wc} - S_{gc}}\right)^{N_g} \tag{5}$$

$$\frac{k_{rw}}{k_{rw}^*} = \left(\frac{S_w - S_{wc}}{1 - S_{wc}}\right)^{N_w} \tag{6}$$

Material Balance Equation. Material Balance Equation is important to calculate Original Gas in Place and fluid mechanisms in conventional and unconventional reservoirs. Basic material balance for coalbed has been developed by King[5]. According to King's considerations, gas is stored both in cleat as free gas and in matrix as adsorbed gas. The assumptions are used on King's material balance equation (Eq.7) in following:

1. Adsorbed gas is stored within matrix and free gas in cleat.
2. The coal is at saturated phase and follows Langmuir Isotherm.
3. The adsorption is at pseudo steady state period.
4. Water compressibility, rock compressibility, and water production are considered.

$$G_p = \left[\frac{Ah\phi(1 - S_{wi})}{B_{gi}} - \frac{Ah\phi[1 - c_f(P_i - P)](1 - S_w)}{B_g}\right] + \left[Ah\rho_B \frac{V_L P_i}{P_L + P_i} - Ah\rho_B \frac{V_L P}{P_L + P}\right] \tag{7}$$

Average water saturation within cleat changes with pressure and water influx/ efflux. Water saturation is affected by three mechanisms:

1. Water expansion caused by water compressibility.
2. Water influx and water production.
3. Pore volume changes as a consequent of rock compressibility.

Average water saturation equation as follows:

$$S_w = \frac{S_{wi}\left[1+c_w(P_i-P)\right]+\dfrac{5.615(W_e-B_w W_p)}{\phi_i Ah}}{\left[1-c_f(P_i-P)\right]} \qquad (8)$$

Analysis Procedures

Recognizing that[1]:

$$W_p^{n+1} = W_p^n + \frac{q_w^n+q_w^{n+1}}{2}\Delta t^{n+1} \qquad (9)$$

Where superscript "n" signs time step.

Substituting Eq. 9 into Eq. 8 and for next equations, each equation is added supercripts "n":

$$S_w^{n+1} = \frac{S_{wi}\left(1+c_w(P_i-P^{n+1})\right)+\dfrac{5.615\left(W_e^{n+1}-\left(W_p^n+\dfrac{q_w^n+q_w^{n+1}}{2}\Delta t^{n+1}\right)B_w^{n+1}\right)}{Ah\phi}}{\left(1-c_f(P_i-P^{n+1})\right)} \qquad (10)$$

Rearranging relative permeability to water (Eq. 6) and substituting Eq.10 into Eq. 6:

$$k_{rw}^{n+1} = \left(\frac{\dfrac{S_{wi}\left(1+c_w(P_i-P^{n+1})\right)+\dfrac{5.615\left(W_e^{n+1}-\left(W_p^n+\dfrac{q_w^n+q_w^{n+1}}{2}\Delta t^{n+1}\right)B_w^{n+1}\right)}{Ah\phi}}{\left(1-c_f(P_i-P^{n+1})\right)}-S_{wc}}{1-S_{wc}}\right)^{N_w} k_{rw}^{*} \qquad (11)$$

Recognizing that[8]:

$$S_g^{n+1} = 1 - S_w^{n+1} \tag{12}$$

Rearranging relative permeability to gas (Eq. 5) and substituting Eq.12 into Eq. 5:

$$k_{rg}^{n+1} = \left(\frac{1 - S_w^{n+1} - S_{gc}}{1 - S_{wc} - S_{gc}} \right)^{N_g} k_{rg}^* \tag{13}$$

Substituting Eq.13 into Eq. 3:

$$q_g^{n+1} = \frac{k_a \left(\dfrac{1 - S_w^{n+1} - S_{gc}}{1 - S_{wc} - S_{gc}} \right)^{N_g} k_{rg}^* h (P^{n+1^2} - P_{wf}^{\;2})}{1422.5 T \left(\mu_g Z \right)_{avg} [\ln \left(\dfrac{r_e}{r_w} \right) - 0.75 + S]} \tag{14}$$

Recognizing G_p from Darcy's equation:

$$G_p^{n+1} = G_p^n + \frac{q_g^n + q_g^{n+1}}{2} \Delta t^{n+1} \tag{15}$$

and G_p from material balance equation:

$$G_p^{n+1} = \frac{Ah\phi(1 - S_{wi})}{B_{gi}} - \frac{Ah\phi\left(1 - c_f(P_i - P^{n+1})\right)\left(1 - S_w^{n+1}\right)}{B_g^{\;n+1}}$$
$$+ \left(Ah\rho_B \frac{V_L P_i}{P_L + P_i}(1 - f_m - f_{ash}) - Ah\rho_B \frac{V_L P^{n+1}}{P_L + P^{n+1}}(1 - f_m - f_{ash}) \right) \tag{16}$$

Substituting Eq.11 into Eq. 4:

$$q_w^{n+1} = \cfrac{k_a\left(\cfrac{S_{wi}\left(1+c_w(P_i-P^{n+1})\right)+\cfrac{5.615\left[W_e^{n+1}-\left(W_p^n+\cfrac{q_w^n+q_w^{n+1}}{2}\Delta t^{n+1}\right)B_w^{n+1}\right]}{\cfrac{Ah\phi}{\left(1-c_f(P_i-P^{n+1})\right)}}}{1-S_{wc}}-S_{wc}\right)^{N_w} k_{rw}^*h(P^{n+1}-P_{wf})}{141.2\mu_w^{n+1}B_w^{n+1}\left[\ln\left(\cfrac{r_e}{r_w}\right)-0.75+S\right]} \qquad (17)$$

There are two unknown variables in Eq.17 such as reservoir pressure P^{n+1} and water rate q_w^{n+1} thus requiring iteration procedures to solve them. But, the iteration procedures in this case are slightly different from the common one. Those procedures can be arranged in the following:

1. Do iteration on q_w^{n+1}, guessing random number for $q_w^{n+1}{}_i$ and P^{n+1} where $P^{n+1} \neq 0$ (i.e. $q_w^{n+1}{}_i = 10$ bbl/day, $P^{n+1} = 1,400$ psi). While iterating $q_w^{n+1}{}_i$, P^{n+1} is assumed constant. Continue to iterate q_w^{n+1} until the error $\leq 10\text{-}6$.

2. Continue the iteration, changing $P^{n+1}{}_i$ with a new value, thereafter, continue to iterate $q_w^{n+1}{}_i$ until the error $\leq 10\text{-}6$ thus we can conclude that for once iteration on P^{n+1}, there are some iterations for $q_w^{n+1}{}_i$. These iterations processes are stopped when G_p from Eq.15 is almost equal to G_p from Eq.16 (error $\leq 10\text{-}6$).

After getting the values of q_w^{n+1}, average reservoir pressure P^{n+1} and G_p^{n+1}, calculate cumulative water production W_p^{n+1} using Eq. 9, water saturation S_w^{n+1} using Eq.10, gas saturation S_g^{n+1} using Eq.12, relative permeability to gas using Eq. 13 and gas production rate using Eq.14. Continue to calculate these variables until the end of time step.

Application to Actual Data

To demonstrate the application of this method, data from literatures are used[1,3]. List of data is on Table 1. The calculation results of predicted reservoir pressure in this method and simulation show both charts are similar (Figure 5). The results of cumulative gas and pressure (Figure 6) indicate that G_p of simulation is higher than G_p of prediction. Those are illustrated by final results at 3,650 days with 2,993 mmscf for simulation and 22,250 mmscf for prediction. This occurs due to predicted calculations done manually. Figure 7 shows gas production profile increases until peak rate and decreases with increasing time. This unique profile is caused by the contrary between relative permeability to gas and reservoir pressure where relative permeability to gas increases with decreasing reservoir pressure. The convergence between G_p of Darcy and G_p of material balance (Figure 8) is the key of this method where the magnitude of error of these $G_p \leq 10^{-6}$ and give accurate results.

Figure 9 shows water production decreases with increasing time and decreasing reservoir pressure. This figure shows produced water is higher for a well at early time. Although water rate decreases with time, the drainage of water in cleat requires long term period of time (Figure 10). Figure 11 indicates the relative permeability to gas and water within cleat system. The straight line of relative permeability to gas and water occur due to the assumptions of $N_w = 1$ and $N_g = 1$. Futhermore, the relationship between relative permeability to gas and water should be simulated. It is caused by the difficulty on determining their correlations in laboratory for fracture system.

Conclusions

In this study, a semi-analytical method has been developed on predicting reservoir pressure, gas production, and water production in coalbed methane wells. This method combines Langmuir Sorption Isotherm, Darcy's equation, material balance equation and Corey's correlation. Futhermore, this method can be used on comparing and analyzing numerical simulation. In addition, this method can also be applied for independent users.

Nomenclature

A = drainage Area, ft^2, acre
a = Warren and Root shape factor
B_g = gas formation volume factor, ft^3/scf
B_{gi} = initial gas formation volume factor, ft^3/scf
B_w = water formation volume factor, res bbl/stb
B_{wi} = initial water volume factor, res bbl/stb
c_f = rock compressibility, psia^{-1}
c_w = water compressibility, psia^{-1}
D_i = diffusion coefficient, ft^2/hr
f_{ash} = ash content, fraction
f_m = moisture content, fraction
G_p = cumulative gas production, scf, mmscf
h = seam thickness, ft
k_a = absolute permeability, md
k_g = effective permeability of gas, md
k_r = relative permeability, fraction
k_{rg} = relative permeability to gas, fraction
k_{rg}^* = relative permeability to gas at end point, fraction
k_{rw} = relative permeability to water, fraction
k_{rw}^* = relative permeability to water at end point, fraction

k_w = effective permeability to water, md
n = incremental superscript, dimensionless
N_g = Corey gas exponent, dimensionless
N_w = Corey water exponent, dimensionless
P = reservoir pressure, psia
P_g = gas pressure, psia
P_i = initial reservoir pressure, psia
P_L = Langmuir pressure constant, psia
P_{wf} = bottom hole pressure, psia
q_g = gas rate, mscf/day
q_w = water rate, bbl/day
r_e = external radius, ft
r_w = well radius, ft
S = skin, dimensionless
S_g = gas saturation, fraction
S_{gc} = critical gas saturation, fraction
S_{gi} = initial gas saturation, fraction
S_w = water saturation, fraction
S_{wc} = connate water saturation, fraction
S_{wi} = initial water saturation, fraction
T = reservoir temperature, °R, °F
V_0 = Initial gas content, scf/cuft
V_E = equilibrium volumetric concentration, scf/ft^3
V_i = adsorbate volumetric concentration, scf/ft^3
V_L = Langmuir volume constant, scf/ton, scf/ft^3
W_e = water encroachment, bbl
W_p = cumulative water production, bbl
Z = gas compressibility factor, dimensionless
μ_g = gas viscosity, centipoise
μ_w = water viscosity, centipoise
τ = sorption time constant, day
ρ_B = bulk density of coal, gr/cm^3, kg/m^3
ϕ = porosity, fraction

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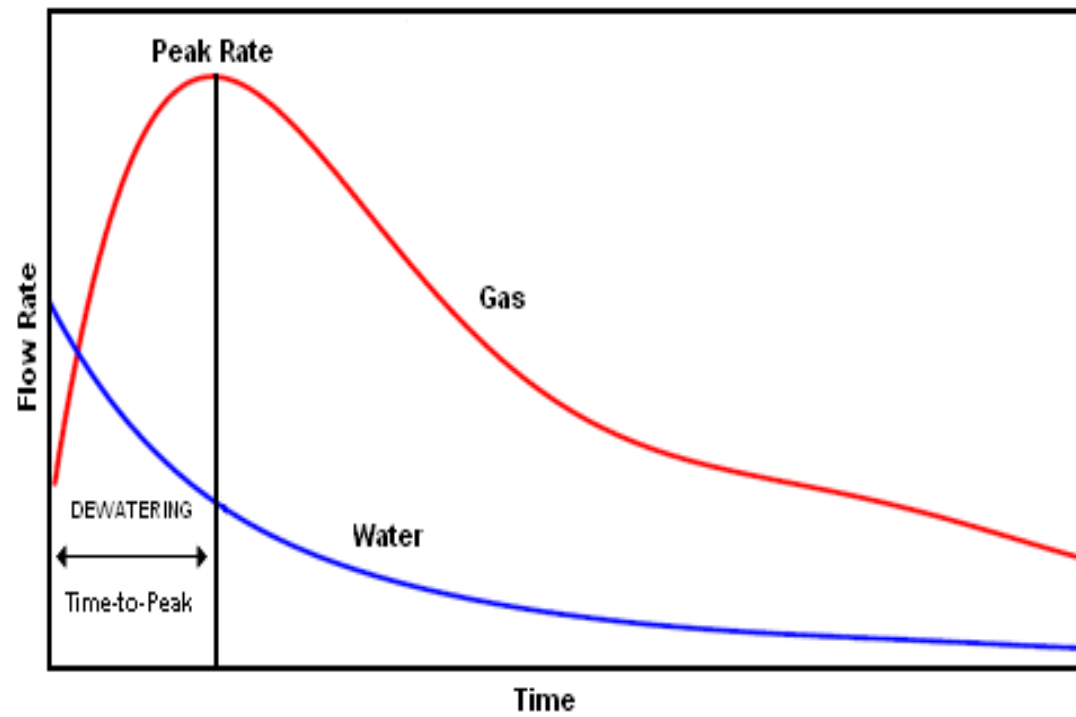http://www.onepetro.org/mslib/app/Preview.do?paperNumber=00021599&societyCode=SPE

Figure 1. Schematic of gas and water rate for coalbed methane.
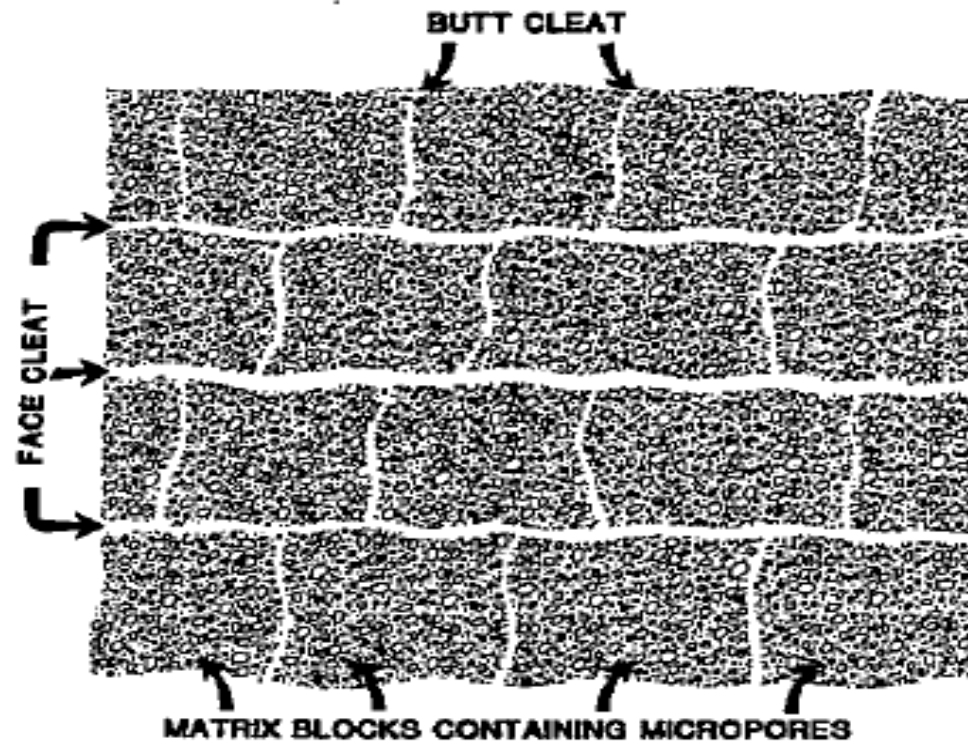
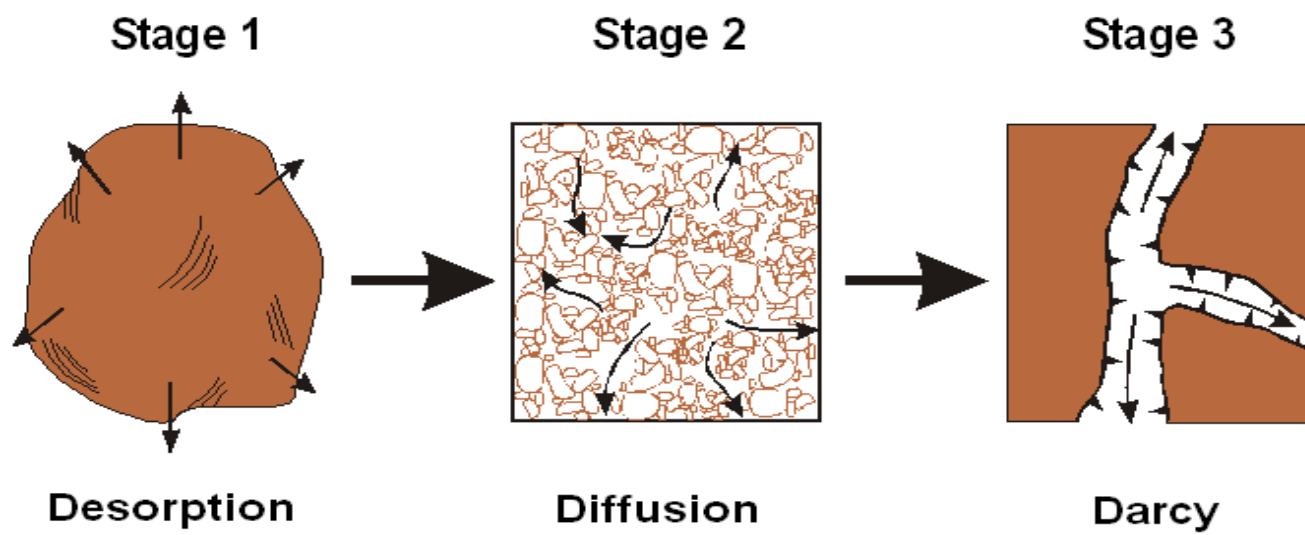Figure 2. Schematic of dual porosity of coal.

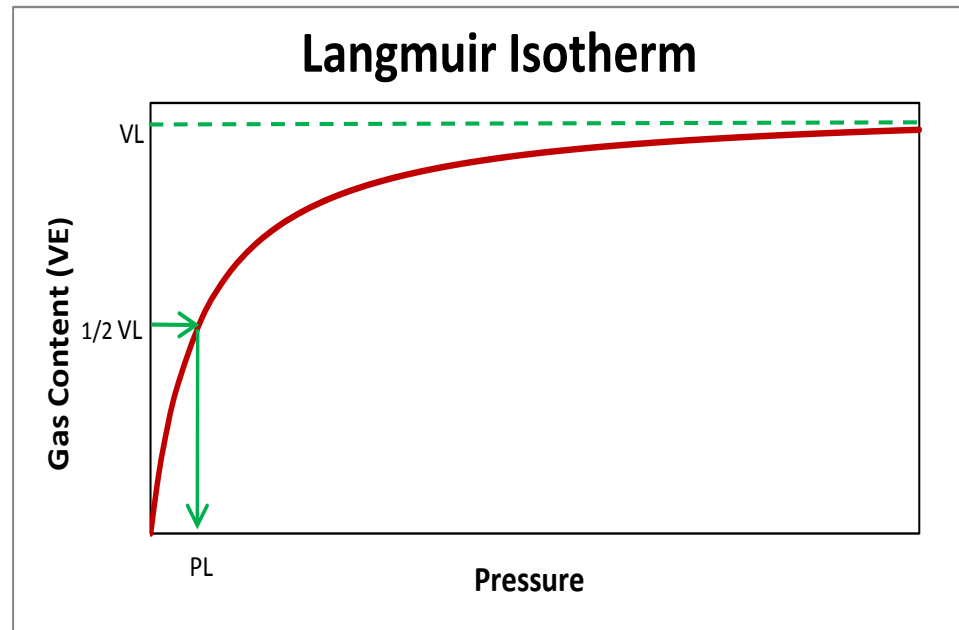Figure 3. Gas transport mechanisms for coalbed methane.

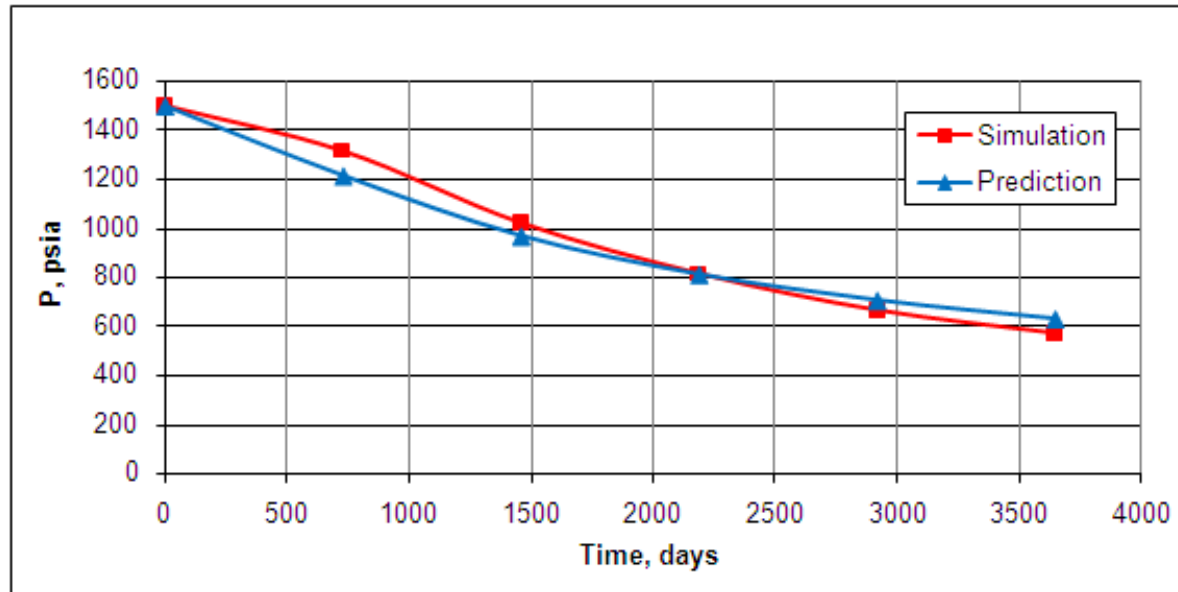Figure 4. Schematic of Langmuir Sorption Isotherm.
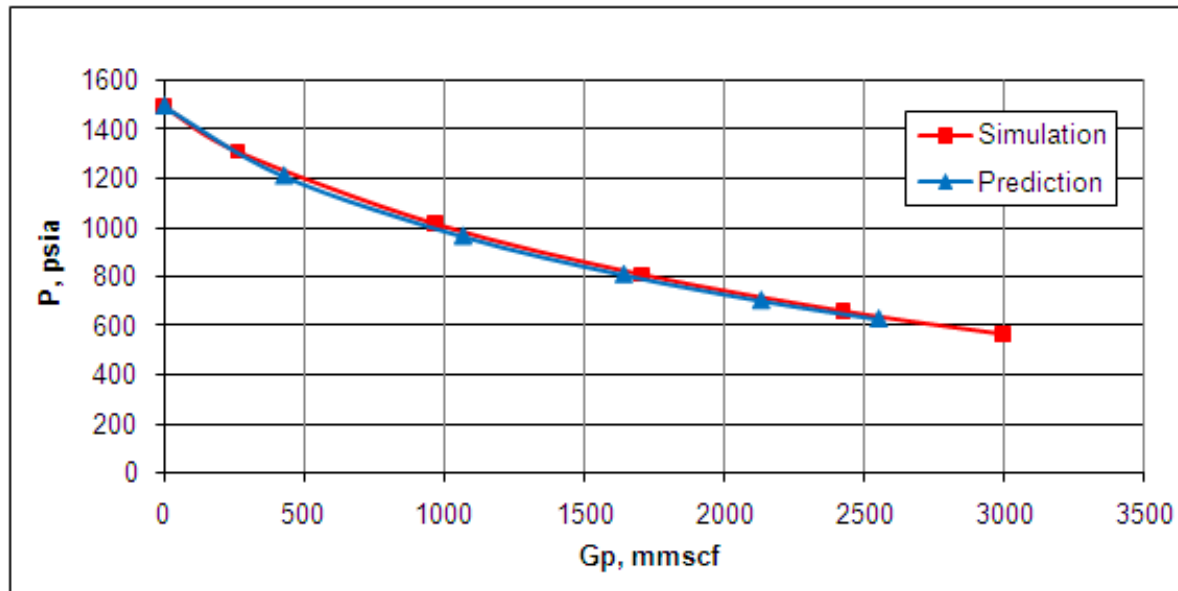
Figure 5. Reservoir pressure versus time.

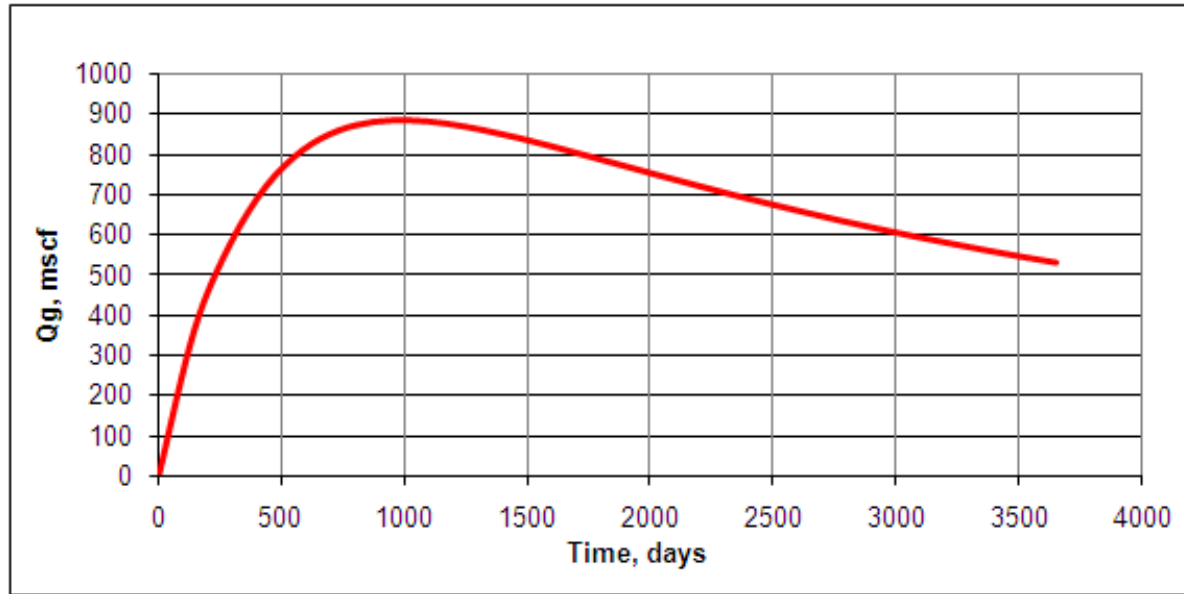Figure 6. Reservoir pressure versus cumulative gas production.
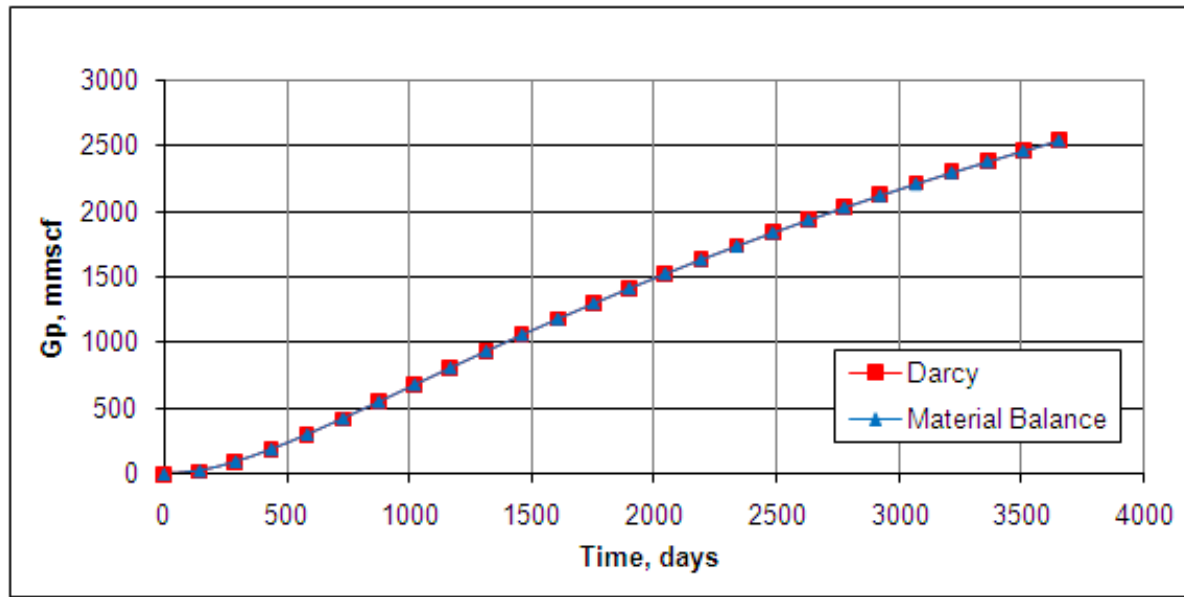
Figure 7. Gas production rate versus time.

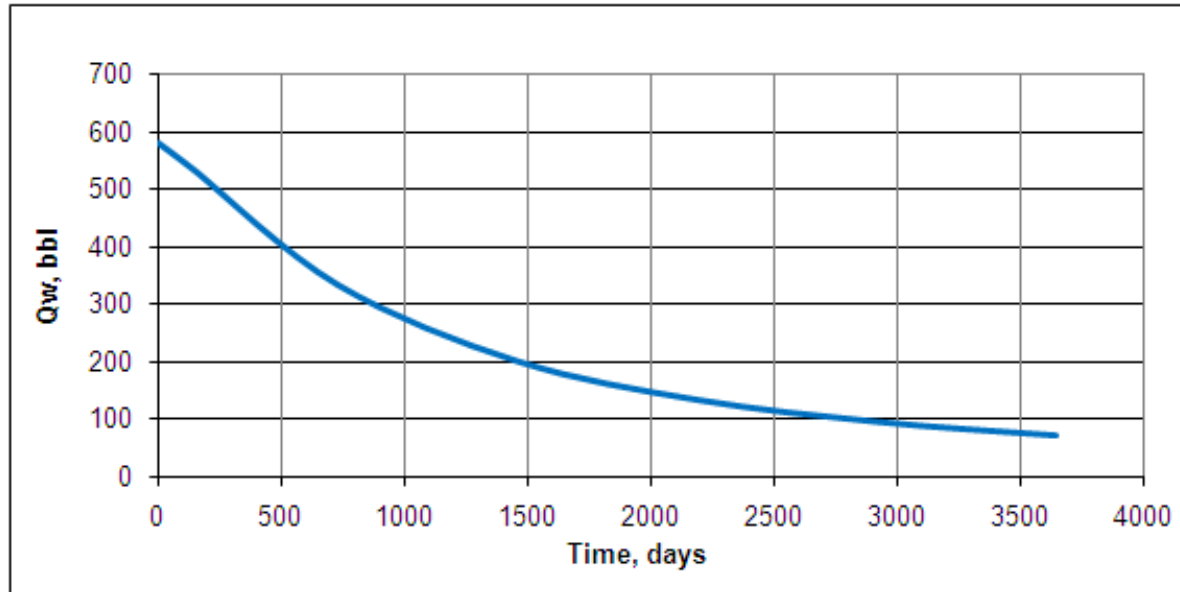Figure 8. Cumulative gas production versus time.

Figure 9. Water production rate versus time.

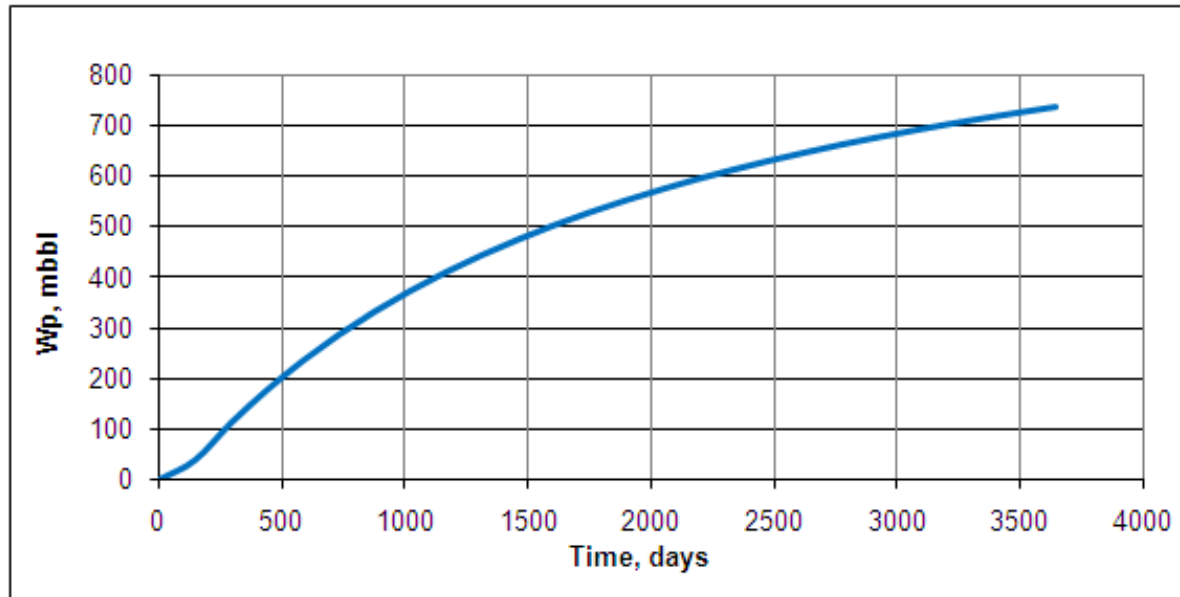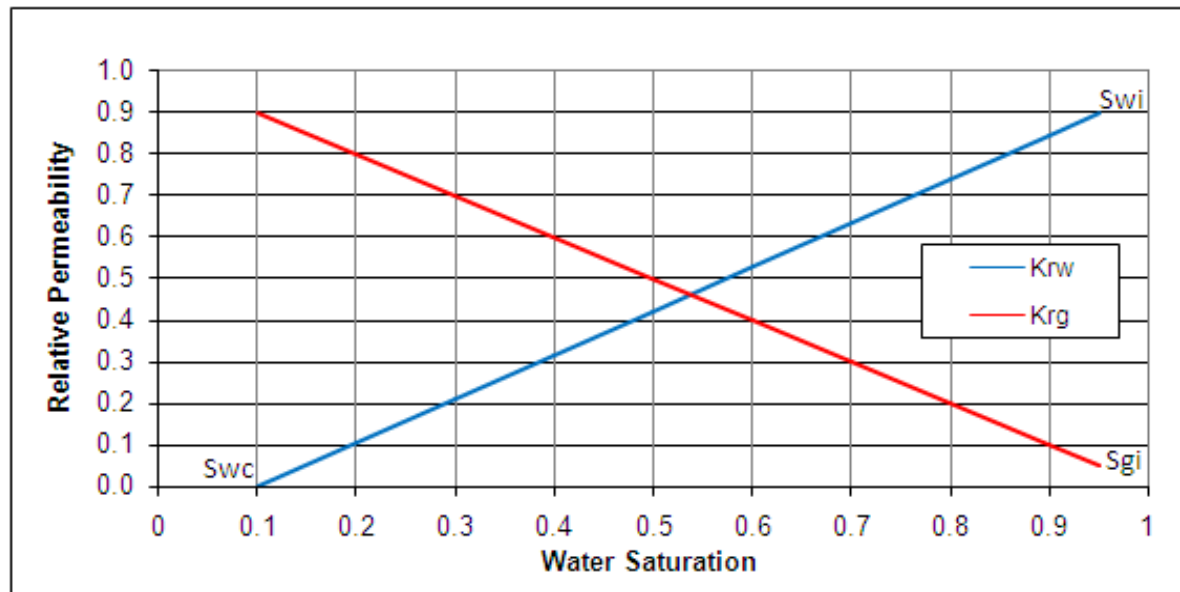Figure 10. Cumulative water production versus time.

Figure 11. Relative permeability versus water saturation.

Parameters and Units	Values
Seam Thickness, h	50 ft
Drainage Area, A	320 acres
Well Radius, r_e	0.5 ft
Skin, S	0
Coal Density, ρ_B	1.7 gr/cm^3
Temperature, T	105 °F
Porosity, Φ	1%
Permeability, k	10 md
Water Exponent, N_w	1
Gas Exponent, N_g	1
Water Encroachment, W_e	0
Initial Reservoir Pressure, P_i	1500 psia
Bottom Hole Pressure, P_{wf}	14.7 psia
Langmuir Pressure Constant, P_L	362.32 psia
Initial Gas Content, V_0	345.1 scf/ton
Langmuir Volume Constant, V_L	428.5 scf/ton
Initial Water Saturation, S_{wi}	0.95
Connate Water Saturation, S_{wc}	0.1
Initial Gas Saturation, S_{gi}	0.05
Critical Gas Saturation, S_{gc}	0
Initial Water Volume Factor, B_{wi}	1 resbbl/stb
Initial Gas Volume Factor, B_{gi}	0.0093 ft^3/scf
Water Compressibility, c_w	3 x 10^{-6} psi^{-1}
Rock Compressibility, c_f	6 x 10^{-6} psi^{-1}

Table 1. List of input parameters for calculation.