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Prediction of coalbed methane reservoir performance with type curves

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**PREDICTION OF COALBED METHANE RESERVOIR PERFORMANCE WITH TYPE
CURVES**

Amol Bhaskar Bhavsar

**Thesis Submitted to the
College of Engineering and Mineral Resources
At West Virginia University
In partial fulfillment of the requirements
For the degree of**

**Master of Science
In
Petroleum and Natural Gas Engineering**

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Water Production Prediction.**

ABSTRACT

PREDICTION OF COALBED METHANE RESERVOIR PERFORMANCE WITH TYPE CURVES

Amol Bhaskar Bhavsar

Coalbed methane is an unconventional gas resource that consists of methane production from the coal seams. CBM reservoirs are dual-porosity systems that are characterized by a complex interaction of coal matrix and cleat system that are coupled through desorption process. In order to effectively evaluate CBM resources, it necessary to utilize reservoir models that incorporate the unique flow and storage characteristics of CBM reservoirs. These models are often complicated to use, expensive, and time consuming. The typical gas producers in the Appalachian Basin suffer from the lack of scientific, user-friendly tools that can assist them in development of CBM resources. Therefore, it is necessary to develop tools that make it possible for typical (small to medium size) producers to seriously consider this important resource.

This study presents a set of production type curves for CBM reservoirs that would help the producers to predict the production from their CBM wells. As a consequence, the producers would be able to make better, more informed decisions regarding the CBM resources in the region. A reservoir model that incorporates the unique flow and storage characteristics of CBM reservoirs was employed in this study to develop the type curves. The type curves provide a reliable tool to predict the production performance of CBM reservoirs during dewatering phase. The application and issues concerning the production performance of CBM reservoirs are also discussed

In order to achieve the objective of this study, four steps were performed:

(a) Development of a base model for Coalbed methane production in Northern Appalachian, (b) development and verification of the dimensionless groups for water production type curves (c) Generation of the CBM water production type curve, and (d) validation of the CBM water production type curve.

A modified correlation for peak gas rate estimation was also proposed as an alternative to forecast gas production along with a correlation for computing initial (maximum) water production rate.

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CHAPTER 1 INTRODUCTION

Methane (natural gas), while perhaps most closely related in our minds with petroleum, also occurs in association with coal, the Nation's most abundant fossil fuel resource.

Conservative estimates suggests that Twenty-four percent of the energy consumed in the U.S. in 2000 was natural gas.¹ Use of natural gas nationwide increased 22 percent during the last decade,² and this trend is projected to continue. Natural gas is the fastest growing energy source for electricity generation. Resources of Coalbed Methane (CBM) are reported as between 3,500 and 9,500 Tcf contained in subsurface coal seams around the world, with anywhere from 1,000 to 3,000 Tcf in North America alone. The exploitation of CBM has been steadily progressing in the United States because of the proximity of resources and improved finding and transporting mechanisms. Annual production from 11 coal basins now exceeds 1.5 Tcf, 10% of the annual gas production.³

Figure 1.1: CBM Production from US Basin

Major coal resources exist in 69 countries; 35 of these countries have some CBM activity, and 17 have active CBM wells. CBM is gaining importance in Australia, China, Indonesia, and Europe.⁴

- Alaska has the greatest potential coal resources—more than Canada and the Continental United States combined.
- China's resource potential is greater than the United States and Australia combined.
- Canada's and Australia's vast resources are under development.

Figure 1.2: Global Coal Distribution

In the Appalachian Basin⁵, operators suffer from the lack of scientific tools that could help them in the development of CBM reservoirs. Analyzing the production performance in CBM reservoirs is challenging, especially at the early stage of the recovery. CBM⁶ reservoirs are characterized by dual porosity systems which consist of a macropore and a micropore structure. The macropore system, also known as cleat, constitutes the natural fractures in all coal seams.

The micropore system, or matrix, is the primary porosity system and contains the majority of the gas in adsorbed state. Because of its large internal surface area, coal stores 6 to 7 times more gas than the equivalent rock volume of a conventional gas reservoir.

In most of the CBM reservoirs, water settles in the cleat system. In order to produce the gas, the reservoir must first be dewatered. This process consists of producing water to lower the pressure so that the methane can be desorbed from the coal. The water production can take a few days or several months. The water production declines throughout the life of the CBM reservoir and reaches a minimum after the peak gas rate has been reached. After the peak gas rate has been reached, the behavior of CBM reservoir becomes similar to conventional reservoirs.

Most of the small producers in the Appalachian Basin cannot afford personnel or meet economical requirements involved in the use of the numerical simulator to evaluate CBM reservoirs. Decline curve analysis cannot be applied to CBM reservoirs to predict the recovery factor or well performance due to its complex characteristics and behavior. The best tool to predict production performance of CBM reservoirs is a numerical simulator because it takes into account all the variables and mechanisms that control CBM production. Simulators are expensive and time consuming and they require highly trained personnel. Therefore, it is necessary to provide simple tools to help small producers to develop the CBM resources in the basins.

CBM reservoirs are characterized by the non-conventional fluid production. The amount of water produced from CBM wells is comparatively high than conventional reservoirs. The water in coal beds contributes to pressure in the reservoir that keeps methane gas adsorbed to the surface of the coal. This water must be removed by pumping in order to lower the pressure in the reservoir and stimulate desorption of methane from the coal. Water coproduced with methane is not reinjected into the producing formation to enhance recovery as it is in many oil fields. Instead, it must be disposed of or used for beneficial purpose.⁷

The disposal of this large amount of water is complicated by the fact that much of the water is of low quality. The main problem with the disposal wells is their cost, ranging from \$400,000 to

1,200,000 depending on depth and stimulation type. This leads to a total disposal cost for underground injection cost averaging approximately \$1.00 per barrel, with a wide range from about \$.50 to \$1.50 per barrel. The high capital cost is a deterrent for small independent operators. In addition, there is a risk that disposal wells will not have the capacity to accept all the water an operator wishes to dispose of.⁸

The majority of the water contains high levels of dissolved sediments and a high sodium absorption ratio. Such water has limited suitability for domestic or animal consumption, and its high saline and sodium content makes it unsuitable for agriculture irrigation.

All the above mentioned factors and complications involved with produced water for CBM, it is of utmost important to know the amount of water that will be produced in the life of the well, especially at the very early stage in the life of the well. Hence it was taken upon to develop type curves for water production in a typical CBM well to predict the behavior of the well to produce water along with the amount of water produced with time.⁸

CHAPTER 2 LITERATURE REVIEW

Natural gas is one of the cleanest, safest sources of energy used for many of the regular needs and common activities that are performed today. Natural gas is a combustible mixture of hydrocarbon gases. For many decades, natural gas has been produced from conventional gas resources. Coalbed methane, tight sands, and shales are considered as

“Unconventional” sources of natural gas. Unconventional reservoirs are more difficult, and more expensive to produce because the technology has not been fully developed.

However, the increasing demand for energy has resulted in development of unconventional sources of natural gas⁹. Through 2008; demand for unconventional natural gas will reach 12.78 trillion cubic feet, rising at an Average Annual Growth Rate (AAGR) of 10.7% from 7.68 trillion cubic feet in 2003². More specifically, advancements in reservoir characterization, simulation, and production have been the keys for economic development of the CBM.⁹

2.1 Coalbed Methane

Coalbed methane is considered an unconventional gas resource. The gas produced from coal beds is almost completely methane, usually containing small amounts of other hydrocarbons, hydrogen, carbon monoxide, carbon dioxide, and nitrogen.¹¹

The most significant difference between CBM and conventional gas reservoirs is the gas storage mechanism. In conventional gas reservoirs, gas is stored as free gas in pore spaces of the rock in the reservoir. In CBM reservoirs however, the gas can be stored as a free gas in the cleats (natural fractures) or it can be stored at almost liquid densities on the surface matrix of the coal. Because of its large internal surface area, coal stores 6 to 7 times more gas than that of an the equivalent rock volume of a conventional gas reservoir¹¹. Methane produced from typical coalbed methane well has a heating value of about 1000±25 British Thermal Units (Btus) per standard cubic foot. One million Btus (the energy equivalent of 1000 cubic feet of methane or one MCF) approximate the energy consumed by a person in the U.S. in about 1.2 days. A million Btu's of fossil fuel can generate about 100 kilowatt-hours of electricity at an electric utility³

In the last two decades the coalbed methane industry has grown significantly. It took time and research to understand the behavior of the coalbed methane reservoirs. By 1992, there was no significant coalbed methane production in the US. In 1993, about 1604 producing wells were reported with an estimated annual production of 6 Bcf.

Through 1994, the coalbed methane production increased considerably to 858 Bcf from more than 6000 wells. In 2000, according to the Gas Research Institute (GRI), CBM production increased more than 35 percent. During that year, CBM production raised 1352 Bcf from 13,936 wells drilled. Currently, 8 percent of the total US natural gas production comes from coalbed methane industry and 12 percent of estimated total gas recoverable in US ¹². CBM production is expected to increase since new coal basins are being explored and developed, and production technologies continue to advance.

2.1.1 Distribution

Currently, natural gas from coal beds accounts for approximately 8 % of total annual U.S. dry gas production. The major coalbed methane resources are located in 13 large basins: Western Washington, Wind River, Greater Green River, Uinta, Piceance, San Juan, Raton Mesa, Arkoma, Warrior, Central Appalachian, Northern Appalachian, Illinois and Power River (Figure 2.1). The two most productive basins are Black Warrior in Alabama and San Juan in northern New Mexico. The estimated gas reserves are 20 Tcf and 88 Tcf respectively. The CBM gas is now estimated to account for some 17% of total recoverable gas reserves in the country.

Source: Advanced Resources, International

Figure 2.1: U.S Major Basins and the Estimated Coalbed Methane Resources
(Adopted from GRI, 1996)

Coalbed Methane development and production began in the Appalachian basin nearly 60 years ago. The best known coalbed methane project in the Northern Appalachian was discovered in 1905. As early as 1932, it began producing from the Pittsburgh Seam in Big Run Field in Wetzel County, West Virginia. Since that time, some studies were undertaken in order to assess and improve understanding of the geologic characterization and production mechanisms. Today, the Northern Appalachian represents one of the most important and attractive sources for natural gas. It contains an estimated 61 TCF of gas in place¹².

The most important geologic characteristics that has been found is referred to the location, coal group ages, and geological and reservoir properties. The Northern Appalachian Basin encompasses parts of Pennsylvania, West Virginia, Ohio, Kentucky and Maryland.

Figure 2.2: Northern Appalachian Province (adopted from USGS)

More specifically in West Virginia, the number of wells drilled has increased significantly. McDowell and Wyoming Counties have increased the production during the last decade, according to the records compiled by the West Virginia Geologic and Economic Survey. In McDowell County the first well was completed in 1995 with a total annual production of 78,289Mcf. In Wyoming County the activity is very similar. The operations started during 1994 with an annual production of 18,973Mcf.

2.1.2 Gas Storage in Coal Reservoirs

Methane is held in the coals in one of the following three stages: (a) as adsorbed molecules on the organic surfaces, (b) as free gas within the pores or fractures and (c) dissolved in solution within the coalbed¹³. However, maximum amount of methane in coal exists as a monomolecular layer adsorbed on the internal surfaces of the coal surface and there is just a small amount of free gas in the cleat system of a coal seam. Since coals have a very large internal surface area and the methane's molecules are tightly packed in the monomolecular layer, the total quantity of gas can be adsorbed. Adsorption process is directly influenced by pressure, temperature and coal rank.

2.1.3 Gas Transport Mechanisms in Coal Reservoirs

In order to produce gas from coal reservoirs, the flow of methane through coal seams experiences three-stage process which are: (a) gas flows from the natural fractures, (b) gas desorbs from the cleat surfaces and, (c) gas diffuses through the coal matrix to the cleats ¹².

The majority amount of methane stored in coal is basically by adsorption in the coal matrix. However, as pressure in the coal is lowered, the main fluid that flows in the cleat system is water and small quantities of free gas and some dissolved gas in the water. After the coal is dewatering, the methane is released (desorption stages-process) from the surface of the coal. Desorption is the process by which methane molecules detach from the micropore surfaces of the coal matrix and enter the cleat system where they exists as free gas ¹² (Figure 2.3)

After desorbing from the coal surface, the methane flow in the matrix starts moving to the cleat system by different gas concentration gradients in both zones governed by the process of diffusion (a process in which flow occurs via random molecular motion from an area of high concentration to an area of lower concentration ¹²(diffusion stage-process) described by the equation derived from Fick's Law.

Figure 2.3: Gas Transport Mechanisms in Coal Reservoirs¹⁴

2.1.4 Production Behavior of CBM Reservoirs

Production behavior of CBM reservoirs completely diverges from the conventional gas reservoirs. In conventional gas reservoirs, the production rate declines with time while in coalbed methane reservoirs production inclines until it reaches a peak and then it declines. Initially water occupies the fracture (cleat) system in the reservoir, and flows to the well. The reservoir must be dewatered first in order to produce gas from the coal. The production can be divided in three phases that are shown in Figure 2.4.

During phase I the reservoir is considered water saturated in the natural cleat system, which requires water to be produced to depressurize the coal and produce gas. Ideally, water production will relieve the hydraulic pressure on the coal in order to start the production by desorption of the gas from the coal. This process is known as Dewatering. The number of days of this dewatering process and the amount of produced water can vary widely. The gas is produced at very low rates during this phase. This phase is characterized by a constant water production rate and a declining flowing bottomhole pressure. At the end of this first phase, the well has reached its minimum flowing bottomhole pressure.

In phase II, the gas production rate increase until it reaches the maximum value, which is called peak gas rate. During this phase, the water production rate begins to decline as the coal is dewatered. The dewatering period for coals can take from weeks to years. During phase II some changes in the reservoir flow conditions occur. The water relative permeability decreases, while gas relative permeability increases. The outer boundary effects become significant¹².

Limit between phase II and phase III is established when the peak gas rate is reached. During phase III, the conditions are stable. A typical decline trend defines the behavior of the gas production. During this phase, water production is low or insignificant. The water and gas relative permeability's do not change extensively. The pseudo-steady state exists for the rest of producing life.

Figure 2.4: Typical Coalbed Methane Production Profiles for Gas and Water Rates (Adopted from GRI) ¹²

There are some physical reservoir properties that control the length of the dewatering process and the magnitude of the producing rates of gas and water. Those physical reservoir properties are:

- The spacing and connection of the fracture system, which are defined by the permeability.
- The amount of gas stored in the coal, which is defined by the absorbed gas content.
- The interactions between gas and water, which are defined by the relative permeability.
- The tendency of the coal organic matrix to release stored gas, which is defined by the diffusion coefficient and the desorption isotherm ¹².

2.1.5. Coalbed Methane Production Type Curves

CBM reservoirs behavior were studied in depth and a set of type curves¹⁵ were developed as an efficient and economical tool to analyze and forecast the performance of CBM reservoirs by Garcia Anangela in 2004 as a part of her MS thesis (Figure 2.5) . During the study the Northern Appalachian Basin CBM reservoir characteristics were used as input to a reservoir simulator to predict the production behavior. A two dimensional, two-phase Cartesian CBM model was built. The Cartesian model grid size was 13 x 13 blocks, each block with a length of 100 ft for a total of 40 acres of spacing area. The reservoir simulation software used was GEM, developed by Computer Modeling group (CMG). The software features a range of dual porosity and dual permeability techniques for modeling fractured formations. It also includes options for gas sorption in the matrix, gas diffusion through the matrix, and two phase flow through the fracture system.

Figure 2.5: CBM Gas Production Type Curve (Adopted from Garcia, 2004)¹⁵

In order to develop a unique type curve, two dimensionless groups were introduced. The dimensionless gas rate and dimensionless time were presented as follows:

$$t_D = \frac{t q_{peak}}{G_i} \quad (1)$$

$$q_D = \frac{q}{q_{peak}} \quad (2)$$

These definitions are based on those originally used for gas production decline type curve (Aminian et al 1990). In the equations, $(q_{peak})_g$ represents the peak gas rate, G_i is the initial gas in place. G_i is calculated from the equation (3)

$$G_i = 43560 A h \rho G c \quad (3)$$

, where Gc is the gas content of coal in SCF/ton, and ρ is the coal bulk density.

Garcia evaluated the dimensionless groups by varying eight different parameters. Garcia concluded that fracture pressure, sorption time, cleat porosity, and critical desorption pressure don't have any significant impact on CBM production whereas, flowing bottom-hole pressure appeared to be one of the properties with highest impact on CBM performance particularly in the latter parts of production history. A set of type curves for several flowing bottom-hole pressure were developed. Figure 2.6 shows the effect of bottom-hole pressure on the CBM gas production type curve.

The impact of stimulation was considered in a previous study by Manual Sanchez¹⁶ and he concluded that skin factor does not influence the shape of the CBM gas type curve, however when the well is stimulated the skin factor alters the gas peak value that is used in development of dimensionless groups.

Arrey in 2004¹⁷ for her master's thesis evaluated the impact of Langmuir isotherm constants, Langmuir Pressure (P_L) and Langmuir Volume (V_L) on the gas production type curves. Arrey concluded that changes in V_L values do not significantly impact the shape of the gas production type curves however; changes in P_L values have a significant impact on the gas production type curves. Figure 2.7 shows the effect of P_L changes on the CBM gas production type curves.

Figure 2.6: Effect of Bottom-hole Pressure on the CBM Gas Production Type Curve¹⁵

Figure 2.7: Effect of P_L Changes on the CBM Gas Production Type Curves.

2.1.6 GEM

Reservoir models are excellent tool to study the impact of reservoir properties on production and organize data for a particular prospect ⁹.

Computer modeling group (CMG) is one engineering computer program capable of simulating oil and gas reservoirs. The computer program is used to characterize reservoirs where the importance of the fluids composition and their interactions are essential to understand and maximize the recovery process. CMG is based on six different applications shown in Figure 2.8.

They are (a) BUILDER, Pre-processing

Applications, (b) IMEX, Black Oil Simulator, (c) STARS, Steam Thermal Advanced Processes, (d) GEM, Generalized Equation-of-State Model Compositional Reservoir Simulator, (e) WINPROP, Phase Behavior Analysis, and (f) RESULTS, Post-processing Applications. During the study there were only three applications used for Coalbed Methane. These applications used were BUILDER, GEM, and RESULTS.

BUILDER is an application used to prepare reservoir simulation models. It makes the design and provides a Windows interface which organizes data in an easy way.

BUILDER presents two modules depending on the objectives which are: (a) GridBuilder and (b) ModelBuilder.

The **GridBuilder** is used to create simulation grids and rock property data for GEM and other applications. It allows the user to easily create, edit, and positioning grids with respect to geological maps, interpolating geological structure, and rock properties. The grid is displayed in 2D and 3D views to allow the user to check the grid performance.

The **ModelBuilder** helps the user prepare input data files for GEM and other applications. It displays Relative Permeability and PVT curves in graphic from which it can be adjusted directly. In addition, the ModelBuilder has an automatic error checking and data validation.

GEM is an essential engineering tool for modeling any type of reservoir with complicated phase behavior interaction where the importance of the fluid composition and their interactions are

essential to the understanding of the recovery process. GEM is a highly optimized simulator that has been proven in numerous field production situations around the world.

RESULTS is GEM's set of post processing applications, designed for visualizing and reporting simulator output. With **RESULTS**, users are able to analyze the output, prepare 2D and 3D plots, generate several informative graphs, and prepare tables of required information to be included in a report. Visualization capabilities offered by **RESULTS** make simulation's output easier to understand and provide new insight to analyze recovery process. **RESULTS** is composed of two modules: (a) Results Graph and (b) Results Report.

Results Graph, produce high quality 3D graphs of well production and injection data from the simulator runs. Data can be displayed for individual wells or well layers, for group of wells or reservoir sectors. It is a great tool to understand the recovery process of the reservoir and to interpret the production of data of a specific well. **Results Report** produces tabular reports of any type of data generated during the reservoir simulation including well data and reservoir grid properties. It can also be used to compare data from different runs and generate economic analysis for discussion

For my research study, I used, ModelBuilder and GridBuilder to build the 2D Cartesian model. GEM was used to run the simulated model. The outputs of the runs were analyzed in **RESULTS** and 2D plots were developed in Results Graph.

Figure 2.8: CMG's Coal Bed Methane Simulator Model

CHAPTER 3 OBJECTIVE AND METHODOLOGY

The goal of this research was to develop a simple and reliable tool to predict the performance of CBM well in order to evaluate the economical feasibility and to maximize potential recovery. More specifically, the objectives of this study were to develop a correlation for the peak gas production rate ($q_{peak}{}_g$) and initial (maximum) water rate q_{iw} .

In order to achieve the objective, a methodology consisting of the following steps was used:

1. Development of unique set of water production type curves for CBM reservoir by introducing new dimensionless groups.
2. To evaluate the impact of various reservoir properties on the water production in a typical coal bed methane reservoir.
3. To develop a correlation for the peak production rate for gas and
4. To develop a correlation for initial maximum water rate.
5. To verify the accuracy of the type curve and the correlation.

Each of these steps will be discussed below.

3.1 Development of unique set of water production type curves for CBM reservoir by introducing a new set of dimensionless groups

3.1.1 Reservoir Base Model Development

A two-dimensional Cartesian (CBM base) model was developed for an under-saturated CBM reservoir with a well located at the center of the drainage area.

Figure 3.1: Cartesian CBM Base Model

The reservoir simulation software used in this study was GEM developed by the Computer Modeling Group (CMG) ¹⁸. GEM is CMGs advanced general equation of state, compositional, dual porosity reservoir simulator. Capable of modeling both coal and shale gas reservoirs. GEM includes options for gas sorption in the matrix, gas diffusion through the matrix, two phase flow through the natural fracture system.

The reservoir parameters used to develop the base model are summarized in Table 1. The simulation runs were made by varying several of the key parameters over the ranges provided in Table 1. The results were compiled into a database containing large number water production histories.

Table 1: Values and Ranges of Parameters Used in the CBM Base Model

PARAMETERS	BASE MODEL VALUE	RANGE
Model	Dual Porosity	-
Shape Factor Formulation	Gilman-Kazemi	-
Matrix- Fracture Transfer Model	Pseudo-capillary Pressure with Correction	-
Model Geometry	2D-Cartesian	-
Grid Size	100ft x 100ft	-
Reservoir Area	40 acres	40,80,160 acres
Thickness	10ft	5 - 15ft
Matrix Porosity	0.5%	-
Fracture Porosity	2%	1 - 5 %
Matrix Water Saturation	0.5%	-
Initial Fracture Water Saturation	100%	70 - 100 %
Matrix Permeability	0.01 md	
Fracture Permeability	10 md	5 - 20 md
Fracture Spacing	0.2 ft	0.1 - 1 ft
Initial Pressure	600 psia	300 - 600 psia
Temperature	113°F	-
Langmuir Pressure (P_L)	675.6 psia	100 - 1000
Langmuir Volume (V_L)	475 SCF/ton	100 - 1000
Coal Sorption Time	50 days	300 - 600 psia
Critical Desorption Pressure	300 psia	40-600 psia
Rock Density	89.63 lb/ft ³	-
Skin Factor	0	-4 to +4
Bottom Hole Pressure (constant)	50 psia	50,75,100 psia

3.1.2: Development of Dimensionless Groups for Water Production Type Curve.

In order to develop type curves, two set of dimensionless rate and time were defined for water. The water dimensionless rate and time were defined similarly as:

$$q_{wD} = \frac{q_w}{q_{iw}} \quad (1)$$

$$t_{wD} = \frac{t * q_{iw}}{W_i} \quad (2)$$

In the above equations, q_{iw} represents the initial (maximum) water rate and W_i is the initial water in the cleat system which can be calculated by the following equation:

$$W_i = 43560 Ah \phi_f S_{wi} \quad (3)$$

Where, A is the reservoir area in acres, h is the thickness of coal in ft, ϕ is the cleat system porosity and S_{wi} is the initial cleat system water saturation.

Calculating q_{iw} will be investigated in the later half of the study.

The base water production histories were converted to dimensionless rate and time using above definitions and the results were plotted both Cartesian and log-log scale.

3.2: Evaluating the Impact of Various Reservoir Properties on the Water Production.

In order to establish the uniqueness of the type curves, the impact of the key reservoir parameters was investigated. The production histories that were generated by varying several parameters over the ranges provided in Table 1 were converted to dimensionless and were compared to the base case results illustrated in Figure below.

Figure 3.2: Water Production Type Curve

The following 7 parameters caused insignificant (less than 5%) deviation from the original type curves:

1. Fracture (Cleat) Permeability
2. Fracture (Cleat) Porosity
3. Fracture (Cleat) Initial Pressure
4. Coal Thickness
5. Drainage Area
6. Sorption Time
7. Initial Gas Content of the Coal

The impact of flowing bottomhole pressure on water type curve, in the range considered (50 to 100 psia), was negligible.

Generally, relative permeability data are difficult to obtain since they cannot be accurately measured in laboratory. History matching is the only practical method to obtain realistic relative permeability values. Therefore, relative permeability is often assumed particularly when production has not been initiated or when production history is limited.

It should be noted that Langmuir constant that defines desorption isotherm characteristics were also varied. Langmuir Volume (V_L) was varied from 200 to 1000 and was found not to have significant impact on the water type curves.

Figure 3.3: Impact of V_L on Water Type Curves @ Constant P_L

On similar lines, Langmuir Pressure was varied from 100 to 1000 psia and was also found not to have significant impact on the water type curves.

Figure 3.4: Impact of P_L on Water type Curves @ Constant V_L

The impact of stimulation was considered for developing the type curves for water. The Skin Factor (S) which is a dimensionless number that was introduced to represent changes near the wellbore permeability caused by formation damage was varied. A series of runs with simulator were conducted by changing the skin factor in the range -4 to +4.

For Skin Factor change, 2 sets of type curves were obtained. First set of type curves for Stimulated coal (i.e. negative skin) and second set of type curves for Damaged coal (i.e. positive skin). Refer Figures 3.5 and 3.6

Figure 3.5: Type Curves for Skin Factor Change (Cartesian)

Figure 3.6: Type Curves for Skin Factor Change (Log-log)

Critical desorption pressure (M_p) is the pressure at which the gas defuses to the well bore. Dynamic changes takes place in reservoir flow conditions once the reservoir reaches the Critical desorption pressure. Hence it became necessary to study the effect of M_p on the type curves. To account for effect of M_p , on the shape of the type curves it was varied in the range of 40 to 600 psia.

The study revealed that the water type curves are significantly impacted by the degree of under-saturation as illustrated in the figure 3.7. The degree of under-saturation is reflected by the ratio of initial reservoir pressure, P_i , to critical desorption pressure M_p

Figure 3.7: Impact of Under-Saturation on the Water Production Type Curves.

3.3 Developing a Generalized Correlation for Dimensionless peak Gas flow Rate

In the section above we have seen that type curves can be used as a simple and quick tool to predict gas and water rates for evaluation of a prospect. To do this, it is necessary to estimate $(q_{peak})_g$ and G_i for gas production predictions from available formation properties. Equations a can be used for calculation of G_i for gas. However, estimation of $(q_{peak})_g$ is complicated due to two-phase flow conditions. To overcome this problem, the variation of $(q_{peak})_g$ with various parameters was investigated to develop a correlation.

Aminian et al in 2004 came up with dimensionless group for $(q_{peak})_g$. The following equation defines the dimensionless peak gas rate.

$$(q_{peak})_{gD} = \frac{(q_{peak})_g * 1422 T \mu_c z_c}{kh * (p_c^2 - p_{wf}^2)} \left[\ln \left(\frac{r_e}{r_w} \right) - \frac{3}{4} + S \right] \quad (4)$$

In Equation 4, p_c is the critical gas desorption pressure which is the pressure at which gas desorption from coal matrix into cleat system begins. Gas viscosity and z-factor in Equation 4 should be estimated at p_c . The use of this dimensionless group minimized the impact of permeability, thickness, and drainage area.

In the studies carried out in the past it was observed that an individual approach was taken to develop a correlation between dimensionless peak production rate for gas and various parameters.

The results from the study conducted by Manual¹⁶ showed that changing the skin factor from -5 to 0 does not alter the shape of the type curve for none stimulated wells, but it has an impact on $(q_{peak})_g$ for gas. In addition, he proposed that, porosity and critical desorption pressure also have an impact on $(q_{peak})_g$ for gas and developed a correlation between those parameters and skin factor to estimate $(q_{peak})_g$. Figures 3.8 shows the correlation between skin factor and critical

desorption pressure (300, 400, 500 and 600 psia) at a porosity of 2%. Figure 3.8 shows the correlation between porosity (1%, 1.5%, 2%, and 3%) for critical desorption pressure of 600psia.

Figure 3.8: Impact of Critical Desorption Pressure, Porosity and Skin Factor on Dimensionless Peak Gas Rate

Efundum¹⁷ in her research studied the impact of Langmuir isotherm constants Langmuir pressure (P_L) and Langmuir volume (V_L) and concluded that V_L changes does not have significant impact on the shape of the type curve while changes in P_L has a major impact on the type curves. Further, she added that V_L has a significant impact on $(q_{peak})_{gD}$ for gas and it increases with increasing V_L . A correlation between $(q_{peak})_{gD}$ and V_L at a constant P_L was developed. She also managed to developed a correlation between $(q_{peak})_{gD}$ and P_L at a constant V_L as indicated in Figure 3.9 and Figure 3.10

Figure 3.9: Plot of Correlation between $(q_{peak})_{gD}$ and P_L @ Constant V_L of 475scf/ton

Figure 3.10: Plot of Correlation between $(q_{peak})_{gD}$ and V_L @ Constant P_L of 150psia

From these studies it was concluded that there is a linear relation between $(q_{peak})_{gD}$ and various reservoir parameters such as porosity (ϕ), skin factor (S), critical desorption (Mp) pressure, , Langmuir Pressure (P_L) and Langmuir Volume (V_L).

All the results from the previous studies on $(q_{peak})_{gD}$ (Manual¹⁶ and Efundem¹⁷) were organized and a study was conducted to investigate the effect of various reservoir parameters on the peak dimensionless production rate for gas $(q_{peak})_{gD}$. It was observed that permeability and bottom hole pressure didn't not have significant impact on the peak production rate for gas, whereas, porosity, skin factor, critical desorption pressure, Langmuir pressure and Langmuir volume had the most significant impact. A linear multiple regression analysis was performed to develop the correlation. To achieve the best fit, reservoir parameters with significant impact on $(q_{peak})_{gD}$ were correlated in varies combinations. In the first combination skin factor, critical desorption pressure, porosity and Langmuir volume were correlated with a R^2 value of 0.854.

	Skin	Mp	Porosity	VL	Constant
Slope	3.9057	-0.021	-21.65	0.0836	114.91
	0.512515	0.007511	0.740385	0.005734	4.435051
R ²	0.8545	12.14823			

Similar combinations were formulated and correlations were obtained as shown below.

	Porosity	VL	Constant
Slope	-19.5	0.0895	91.5584467
	0.83387	0.006738	3.509871143
R ²	0.7951	14.35631	

	Skin	Mp	Constant
Slope	1.7795	0.018	82.365
	1.309356	0.019279	7.343858
R ²	0.0082	31.58293	

In the last combination skin factor, critical desorption pressure, porosity, Langmuir volume and Langmuir pressure were correlated with a R² value of 0.856 as the best fit to the data.

Corr-IV	Skin	Mp	Porosity	VL	PL	Constant
Slope	4.1977	-0.024	-21.47	0.0836	0.0119	108.77574
	0.537326	0.007626	0.744123	0.00571	0.006866	5.654372621
R ²	0.8563	12.09727	#N/A	#N/A	#N/A	#N/A

Following is the correlation for peak production rate for gas.

$$(q_{peak})_g D = 4.1977*S - 0.024*Mp - 21.47*\phi + 0.0836*V_L + 0.0119*P_L + 108.78 \quad (5)$$

By comparing equation 7 and the above correlation we can calculate the peak gas rate for any case in a coal bed methane reservoir.

3.4 Determination of Initial (maximum) Water Rate q_{iw}

For the type curves to be used as a simple and reliable tool to predict the performance of CBM wells, it is necessary to estimate the initial (maximum) water rate q_{iw} and W_i the initial water in the cleat system. Equation (3) can be use for the calculation of W_i

However, it was a query as to how to estimate q_{iw} for water. We started digging the books and tried to see if the theories for a conventional reservoir can be applied for CBM reservoir. We concluded that CBM reservoir is in a single-phase unsteady state during the initial period in the life of the reservoir since the coal cleat system is assumed to be fully saturated with water initially. Hence, we applied the single-phase liquid unsteady state solution to find the initial water rate q_{iw}

Following is the equation that we used to calculate q_{iw} .

$$q_{iw} = \frac{kh(P_i - P_{wf})}{162.6\beta\mu[\log(\frac{kt}{\phi\mu c_i r_w^2}) - 3.23 + 0.87S]} \quad (6)$$

In the above equation, k and h are the fracture (cleat) permeability in md and coal thickness in ft respectively. P_i is the initial reservoir pressure in psia with P_{wf} being the flowing bottomhole pressure in psia. μ is the water viscosity which is 1 along with β . The time t is in hrs. ϕ is the fracture (cleat) porosity. r_w is the wellbore radius in ft. The total compressibility, C_i is a characteristic property of the coal. S is the skin factor

The simulation runs were made by varying several of the key parameters over the ranges provided in the table. The simulation output was run in Results 2D to get a plot of instantaneous water rate (bbl/day) against time and the maximum water rate q_{iw} was tabulated. The q_{iw} values from the simulator results were compared with the actual calculated values and were found to be 80to 85% accurate.

The only factor that significantly affected the calculated q_{iw} value was Skin Factor (S).

We decided to develop a correlation and identify the relation between Skin Factor and q_{iw} for water. A ratio of calculated q_{iw} to actual q_{iw} (from simulator) called as dimensionless q_{iw} $[(q_{iw})_D]$ was obtained and compared with Skin factor.

Following is the graph identifying the correlation between dimensionless q_{iw} to skin factor

Figure 3.11: Correlations for $(q_{iw})_D$ with Skin Factor

Thus from the above plot, we conclude that,

$$(q_{iw})_D = -0.0162(S)^2 + 0.1027(S) + 1.0042 \quad (7)$$

Thus from the above equation we can calculate the As indicated above, by using the single-phase liquid unsteady state solution (equation 6) we can calculate q_{iw} for a known skin factor and comparing it with the above equation for ratio, we can predict the q_{iw} by model.

CHAPTER 4 RESULTS AND DISCUSSION

The water production type curves developed in this study can serve as a quick and simple tool for production data analysis and production prediction analysis. In order to efficiently utilize the type curves for evaluation of a prospect it was necessary to estimate peak gas production rate which led us to development of a correlation for $(q_{peak})_{gD}$ involving Langmuir Volume (V_L), Langmuir Pressure (P_L), Porosity (ϕ), Critical Desorption Pressure (M_p), Skin Factor (S). Studying the factors affecting initial (maximum) water rate q_{iw} and developing a correlation incorporating the results of the effect caused by these parameters (Skin Factor, S) was also accomplished.

To evaluate the reliability of the water production type curves and outlined correlations for $(q_{peak})_{gD}$ and $(q_{iw})_D$ a set of reservoir characteristics as summarized in table (2) were considered.

The parameters in table (2) were used as inputs to CBM reservoir simulator to generate the production histories. These production histories were used for the purpose of type curve matching along with prediction of gas peak rate and initial (maximum) water rate. A unique match was obtained with the type curves as shown in Figure 4.1

Figure 4.1: Comparison of the Predicted Water Production

As it can be seen from the figures the predicted production rates from the type curves closely match those from simulator.

$(q_{peak})_g D$ value was calculated for the case study by using the correlation developed as in equation (5) and then the value of $(q_{peak})_g$ was computed by using the calculated value of $(q_{peak})_g D$ in equation (4). The results are indicated in Table 2. The comparison of the calculated and estimated value of $(q_{peak})_g$ for the case study, as illustrated by errors in Table 2 leads to conclusion that the correlation developed for $(q_{peak})_g D$ can provide reliable results.

Further, the value of Initial (maximum) Water Rate $Q_{i_w}(\text{max})$ was calculated by using equation (6). This value was corrected for skin factor by using the correlation developed as in equation (7). The calculated values of q_{i_w} using Equation (7) and that from the simulator based on the input values to the model are also provided in Table 2. The comparison of the calculated and estimated value of q_{i_w} for the Case Study, as illustrated by errors in Table 2, leads to the conclusion that the correlation developed for $(q_{i_w})_D$ can provide reliable results.

The estimated q_{i_w} from equations (6, 7) can be used to convert the dimensionless rate and time from the type curve to actual values using equations (1) and (2).

Table 2: Input data and Prediction Results for the Case Study

Property	
Area (Ac)	40
Thickness (ft)	12
Cleat Porosity (%)	3.5
Face Cleat Permeability (md)	14
Initial Gas Content (SCF/ton)	162.1
Initial Pressure (psia)	850
Sorption Time (days)	120
Skin Factor	-1
Flowing Bottomhole Pressure (psia)	50
Initial Water Rate, q_{iw} (BBL/D) from Simulator	237.6
Initial Water Rate, q_{iw} (BBL/D) by calculation (equation 6)	249.3
Initial Water Rate, q_{iw} (BBL/D) corrected (equation 7)	220.4
Peak Gas Rate (q_{peak}) _g (MCF/D) from Simulator	22.875
Peak Gas Rate (q_{peak}) _g (MCF/D) from correlation (equation 4)	22.412
Error in q_{iw} (%)	1.0
Error in Peak Gas Rate (q_{peak}) _g (%)	1.0

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached in the study:

1. A new set of gas and water production type curves for coalbed methane reservoirs were introduced.
2. A set of new dimensionless groups were introduced that lead to development of a unique set of type curves.
3. The effects of 9 formation and operational parameters on the type curves were studied.
4. Flowing pressure, Critical Desorption Pressure and Skin Factor were found to influence the type curves.
5. Type curves can be also used to predict production performance of CBM prospects based on the available or estimated formation properties.
6. A correlation for peak gas rate was developed and tested that will allow the use of the type curve as simple tool for production predictions.
7. A correlation for Initial (maximum) Water Rate was developed and tested that will allow the use of type curve as reliable tool for production data analysis.

It is important to mention that this study was done taking into account the typical isotherm and relative permeability data from the Northern Appalachian basin. Since relative permeability data is an important parameter for the gas production from CBM wells, it is recommended to study this variable in detail in developing correlations for both gas and water prediction. Last but not least, a project for development of scientific, user friendly computer tool integrating the correlations and the type curves for both gas and water production should be promoted to provide independent gas producers and operators with a convenient, handy, manageable, and controllable economically efficient means to evaluate the production performance of CBM prospects, in short a thingamabob for CBM.

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