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A Coalbed Methane Reservoir Simulator Designed and Developed for the Independent Producers

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Abstract

There are many coalbed methane reservoir simulators in the market. The two most important characteristics of these models that, for all practical purposes, put them out of the reach of most of the independent producers are their price and complexity of use. In order to effectively use these commercial simulators, the average CBM producer must have at least one dedicated engineer, preferably with a graduate degree, on the staff that is willing and capable of performing effective modeling and simulation. It seems that the commercial simulation packages have been designed for majors, large independents and consultants. This leaves the majority of independent producers that are in the business of CBM production in a class by themselves. The model that is presented in this paper targets this class of CBM producers.

A new CBM reservoir simulator has been developed at West Virginia University in order to address this specific need of our industry, specifically in the northeast of the United States where new interests in coalbed methane have been growing steadily. The WVU CBM model uses a previously developed legacy code by King and Ertekin at PSU as its point of departure. The nearly twenty year old King & Ertekin's formulation which has been verified and proven to be robust, forms the foundation of WVU CBM model. The WVU CBM model is PC-Windows based and has a user friendly and graphical interface. The PSU model used a commercial solver that if was used in this model it would have made it prohibitively expensive for the independent producers. A new solver was developed and is used in this model. The new WVU CBM model is a single-well radial model with a graphical input interface that includes default values for the Pittsburgh coal for all parameters in case some of the values are unavailable. It generates graphical outputs in form of gas and water production rate vs. time, cumulative production vs. time, pressure, saturation and gas desorption distribution throughout the reservoir. It allows for production scheduling for detail history matching process. It lets the user to plan hundreds of runs in the form of a batch file that can be run over night.

The model has a unique feature that allows user to provide input parameters in the form of probability distribution functions with minimum, maximum, and, if they choose, most likely values instead of crisp numbers. The output in such cases will be probability distribution functions rather than crisp numbers. The WVU CBM model will be available to the industry through our web sites.

King & Ertekin Model

King and Ertekin built a two-phase coalbed methane model in 1985. The code was written in FORTRAN. The model incorporated radial coordinates for non-fractured reservoirs and elliptical coordinates for fractured reservoirs. A brief summary of formulation used in the model follows.

To develop water and gas equations, two assumptions were made: 1) the choice of an equation of state and 2) a transport law.

The general form of the continuity equation for phase 'p' in a porous medium is: [1]

$$-\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho_p\vec{v}_p\right)+\frac{Q_p}{V_{bma}}=\frac{\partial}{\partial t}\left(\phi_{ma}\rho_p S_p\right) \qquad (1)$$

Where:

King & Ertiken assumed that the free gas in the macropore system behave like a real gas. So they used the real gas law as the equation of state.

$$\rho_g = \frac{(MW)P_g}{ZRT} \tag{2}$$

This equation is substituted into equation (1). Also, the source/sink term is separated into an external term (fissure transfer) and an internal term (matrix/fissure transfer). Since the coalbed methane reservoirs have a low pressure with relatively low absolute permeabilities, the gas transport equation should allow for the gas slippage phenomenon. The correction of the slippage is made by applying the Klinkenberg equation to obtain an effective permeability to gas. [2]

The macropore gas transport equation in radial coordinate system is: [3]

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{rk_\infty k_{rg}P_g}{\mu_g Z}\frac{\partial P_g}{\partial r} + D\frac{\partial}{\partial r}\left(\frac{S_g P_g}{Z}\right)\right) + \frac{P_{sc}T}{T_{sc}}q_{sc} = \frac{\partial}{\partial t}\left(\frac{\phi S_g P_g}{Z}\right) \tag{3}$$

The macropore water transport is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{rk_\infty k_{rw}}{B_w\mu_w}\frac{\partial}{\partial r}\left(P_w - \frac{1}{144}\frac{g}{g_c}\rho_w h\right)\right) + q_w = \frac{1}{5.615}\frac{\partial}{\partial t}\left(\frac{\phi S_w}{B_w}\right) \tag{4}$$

Four dependent variables (Pw, Pg, Sw, and Sg) exist in the equations above. Two more equations are required in order to solve the system of equations. These auxiliary equations are:

$$P_w = P_g - P_c \tag{5}$$

and

$$S_w = 1 - S_g \tag{6}$$

Substitution for Pw and Sw in the water equation results in a system of two equations with two unknowns.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{rk_\infty k_{rg}P_g}{\mu_g Z}\frac{\partial P_g}{\partial r} + D\frac{\partial}{\partial r}\left(\frac{S_g P_g}{Z}\right)\right) + \frac{P_{sc}T}{T_{sc}}q_{sc} = \frac{\partial}{\partial t}\left(\frac{\phi S_g P_g}{Z}\right) \tag{7}$$

and

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{rk_\infty k_{rw}}{B_w\mu_w}\frac{\partial}{\partial r}\left(\left(P_g - P_c\right) - \frac{1}{144}\frac{g}{g_c}\rho_w h\right)\right) + q_w = \frac{1}{5.615}\frac{\partial}{\partial t}\left(\frac{\phi\left(1 - S_g\right)}{B_w}\right) \tag{8}$$

Close external boundary condition was used for the simulator.

Enhancement to King & Ertekin's Model

The purpose of this study was to build on the original King and Ertekin Model and develop a new model that is accessable and easy to use for the independent producers. During this development several new features were added to the model in order to increase its usability for the independent producers. Following sections describe these new features.

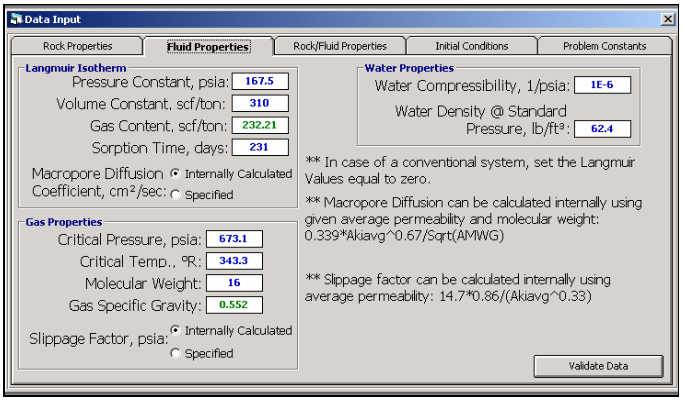
Internal Solver

The King and Ertekin model used an external commercial solver (the solver may not have been commercial when the original code was developed, but since then a new company has emerged that owns the rights to the solver and requested royalty if we wanted to use their solver in our model) in order to solve the Jacobian matrix. This made that model dependent on commercial software and quite expensive for the user. WVU CBM model incorporates a solver that was developed in-house in order to solve the Jacobian matrix. This solver was coded and verified with commercial solvers such as MATLAB. Gaussian Elimination[4] was used to build the solver.

Graphical User Interface

The WVU CBM model has a graphical user interface that makes it easier for the user to work with the model. Some of the advantages of the graphical user interface are:

- Input data: data required by the model can be entered using Data Input window, which shows the input data in a categorized fashion. It has been tried to keep this part as simple as possible in order to avoid confusing the users. Figure 1 is a screen shot of the Data Input module. This module includes a set of default input values that can assist the user in completing the task quickly.



Data Input

Langmuir Isotherm

Pressure Constant, psia: 167.5
Volume Constant, scf/ton: 310
Gas Content, scf/ton: 232.21
Sorption Time, days: 231
Macropore Diffusion Coefficient, cm²/sec: ● Internally Calculated ○ Specified

Water Properties

Water Compressibility, 1/psia: 1E-6
Water Density @ Standard Pressure, lb/ft³: 62.4

** In case of a conventional system, set the Langmuir Values equal to zero.

** Macropore Diffusion can be calculated internally using given average permeability and molecular weight: 0.339*Akiavg^0.67/Sqrt(AMWG)

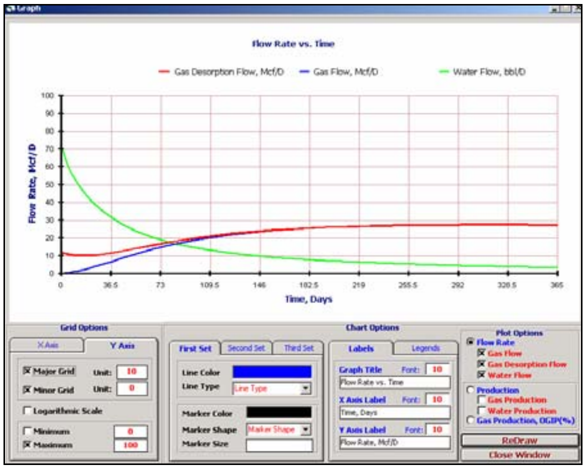
Gas Properties

Critical Pressure, psia: 673.1
Critical Temp., ºR: 343.3
Molecular Weight: 16
Gas Specific Gravity: 0.552
Slippage Factor, psia: ● Internally Calculated ○ Specified

** Slippage factor can be calculated internally using average permeability: 14.7*0.86/(Akiavg^0.33)

Figure 1. Data Input window from WVU CBM Simulator

- Output of Results: after running the simulation and getting the results, user can view the results in a graphical manner. Results can be plotted or shown on a spreadsheet. Gas and water flow rates and cumulative production can be viewed on a chart. User can also change the format of the axes from linear to logarithmic or otherwise. All the attributes of the graphs in this software package can be controlled by the user in order to generate presentation or publication quality graphs.

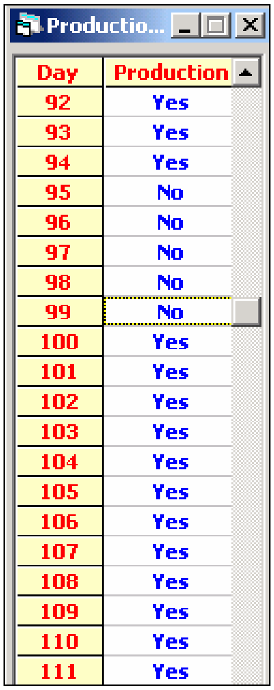


☒ Major Grid Unit: 10
☒ Minor Grid Unit: 0
☐ Logarithmic Scale
☐ Minimum 0
☒ Maximum 100
Line Color
Line Type: Line Type
Marker Color
Marker Shape: Marker Shape
Marker Size
Graph Title Font: 10 — Flow Rate vs. Time
X Axis Label Font: 10 — Time, Days
Y Axis Label Font: 10 — Flow Rate, Mcf/D
● Flow Rate
☒ Gas Flow
☒ Gas Desorption Flow
☒ Water Flow
○ Production
☐ Gas Production
☐ Water Production
○ Gas Production, OGIP(%)

Figure 2. Results of simulation runs can be plotted and viewed graphically.

- Production Scheduling: user can have more control on the reservoir production and simulation. Production scheduling is a feature that gives the user the power to control the well production by building a production schedule as shown in Figure 3. This feature can be used effectively during history matching procedures.

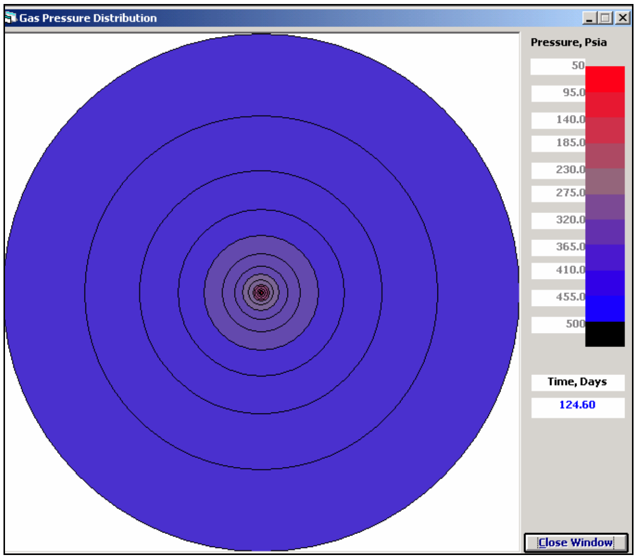
  User also has control on the simulation process. The simulation can be terminated anytime. Gas and water pressure distribution and gas and water saturation distribution can be viewed throughout the simulation. So the user has a graphical view of the pressure or saturation distribution of the reservoir as shown in Figure 4.



Productio...

Day	Production
92	Yes
93	Yes
94	Yes
95	No
96	No
97	No
98	No
99	No
100	Yes
101	Yes
102	Yes
103	Yes
104	Yes
105	Yes
106	Yes
107	Yes
108	Yes
109	Yes
110	Yes
111	Yes

Figure 3. Production schedule window. The well doesn't produce between days 95-100.



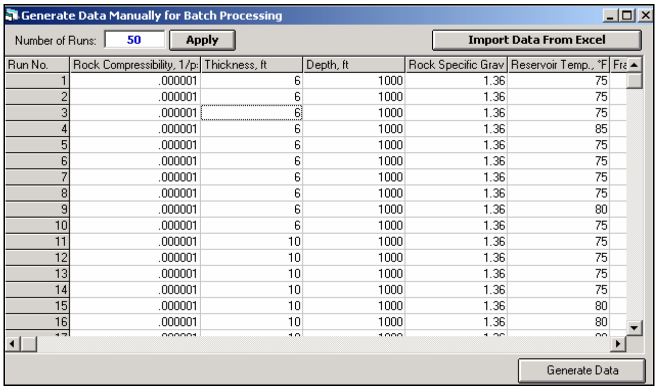
Time, Days: 124.60

Figure 4. Gas pressure distribution throughout the reservoir.

- Default Values: all the variables needed by the simulator already have a default value based on the data collected for Pittsburgh coal. In case the user doesn't have a value for some of the variables, the simulator can still be used. Some of these vlues were shown in

Figure 1.

- Batch Processing: another new feature of this model is the batch processing ability. By providing the input data for a number of runs, the simulations can be performed overnight for all of the datasets and the results are stored.



Number of Runs: 50

Run No.	Rock Compressibility, 1/p:	Thickness, ft	Depth, ft	Rock Specific Grav	Reservoir Temp., °F	Fra
1	.000001	6	1000	1.36	75	
2	.000001	6	1000	1.36	75	
3	.000001	6	1000	1.36	75	
4	.000001	6	1000	1.36	85	
5	.000001	6	1000	1.36	75	
6	.000001	6	1000	1.36	75	
7	.000001	6	1000	1.36	75	
8	.000001	6	1000	1.36	75	
9	.000001	6	1000	1.36	80	
10	.000001	6	1000	1.36	75	
11	.000001	10	1000	1.36	75	
12	.000001	10	1000	1.36	75	
13	.000001	10	1000	1.36	75	
14	.000001	10	1000	1.36	75	
15	.000001	10	1000	1.36	80	
16	.000001	10	1000	1.36	80	

Figure 5. Grid shows the data entered for batch processing

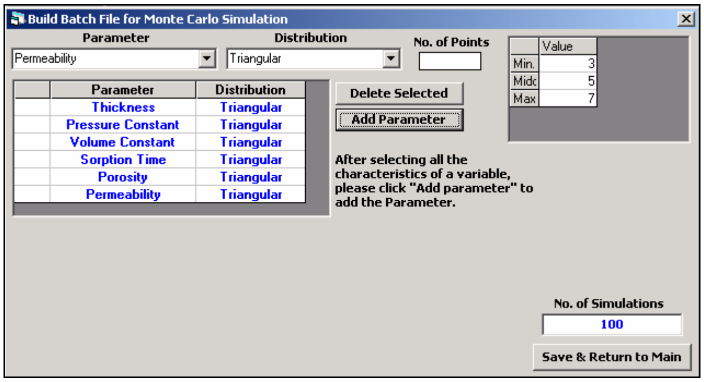
User can either enter the data using the provided table in the model or import an Excel file. The Excel file needs to have a certain format to be useable by the program. Therefore, the program can make a template for the user. After the simulation is completed for all the models, the results can be viewed using the chart module in the model.

Unique Feature of WVU CBM Simulator

The model has a unique feature that allows the user to provide input parameters in the form of probability distribution functions with minimum, maximum, and, if they choose, most likely values instead of crisp numbers. The output in such cases will be probability distribution functions rather than crisp numbers. This unique feature of the WVU CBM model accommodates the uncertainty associated with most of the CBM reservoirs. The model uses a Monte Carlo Simulation procedure in order to perform its calculations. Uncertain input values are presented to the model in the form of probability distribution functions and production indicators are calculated and presented in the form of probability distribution functions. Figure 6 shows the interface of the model that accommodated this feature of the WVU CBM model.

Results & Discussion

King and Ertiken model is a well established model that has been tested and verified numerous times. In order to verify the accuracy of the WVU CBM model its output was compared with published King and Ertiken model [2]. The results are shown in this section. Table 1 shows the input data that was used during this test and comparison process.



Parameter: Permeability
Distribution: Triangular
No. of Points:

	Value
Min.	3
Midc	5
Max	7

Parameter	Distribution
Thickness	Triangular
Pressure Constant	Triangular
Volume Constant	Triangular
Sorption Time	Triangular
Porosity	Triangular
Permeability	Triangular

After selecting all the characteristics of a variable, please click "Add parameter" to add the Parameter.

No. of Simulations: 100

Figure 6. The batch module of the WVU CBM model.

Table 1. The input data used in the comparison study.[2]

Data Used In SWRM	
Variable	**Numerical Value**
Well Radius, r_w	0.5 ft
External Radius (closed), r_e	500 ft
Seam Thickness, h	6 ft
Initial Seam Pressure, Piag	500 psia
Seam Temperature, T	70 °F
Macropore permeability, k_∞	3 md
Macropore porosity, ϕ_a	1 %
Macropore Diffusion Constant, Da	0.177 cm²/sec
Time Constant	231 days
Langmuir Volume constant,V_L	480 scf/ton
Langmuir pressure constant, p_L	167.5 psia

The Comparison of the results from the WVU CBM model with King & Ertekin's results shows complete agreement. These results are shown in Figures 7 through 9.

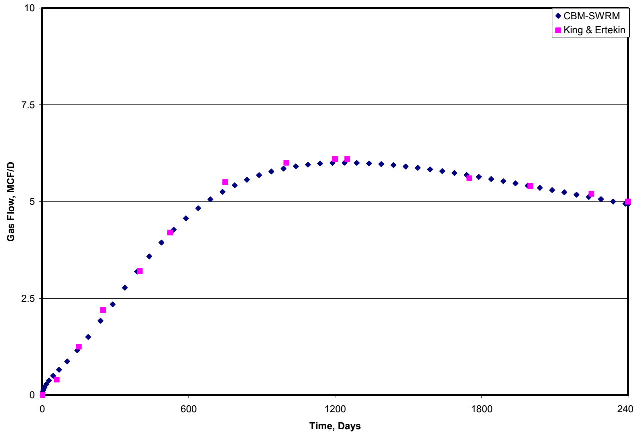


Figure 7. Gas flow rate results from WVU CBM model and King & Ertekin's model.

Figure 7 shows the gas flow rate from a CBM reservoir. The typical negative decline of gas production at early time is quite visible. This increase is due to desorption of gas from the matrix into the fracture system. Most of the gas in coal is stored inside the coal matrix in form of adsorbed gas. The adsorbed gas will start desorbing when the fracture pressure is low enough that allows for desorption of the gas from the matrix.

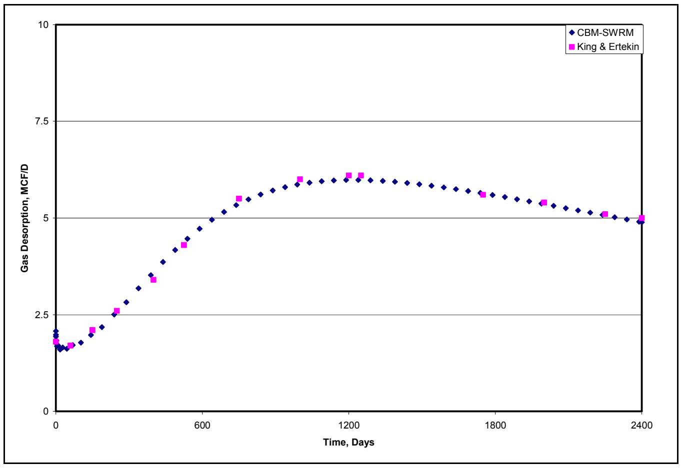


Figure 8. Gas desorption results from WVU CBM model and King & Ertekin's model.

Figure 8 shows the results of WVU CBM model and King & Ertekin's model for gas desorption from the same CBM reservoir as Figure 7. Gas desorption starts at a high rate following by a quick drop. Gas desorption will increase again and it will reach a maximum and then starts declining. The high rate of gas desorption in the early time is because of the low pressure around the wellbore that causes gas desorption from the matrix. With producing gas around the wellbore, there will not be enough gas for desorption. Therefore, the gas desorption will decrease, but it will start increasing with decreasing pressure in areas farther from the wellbore. This increase will continue until pressure drop is reached to the outer boundary. At this point, the reservoir reaches its maximum gas production. After this point, gas desorption starts declining and the reservoir acts like a conventional reservoir.

Figure 9 shows the water production resulted from WVU CBM model and King & Ertekin's model. Water production starts at a high rate followed by a declining behavior. Most of coalbed methane reservoirs are fully saturated with water at the beginning and in order the produce the gas they must go Cthrough a dewatering process.

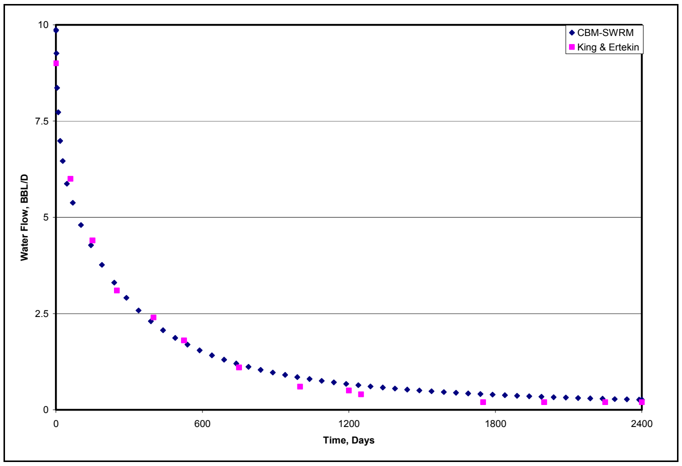


Figure 9. Water flow rate results from WVU CBM model and King & Ertekin's model.

Monte Carlo Simulation:

As mentioned earlier, the unique feature of this simulator is the ability of using reservoir properties in the form of Probability Distributions Functions (PDF) instead of using crisp numbers. Therefore, the results of the simulation will be in the form of probability distribution functions instead of crisp numbers. To show the performance of the simulator for batch processing, some reservoir properties were chosen to have a probability distribution instead of a crisp number. Upon defining the PDFs and following a Monte Carlo Simulation technique the model was run 200 times and some pre-defined production indicators were generated for each run. These properties are shown in Figure 6. Results of the batch processing will be stored in a new folder. In addition to the results for each run (which includes gas and water rates) another file is generated that stores the production indicators for the simulation models. These production indicators are the peak gas flow rate, time to peak gas flow rate, and cumulative gas production by the time that reservoir reaches the peak gas rate. These production indicators can be viewed as probability distribution functions as shown in Figures 10 through 12.

Reservoir properties will be entered for batch processing & Monte Carlo simulation and problem constants are read from the main project data file. After the simulation is done, a file with name "Batch_PIs.txt" will be generated. The properties selected for Monte Carlo Simulation are shown in Table 2.

Table 2. Reservoir properties entered as probability distribution functions

Variable	Minimum	Most Likely	Maximum
Thickness, ft	3	5	7
Pressure Constant, psia	100	200	300
Vol. Constant, scf/ton	400	500	600
Sorption Time, days	100	200	300
Porosity, %	1	3	5
Permeability, md	3	5	7

The probability distribution function for production indicators can be viewed using the chart module of the model.

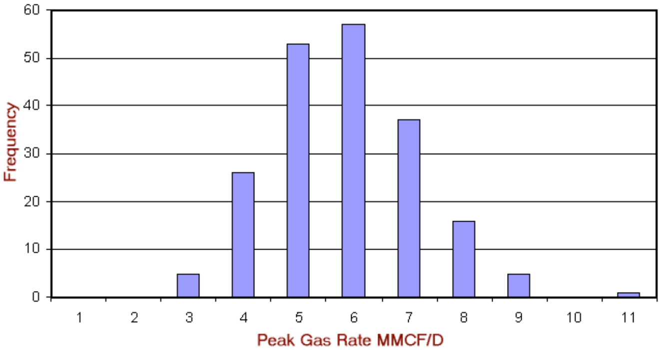


Figure 10. Peak gas flow rate for 200 CBM models.

Figure 10 shows the probability distribution function for the peak gas flow rate for the problem defined by the uncertain values shown in Table 2. This graph provides some important information to the user. Under uncertain situation where a crisp number cannot possibly be identified for a particular reservoir property (which seems to be the rule in the CBM reservoirs rather than exception) the model output is just as uncertain providing the user with a range of potential answers. Furthermore, the probability distribution function shows that the most probable gas peak rate under such circumstances is approximately 6 MMCF/D.

Figure 11 shows the probability distribution for the time it takes this well to reach the peak rate. Above figure demonstrates that the most probable time for this well to reach the peak rate is about 1500 days. This simply means that this well most probably will not reach its peak rate until 4 years into production.

Figure 12 shows the probability distribution function for cumulative gas production at the peak time. Most of the models have a cumulative gas production of approximately 50 MMCF by the time they reach their peak gas flow rate. There are a small number of models that have a high cumulative production at the peak time but mostely have less than 70 MMCF.

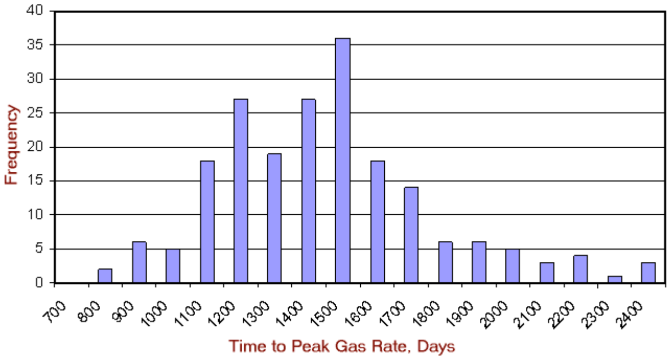


Figure 11. Time to reach the peak gas flow rate for 200 models.

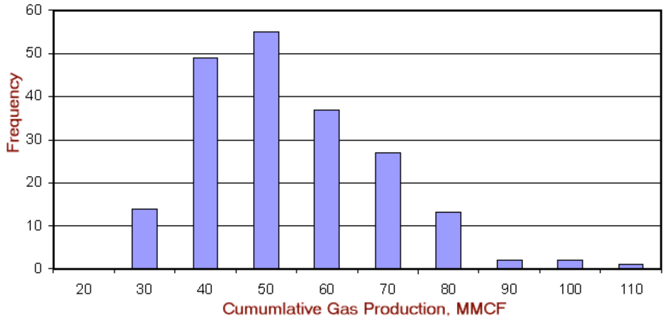


Figure 12. Cumulative gas production at peak time for 200 models.

Conclusion:

A new CBM reservoir simulator was developed and verified at West Virginia University based on King & Ertekin's model developed in 1985. The ease of use and low price of this simulator makes it attractive for the industry especially for independent producers. Graphical interface, production scheduling, batch processing and Monte Carlo simulation technique are some of the features of this model that distinguishes this model from its original version. Unlike the King & Ertekin's model that was using an external software to solve the Jacobian matrix (which makes it expensive for the users), WVU CBM has an internal solver that has been tested and verified with other commercial solvers such as MATLAB.

Nomenclature:

ρ_p : p phase density

$\vec{v}_p$: volumetric flux of phase p

Q_p : Mass flow rate of phase p

V_{bma} : macropore bulk volume

ϕ_{ma} : Macropore porosity

S_p : p phase saturation

k_∞ : Absolute permeability

k_{rg} : relative permeability to gas

k_{rw} : relative permeability to water

MW : Molecular Weight
Pg : Reservoir Pressure
Z : Gas supper compressibility factor
R : Universal gas constant
T : Reservoir temperature

Reference:

1- Gregory R. King: "Numerical Simulation of the Simultaneous Flow of Methane and Water Trough Dual Porosity Coal Seams During the Degasification Process," PhD Thesis, Pennsylvania State University, 1985
2- Gregory R. King, Turgay Ertekin, and Fred C. Schwerer: "Numerical Simulation of the Transient Behavior of Coal-Seam Degasification Wells," SPE paper 12258, 1986
3- David J. Remner, Turgay Ertekin, Wonmo Sung, Gregory R. King: "A Parametric Study of the Effects of Coal Seam Properties on Gas Drainage Efficiency," SPE paper 13366, 1986
4- Turgay Ertekin, Jamal H. Abou-Kassem, Gregory R. King: "Basic Applied Reservoir Simulation," SPE Textbook Series Vol. 7, 2001