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Development of water production type curves for horizontal wells in coalbed methane reservoirs

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**DEVELOPMENT OF WATER PRODUCTION TYPE CURVES FOR
HORIZONTAL WELLS IN COALBED METHANE RESERVOIRS**

Praveen Kumar Burka Narayana

**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**

Approved by

**Dr. Khashayar Aminian, Chair
Professor. Samuel Ameri
Dr. Ilkin Bilgesu**

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Natural Gas Water Production and Prediction**

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ABSTRACT

DEVELOPMENT OF WATER PRODUCTION TYPE CURVES FOR HORIZONTAL WELLS IN COALBED METHANE RESERVOIRS

PRAVEEN KUMAR BURKA NARAYANA

Coalbed methane is an unconventional gas resource that consists of methane production from the coal seams. The key parameters for the evaluation of coalbed methane (CBM) prospects are the gas resources, reserves and deliverability. Coalbed methane reservoirs are dual-porosity media where the vast majority of the gas is stored in the low permeability coal matrix (primary porosity) by sorption. The flow to production wells, however, occurs through the coal's natural fracture system (secondary porosity), which stores relatively small amounts of gas, because coal matrix practically has no permeability.

For the gas to be released from the coal, its partial pressure must be reduced, and this is done by removing water from the coalbed fractures. During the dewatering process, the gas desorbs from the coal matrix, thereby gas rate increases and the water saturation decreases. The water production declines rapidly until the gas rate attains a peak value and water saturation approaches the irreducible water saturation i.e., reaches connate water saturation. Once the peak gas rate is attained, CBM reservoirs act like a conventional reservoir. Reservoir engineers usually use production decline curves in order to predict well performance.

Since the behavior of CBM reservoirs are complex when compared to conventional reservoir, the use of a numeric simulator is the best way to predict the CBM production behavior. Operating a simulator requires in-depth knowledge and detailed data to get accurate results. They are also expensive to small producers. Considering these factors, using a simulator might not be the best

option. Hence, in order to develop a simple and yet a reliable tool to forecast the production in a CBM reservoir with good accuracy, it was taken upon to develop type curves for both gas and water production.

The objective of this study was to develop a simple and reliable tool was developed to help with water production predictions in horizontal coalbed methane wells that are located in the (Northern Appalachian Basin). Upon development of a unique set of type curves, independent producers will be able to evaluate the future production of water from the wells. A correlation for the peak water rate was also developed in order to forecast production if no production data is available.

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I dedicate my work to my Parents, My Brother and Sisters, who represent the best inspiration in my life. Mom and Dad, your unique ways of encouragement always filled my heart with joy and enthusiasm to progress ahead in life and I feel fortunate to be the special one. Thanks for all your noble upbringing and self-sacrificing love, guidance, support and encouragement that helped me with years to survive this harsh phase of life.

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NOMENCLATURE

A = Area.

C_t = Compressibility Factor, 1/psia.

h = Thickness, ft.

κ or k_x = Permeability, md.

K_y = Permeability in y-direction, md.

K_z = Permeability in z-direction, md.

L_w = Horizontal Well Length, ft.

P_i = Pressure at initial conditions (Fracture Pressure), psia.

P_{wf} = Flowing bottomhole pressure, psia.

P_L = Langmuir pressure constant, psia.

$P_{(Initial)}$ = Initial Reservoir Pressure, psia.

$P_{(Desorption)}$ = Critical Desorption Pressure, psia.

q_{peak} = Peak water rate, Bbl/day.

q = Water rate, SCF/D.

$q(peak)_{WD}$ = Dimensionless water peak rate.

r_w = radius of wellbore, ft.

t = Time, days.

t_D = Dimensionless time.

V_L = Dry-ash-free Langmuir volume constant, SCF/ton.

W_i = initial Water in place, SCF.

z = Compressibility factor.

Symbols Used

ρ = Density, g/cm³.

μ_i = Viscosity, cp.

ϕ_f = Fracture porosity, %.

Chapter I

Introduction

Ever since coal mining started, coalbed methane posed a problem to miners. At the start coalbed methane was disposed by venting or flaring. Although coal miners were aware that methane from coal beds could be a potential fuel, due to many factors they were not successful in capturing and marketing the gas from coalbed methane reservoirs. First being that coal mines in those days were shallow when compared to today's coal mines, and generally, the amount of gas differs with depth. As the mines were shallow, there was less coalbed methane to be captured in the mining process. Second, most of the gas is held by the process of adsorption. It is released from coal at very low pressure, and the technology needed to extract this methane at low pressure, and pressurize it, at the same time keeping the mines safe, was not available. Third, there was too much methane available from traditional oil and gas operations, so there was no strong interest in developing the technology needed for commercial production of coalbed methane¹.

CBM wells produced more water initially when compared to conventional reservoirs. Methane gas is adsorbed to the surface of the coal because of the water-contributed pressure in the coal bed reservoir. Removal of this water by pumping is necessary for same reasons; it helps lower the pressure in the reservoir and it stimulates desorption of methane from the coal. The water in coal beds contributes to pressure in the reservoir that facilitates methane gas adsorbed to the surface of the coal. The water coproduced with methane is not reinjected into the producing formation to enhance recovery, but is disposed of or treated to remove dissolved sediments before used for beneficial purposes².

Disposal of this large amount of water is complicated as much of the water is of low quality. The main problem with the disposal of well is their cost, ranging from

\$400,000 to \$1,200,000 depending on depth and stimulation type. The total disposal cost for water to bring to the surface will be approximately \$1.0 to \$4.0 per barrel. The high capital cost is a restriction for small independent operators. Some of the factors attributed to the disposal costs included pipeline maintenance and repair costs, electrical costs to operate pumps, virtually round-the-clock staffing to operate electrical generators, life of the facility, depth of the injection well, chemical treatments to disinfect water that is reused for livestock³.

Water from CBM wells contain high concentration of dissolved sediments and a high sodium absorption ratio. This water cannot be used for domestic or animal consumption, and its high saline and sodium content makes it unsuitable for agriculture irrigation³.

Looking at facts and complications associated with water produced from CBM, it is important to predict the amount of water that will be produced in the CBM wells, especially in the early stages of the production. Hence, it was taken upon to develop type curves for water production in a horizontal well to predict the behavior of the well to produce water along with the amount of water produced with time.

Table 1.1: Amount of Water Produced in Different Basins (EIA, 2006)⁴

Basin	State	Produced Water	Water Production (Bbl/d/well)
Powder River	Wyo., Mont.	500	400
Raton	Colo. NM	1500	226
San Juan	Colo., NM	8000	25
Unita	Utah	15000	215

Chapter II

Literature Review

2.1 Origin and Discovery of Coalbed Methane.

Methane gas is generated during the formation of coal through „coalification process of vegetal matter. This can broadly be divided into biochemical and physico-chemical stages of coalification incorporating five successive steps⁵.

Peatification - Anaerobic degradation of organic materials in the peat swamp⁵.

Humification - Formation of dark colored humic substances by anaerobic degradation⁵.

Bituminization - Generation of hydrocarbons with increase in temperature and pressure⁵.

Debituminization - Thermal degradation of matter and generated hydrocarbons⁵.

Graphitization - Formation of graphite⁵.

Many physical and chemical changes, governed by biological and geological factors, occur during these processes. Whereas darkening in color and increase in hardness and compactness are the main physical changes, loss in moisture and volatile contents, and increase in carbon content are the main chemical changes. Many acids (humic, fatty, tannin, gallic, etc.) and dry and wet gases (CH₄, CO₂, N₂, N₂O, H₂S, ethane, propane, butane, etc.) are formed during decomposition of the organic matter. All the changes brought about are attributable to the release of –COOH (carboxyl), >C=O (carbonyl), –OH (hydroxyl) and –OCH₃ (methoxyl) functional groups from the organic compounds which cause the decomposition of vegetal source matter⁵.

Biochemical stage of coalification, beginning with the accumulation of vegetal matter and terminating at the sub-bituminous stage of coal formation, leads to the formation of a wide range of degradational products.

The organo-petrographic entities of coal (termed „macerals“) by the partial oxidation and hydrolytic decomposition of dead vegetal matter accumulated in water-saturated wet lands (basins) by micro-organisms (fungi, aerobic bacteria, insects, etc.). Further decomposition by anaerobic bacteria extracts oxygen from organic molecules of vegetal matter and results in high concentration of hydrogen. Part of this hydrogen is released as methane or „marsh gas and the rest is absorbed by humic colloids⁵.

During subsequent geochemical stage of coalification, rising temperatures and pressures, due to subsidence of the basin, either by growing thickness of overburden or by tectonic activities, generate hydrocarbons (hydrogen-rich constituents). Thermal cracking of the free lipid hydrocarbon fraction and/or cracking of the kerogen fraction of coal generates methane gas. Thus, the generation of coal bed methane during coal formation occurs in two ways:

- (i) By metabolic activities of biological agencies (biological process), and
- (ii) By thermal cracking of hydrogen-rich substances (thermogenic process)⁵.

Figure.2.1: Coalification Process⁵

The course of biochemical decay and metamorphic transformation of vegetable matter generates large quantities of gases, as much as 1,300 cubic meters per tonne of coal formed. The amount of gas produced differs with the rank of coal. The ability of the coal to retain the gas, i.e., its adsorptive capability, also depends on the rank of coal being formed (CIAB, 1993)⁶.

As temperature and pressure increases during the coalification process, the rank of the coal also changes thus allowing it to adsorb different volumes of methane(CIAB, 1993)⁶.

Figure 2.2 shows the Desorption Isotherms as a Function of Coal Rank

Figure.2.2: Desorption Isotherms as a function of Coal Rank

Coalification process yields large amounts of gas, as much as 1,300 cubic meters per ton of coal formed, in which a large amount escapes during burial and

metamorphosis of the decaying material. The gas retained will range from negligible to as much as 25 cubic meters per tonne (CIAB, 1993)⁶.

Gas production from coal represents a recent technology in petroleum industry. Not so long ago, did a methane gas that is associated with coal mining represent only great threat and main danger to mineworkers. Twenty years ago, people started to realize that producing gas from the coals before mining not only help and drastically decrease the danger of blowout in the mines, but can also be used as a fuel. In 1982, the gas production from the coals in the United States was zero (CIAB, 1993)⁶.

The gas produced from coal beds is almost completely methane, usually containing small amounts of other hydrocarbons, hydrogen, carbon dioxide, carbon monoxide, and nitrogen. However, with the increase in demand for energy, there is a tremendous technical development for producing unconventional sources of natural gas. More specifically, advancements in reservoir characterization, simulation, and production have been the keys for economic development of the CBM. It is expected that until 2010, 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 (CIAB, 1993)⁶.

2.2 Global Coal Distribution

Worldwide CBM resources are estimated to range between 5,800 and 24,215 Tcf. Production and usage of CBM in the United States has increased in the last 15 years. CBM accounts for 9% of the total US gas production. North America's resources range between 951 to 4,383 Tcf⁷.

The major coal resources exist in 69 countries. Around 5800 millions short tons of coal is consumed by world annually, out of which 75% is used for electricity

generation. The regions including India and China use 1800 million short tons. This figure is predicted to increase to 3000 million short tons by the year 2025. USA consumes about 1100 short tons of coal every year, using 90% of it for electricity. Coal is the fastest growing energy source in the world, with coal use increasing by 25% for the three-year period ending in December 2004⁷.

Thirty-five major coal countries have some CBM activity. Figure 2.3 shows the major sectors of coal distribution over the globe. The largest potential resources, which also have the largest degree of uncertainty, are in the former Soviet Union with 4,000 to 16,116 Tcf, whereas South America and Europe range from 15 to 32 Tcf and 161 and 269 Tcf, respectively. Africa ranges between 27 and 55 Tcf; the Middle East has no CBM resources. CBM resources of the Asia Pacific region, which includes China, ranges from 646 to 3,360 Tcf⁷.

Figure 2.3: Global Coal Distribution (Reprinted from Mawor et al., 1996)

2.3 Coalbed Methane in US

There were 6,494 CBM wells drilled during 2005, up 12% from 2004's figure. The number of CBM wells under production in 2004, has been revised upward by 436 wells as new, more complete data have trickled in from several states. This year,

a nearly 18% jump in CBM drilling is forecast for 7,652 wells, with more than 3,600 wells already spudded in the first half. Furthermore, permitting will remain at a high level, with 12,264 permits expected this year for a 1% increase. The leading state for CBM drilling remains Wyoming, followed by Kansas and Colorado. About 60% of all US CBM wells are drilled to a depth of 1,100 ft or less. Typical half-life of a well is 13 years. (The US Energy Information Administration - EIA)⁸.

CBM production took a 7.5% jump to 1.72 Tcf in 2004, after declining slightly in 2003. Although EIA has yet to report a 2005 figure, World Oil is estimating last year's output at about 1.78 Tcf, or a 3.5% increase (The US Energy Information Administration - EIA)⁸.

The leading US CBM producing region is the San Juan basin of Colorado and New Mexico. Together, these states contribute about 60% of all US CBM output, which EIA said was 2.87 Bcfd in 2004, and which likely climbed above 2.9 Bcfd in 2005. EIA's 2004 proved reserve figure for the two states was 10.95 Tcf (The US Energy Information Administration - EIA)⁸.

The next largest CBM production area is the Powder River basin, where Wyoming and Montana produced CBM of a combined rate of just over 900 MMcfd in 2004, a figure that increased to nearly 1.0 Bcfd in 2005. EIA's 2004 proved reserve figure for these two states, together, was roughly 2.4 Tcf. There is an estimate that more than 32,000 CBM wells are now producing in the Powder River basin (The US Energy Information Administration - EIA)⁸.

As per EIA 2005 annual report, present coalbed resources are 83 Tcf, from which 63 Tcf is located in Rocky Mountains, and 5 Tcf in Gulf Coast/ E&C Texas, and 6 Tcf in Mid-continent, and 1 Tcf in southwest and about 8 Tcf in other parts of US(EIA, Annual Report)⁸.

Coalbed methane currently accounts for 10% of the total natural gas being produced in the United States. However, the Rocky Mountain States of New

Mexico, Utah, Colorado, Wyoming, and Montana are estimated to hold more than 1.5 trillion cubic meters of undiscovered natural gas being placed and drilled. It is anticipated that there will be more than 400,000 operating CBM wells in the five-state area by 2010⁹.

The major coalbed methane resources in the United States are located in 12 basins: San Juan (10 Tcf), Black Warrior (4.4 Tcf), Powder River (24 Tcf), Uinta & Piceance (5.5 Tcf), Central and Northern Appalachian (10.6 Tcf), Raton-Mesa (3.7 Tcf), Hanna-carbon (4.4 Tcf), and SW coal Region⁹.

The two most productive basins are Black Warrior in Alabama and San Juan in northern New Mexico with the total estimated CBM gas reserves of 20 Tcf and 88 Tcf respectively⁹.

Development and production of CBM began in the Appalachian basin nearly 60 years ago. Coal mines in the Appalachian basin emit approximately 180 million cubic feet (MMcfd) of high-quality methane into the atmosphere daily⁹.

Figure.2.4: Coalbed Methane Basins in United States (DOE, 2005)⁹

The existence of mines in West Virginia, Southwest Virginia, Eastern Kentucky, Ohio, Pennsylvania, Tennessee, and Alabama with high gas emissions of methane resulted in further investigation into the economic development of this unconventional energy source is warranted. Appalachian coals occur as multiple beds, individually up to 14 feet thick (Pittsburgh coalbed in Pennsylvania and West Virginia). The gas content of these bituminous coal seams has been measured at 93 cubic feet per ton(cu ft/t) from a depth of 149 feet (Waynesburg Coalbed, Pennsylvania) to over 560 cu ft/t have been measured where the overburden is 685 feet thick(Peach Mountain Coalbed).

Figure 2.5: CBM Reserves. (DOE/EIA-0216)

Figure 2.6: CBM Production. (DOE/EIA-0216)

2.4 Transport Mechanism in CBM Reservoir

The characteristics of CBM reservoirs vary from conventional gas reservoirs in several areas (Table.2.1) .Coal is a heterogeneous and anisotropic porous media which is characterized by two distinct porosity (dual-porosity) systems: macropores and micropores. The macropores, also known as cleats, constitute the natural fractures common to all coal seams. Micropores, or the matrix, contain the vast majority of the gas. This unique coal characteristic has resulted in classification of CBM as an “Unconventional” gas resource¹⁰.

Table.2.1: Difference between Conventional Reservoirs and CBM Reservoir¹⁰.

Characteristics	Conventional	CBM
Gas Generation	Gas is generated in the source rock and migrates into reservoir	Gas is generated and trapped within the coal.
Structure	Randomly-spaced Fractures	Uniformly-spaced Cleats
Gas Storage Mechanism	Compression	Adsorption
Transport Mechanism	Pressure Gradient (Darcy's Law)	Concentration Gradient (Fick's Law) and Pressure Gradient (Darcy's Law)
Production Performance	Gas rate starts high then decline. Little or no water initially. GWR decreases with time	Gas rate increases with time then declines. Initially the production is mainly water. GWR increases with time
Mechanical Properties	Young Modules~ 10^6 Pore Compressibility~ 10^{-6}	Young Modules~ 10^5 Pore Compressibility~ 10^{-4}

Gas in the coal can be present as free gas within the macropores or as an adsorbed layer on the internal surfaces of the coal micropore. The micropore of coal has immense capacity for methane storage. Typically, coal can store far more gas in the adsorbed state than conventional reservoirs can hold by compression at pressures below 1000 psia. The porosity of the cleat system is small, and if any free gas is present, it would account for an insignificant portion

of the gas stored in the coal. Most of the gas in coals is stored by adsorption in the coal matrix (Remner D.J., et al., 1986)¹¹.

Figure 2.7: Transportation of Methane in CBM Reservoir¹²

2.5 Production Behavior in CBM Reservoirs

Gas production from coalbed methane reservoirs may follow three stages as the reservoir pressure declines from reduction of hydrostatic pressure by pumping off the water in the reservoir (Figure 2.8). Most coalbed methane reservoir are found to be under near hydrostatic pressure and are saturated with water. Methane is held within the porous coal matrix by an adsorption mechanism that is controlled by the reservoir pressure. When a water-saturated coalbed methane well is first produced, it is common to encounter only single-phase or saturated flow i.e., only water is produced. This is Stage 1 where only one phase exists and pore spaces are fully saturated with water¹³.

As water is removed and reservoir pressure is reduced further; methane-gas bubbles begin to form as a result of desorption from the coal, and pore spaces are partially saturated with water. The bubbles block some of the pathways that were originally available to water flow; thus the relative permeability of the formation to water reduces. The gas does not yet flow, however (except as

trapped gas bubbles in water), because the bubbles are not connected within the porous coal matrix nor in the cleat or natural fracture system of the coalbed. Stage 2 is called an unsaturated, single-phase flow regime where, although two phases are present (water and gas), only the water phase is mobile. Because of reduced permeability to water, the pressure drop in this regime increases faster than in a fully water-saturated flow regime¹³.

Figure 2.8: Typical Coalbed Methane Production Profiles for Gas and Water Rates: Three Phases of Producing Life¹⁴.

Stage 3 is reached as the reservoir pressure decreases and additional gas is desorbed. The gas saturation builds until the gas bubbles connect and form a continuous pathway to the wellbore. As shown in Figure 2.8 two-phase flow begins at the point where the relative permeability to gas becomes nonzero. As the reservoir pressure is further reduced and water saturation declines, the relative permeability to gas increases at the expense of the relative permeability to water. This sequence of regimes progresses outward from the wellbore into the formation over time, i.e., when two-phase flow occurs at the wellbore,

unsaturated and saturated single-phase flows occur simultaneously farther into the formation¹³.

2.6 Necessity to Develop Type Curves

For the gas to be released from the coal, its partial pressure must be reduced, and this is done by removing water from the coalbed fractures. During the dewatering process, the gas desorbs from the coal, thereby gas rate increases and the water saturation decreases. The water production declines rapidly until the gas rate attains a peak value and water saturation approaches the irreducible water saturation i.e., reaches connate water saturation. The dewatering process usually lasts between 6 and 18 months. Once the peak gas rate is attained, CBM reservoirs act like a conventional reservoir. Reservoir engineers usually use production decline curves in order to predict well performance.

Since the behavior of CBM reservoirs are complex when compared to conventional reservoir, the use of a numeric simulator is the best way to predict the CBM production behavior. Operating a simulator requires in-depth knowledge and detailed data to get accurate results. They are also expensive to small producers. Considering these factors, running a simulator might not be the best option. Hence, in order to develop a simple and yet a reliable tool to forecast the production in a CBM reservoir with good accuracy, it was taken upon to develop type curves for both gas and water production.

2.7 Horizontal Wells in Coalbed Methane

Horizontal wells in coalbed methane is a comparatively new concept and many of the drilling projects that have been proposed using this technology are still in their infancy. Significant potential natural gas resources remain in low permeability reservoirs of the Appalachian basin.

The main advantage of horizontal well technology compared to vertical is that, the direction of the borehole can be controlled with respect to the principal permeability directions of the coal seam. Therefore, in coalbed methane

reservoirs, a more effective production technique may be a horizontal borehole placed perpendicular to the maximum permeability direction. This would result in enhanced access to the reservoir through the natural fracture network and improve the rate of water production, accelerating the gas desorption process. The production profile for horizontal CBM wells varies from that of a vertical CBM well. Since the horizontal well is drilled perpendicular to the maximum permeability direction, there is more accessibility for the water to flow into the wellbore, thus allowing the dewatering process to be accelerated. When compared with Figure 2.9 one can notice that dewatering stage, occurs faster in in horizontal wells. In deciding between drilling a horizontal wells over vertical well, three properties are taken in account; (1) coal thickness; (2) natural fractures; (3) anisotropic permeability (Osisanya S. O. and Schaffitzel R. F., 1996)¹⁵

Figure 2.9 Water production in Vertical and Horizontal Wells

2.8 Langmuir Isotherms

The basis for CBM reservoir engineering is the Langmuir Isotherm equation, which can be written as shown in equation 1. The Langmuir Volume (V_L) or maximum adsorbed volume is the maximum volume (normally measured under standard temperature and pressure) adsorbed per unit volume of the reservoir at infinite pressure, and the Langmuir Pressure (P_L) is the pressure at which the total volume adsorbed is equal to one half of the Langmuir Volume (V_L)¹⁶. Langmuir volume and pressure values employed in this study are tabulated in Appendix-A

$$V = V_L \frac{P}{P_L + P} \quad (1)$$

Where:

V = Volume. SCF/ton

P = Pressure, psia

V_L = Langmuir volume, scf/ton

P_L = Langmuir pressure, 1/psi

2.9 Coalbed Methane Production Type Curves

The use of conventional decline curve analysis cannot be utilized because there is a complex interaction of coal matrix and cleat system properties that are coupled through desorption process. (Aminian K, et.al, 2004).

CBM reservoirs behavior were studied in depth and a set of type curves were developed as an efficient and economical tool to analyze and forecast the performance of CBM reservoirs by Garcia¹⁷ in 2004 as a part of her MS thesis (Figure 2.10) . 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 2.10: CBM Gas Production Type Curve (Adopted from Garcia, 2004.

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

$$t_D \frac{t q_{peak}}{G_i} \quad (2)$$

$$q_D = \frac{q}{q_{peak}} \quad (3)$$

$$G_i = 43560 \frac{A h}{Gc} \quad (4)$$

The impact of stimulation was considered in a previous study by Sanchez¹⁸ 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.

Arrey¹⁹ in 2004, 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 2.11 shows the effect of P_L changes on the CBM gas production type curves.

Bhavsar²⁰ in 2005 evaluated the impact of reservoir properties on the gas production type curves for Northern Appalachian. He also developed correlation for peak gas rate, correlation for initial (maximum) water rate, and dimensionless groups for water production type curves. Bhavsar developed a set of CBM water production type curve. He concluded that flowing pressure, critical desorption pressure and skin factor influenced the type curves.

Figure 2.11: Effect of Bottom-hole Pressure on the CBM Gas Production Type Curve (Adopted from Arrey, 2004.)

Figure 2.12: Effect of P_L Changes on the CBM Gas Production Type Curves (Adopted from Arrey, 2004.)

**Figure 2.13: Impact of V_L on Water Type Curves at Constant P_L
(Adopted from Bhavsar, 2005)**

**Figure 2.14: Impact of P_L on Water type Curves at Constant V_L
(Adopted from Bhavsar, 2005)**

Figure 2.15: Type Curves for Skin Factor Change (Cartesian) (Adopted from Bhavsar, 2005)

Figure 2.16: Type Curves for Skin Factor Change (Log-log) (Adopted from Bhavsar, 2005)

Figure 2.17: Impact of Under-saturation on the Water Production Type Curves (Adopted from Bhavsar, 2005)

Sunil Lakshminarayanan²¹ in 2006 evaluated the impact of the impact of relative permeability on type curves for coalbed methane reservoirs. He concluded the following points.

The values of relative permeability in coal bed methane reservoirs primarily depends upon 3 constants, which are n , m and k . Using the relative permeability values from 4 different samples of coal, the range values for the three constants were obtained and the effect of these constants on the production type curves of gas and water were studied.

$$k_{rg} = k(1 - S_w^*)^{m'} \quad (5)$$

$$k_{rw} = (S_w^*)^{n'} \quad (6)$$

1. The value of constant k does not affect the performance by any extent.
2. The value of m seemed to be more significant with the gas curves. As the value of m increased, the production of the reservoir slowed down. However, m did not have significant effect on water curves.

3. The value of n seemed to be more significant with the water curves. The variation in the water curves for the extreme ranges seemed very significant. Whereas, the variation in the gas curves was comparatively negligible.

Figure 2.18: Impact of m' on the Shape of the Type Curve (Adopted from Lakshminarayanan, 2006)

Figure 2.19: Impact of n' on the Shape of the Type Curve (Adopted from Lakshminarayanan, 2006)

Nfonsam²² in 2006 studied impact of reservoir properties on gas production type curves in horizontal wells for Northern Appalachian basin. The impact of nine (9) formation and operational parameters; permeability, porosity, thickness, critical desorption pressure, fracture pressure, flowing bottomhole pressure, and a ratio of horizontal length to area, langmuir pressure and volume were studied to evaluate their impact on the type curve. He concluded that permeability and Langmuir pressure (P_L) significantly impact on the type curve.

Figure 2.20: Effect of Permeability on Shape of Type Curves for Horizontal Wells (Adopted from Nfonsam, 2006)

Figure 2.21: Effect of Langmuir Pressure on Shape of Type Curves for Horizontal Wells (Adopted from Nfonsam, 2006)

Figure 2.22: Average Type Curve for Permeability for Horizontal Wells (Adopted from Nfonsam, 2006)

Figure 2.23: Average Type Curve for Langmuir Pressure for Horizontal Wells (Adopted from Nfonsam, 2006)

2.9 GEM²³

The reservoir models developed using simulators, are excellent tools to study the impact of reservoir properties on production. CMG (Computer Modeling Group) is one such kind of software extensively used for research²³.

CMG works on six different applications such as (1) BUILDER, Pre-processing Applications, (2) IMEX, Black Oil Simulator, (3) STARS, Steam Thermal Advanced Processes, (4) GEM, Generalized Equation-of-State Model Compositional Reservoir Simulator, (5) WINPROP, Phase Behavior Analysis, and (6) RESULTS, Post-processing Applications. During this study, three applications of CMG were used for developing Reservoir model for coalbed methane, BUILDER, GEM, and RESULTS²³.

Figure 2.24: CMG's Modeling Tools

BUILDER is module used to prepare reservoir simulation models. Again, BUILDER has two modules, for two different applications, which are: (1) Grid Builder and (2) Model Builder²³.

The **Grid Builder** 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 performance²³.

The **Model Builder** is used to 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 Model Builder has an automatic error checking and data validation²³.

GEM is a second module of CMG that we used in this study. This tool modifies any type of reservoir with complex phase behavior and their interaction where the importance of the fluid composition and their interactions are essential to

understand the recovery process. GEM is a highly optimized simulator that has been proven in numerous field production situations around the world²³.

RESULTS is GEM's set of post processing applications, designed for visualizing and reporting simulator output. With RESULTS, users can generate several informative graphs, and export simulation data onto excel sheets for further study. A RESULT is composed of two modules: (a) Results Graph and (b) Results Report²³.

Results Graph, produce high quality graphs of well production 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 discussion²³.

In this study, Model Builder and Grid Builder to build the 2D Cartesian model, GEM were used to run the simulated model. The outputs of the runs were analyzed in RESULTS and plots were developed in Results Graph²³.

Chapter III

OBJECTIVE AND METHODOLOGY

The main purpose of this study was to develop a simple and reliable tool to forecast the performance of water for horizontal wells in CBM reservoirs. Also to develop a correlation for peak water production rate $(q_{peak})_{wd}$. In order to achieve the objective, methodologies consisting of the following steps were employed:

1. Develop a set of type curves for water production.
2. Develop a methodology to predict water production using type curves.
3. To verify the accuracy of the type curve and the correlation using a test run.

3.1 Development of Reservoir Model for the Northern Appalachian Basin

As a first step of thesis, literature survey was done on Appalachian basin to identify the range of all the parameters, which are to be studied. Once data was acquired, a two-dimensional cartesian base model was developed for a CBM reservoir.

The reservoir simulation software used in this study was GEM developed by the Computer Modeling Group (CMG). 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. Table 3.1 shows the input parameters used for the base case.

Permeabilities vary in i, j and k (k_x , k_y and k_z) directions. Since coal is anisotropic, the horizontal well was drilled perpendicular to the direction with the highest permeability, that is, in i-direction (Figure 3.1). The permeability values for each

Figure 3.1: Input Parameters used for base case

Input Parameters	Horizontal CBM Model	
		Value
Period of production		25 years
Porosity Model	Dual Porosity	-
Shape Factor Calculations	Gilman and Kazemi Style Formulations	-
Matrix-Fracture Transfer Calculations	Pseudo-capillary pressure model with corrections	-
Grid	Cartesian	26 x 54 x 1
Reservoir Area		320 Ac
Grid's Size		100ft x 100ft
Grid Properties	Grid top	1200 ft
	Grid Thickness	10 ft
	Porosity Matrix	0.5%
	Porosity Fracture	2%
	Permeability Matrix	0.01 md(i, j, k)
	Permeability Fracture	10md i, 3.3md j, 1md k
	Fracture Spacing	0.2ft
Rock Compressibility	Matrix and Fracture: Reference Pressure	1100 psia
	Rock Compressibility	1.0×10^{-6} 1/psia
EOS Model	Peng-Robinson	
Library Components	Methane	CH ₄
Constant Reservoir Pressure		113 F
Rock Fluid Data-Grid Properties	Maximal Adsorbed mass (CH ₄)	Matrix:0.2845 Fracture: 0
	Langmuir Adsorption (CH ₄)	Matrix: 1.48E-03 Fracture: 0
	Rock Density	Matrix: 89.63 lb/ft ³ Fracture: 89.63 lb/ft ³
	Coal Sorption time(CH ₄)	Matrix: 50 days Fracture: 50 days
Initial Conditions-Grid Properties	Water Saturation	Matrix: 0.005 Fracture: 1
	Pressure	Critical Desorption Pressure: 300 psia Fracture: 600 Psia
	Gas Composition (CH ₄)	Matrix: 1 Fracture: 1
Constraints	Minimum Bottom Hole Pressure	50 psia
	Maximum Gas Rate	350, 000 ft ³ /day
Well Length		1100 ft

direction were changed at a ratio of 1:3 (1/3 of the maximum permeability; $i = 10$ md, $j = 3.3$ md and, $k = 1$ md). Permeability of 20 md is considered as extreme case for the Northern Appalachian basin. It was included in this study to fully demonstrate the effect, of permeability on the type curves.

The horizontal well length is changed for all the different areas and this change is based on a ratio of 11:38, 15:38, and 30:38 to study the effect of ratio of well length to reservoir length at different areas. Table 3.2 summarizes the parameters and their ranges

Figure 3.1: Horizontal Well in a Box-shaped Drainage Volume (Babu and Odeh, 1989)²⁴

Table 3.2: Parameters range employed during this study

Variable	Range	Values Used			
Fracture Permeability i, j, k (md)	5 20	5i, 1.7j, 1k	10i, 3.3j, 1k	15i, 5j, 6.7k	20i, 6.7j, 2k
Fracture Porosity (%)	1.5 3	1.5, 2, 2.5, 3			
Area(Ac)	160 320	160, 240, 320			
Thickness (ft)	5 20	5, 10, 15, 20			
Critical Desorption Pressure(psia)	300 600	300, 400, 500, 600			
Initial Fracture Pressure (psia)	300 - 600	300, 400, 500, 600			
Flowing Bottomhole Pressure (psia)	50 - 100	50, 75, 100			
Changing the Ratio of Well length to Reservoir Length	1100ft-4300ft	Ratio	11:38	15:38	30:38
		160 Ac	1100	1500	3000
		240Ac	1300	1800	3600
		320Ac	1600	2100	4300

3.2 Dimensionless Groups for Water Production Type Curve

Set of dimensionless rate and time were utilized by Bhavsar²⁰ to develop type curve for water. They do not require reservoir properties and they are presented as followed. The water dimensionless rate and time were defined as:

$$q_{wD} = \frac{q_w}{q_{iw}} \quad (7)$$

$$t_{wD} = \frac{t}{W_i} \frac{q_{iw}}{W_i} \quad (8)$$

Where, 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:

$$W_i = 43560 \times A \times h \times \phi \times S_{wi} \quad (9)$$

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.

3.3 Determination of initial (maximum) water rate q_{iw}

The most important parameter in developing the type curve are to estimate q_{iw} and W_i for water production. Estimation of q_{iw} is complicated for water. An extensive literature survey was performed to see if theories of a conventional reservoir can be applied to CBM reservoir. Since coal cleat is filled with water in the early stages, CBM reservoir act as single phase unsteady state. Hence we applied the single phase liquid unsteady state solution to find the initial water rate q_{iw}

The following equation developed by Joshi²⁵ used to calculate q_{iw} .

$$q_{iw} = \frac{\sqrt{k_y \times k_z} \times L_w \times (P_i - P_{wf})}{162.6 \times \mu \times [\log(\frac{\sqrt{k_y \times k_z} \times t}{\mu \times c_t \times r_w^2}) - 3.23]} \quad (10)$$

3.4 Development and verification of dimensionless groups for type curve generation.

The development of a generalized correlation for dimensionless peak water rate in horizontal wells follows the same procedure as in vertical wells as discussed earlier. The dimensionless groups are essentials for generating the production type curve to analyze and predict CBM performance. These dimensionless variables represent the values for the ordinate and abscissa of the type curve. Knowing the effect of two-phase flow through the porous media in CBM, it is required to carefully analyze the impact of each variable of the equation in the behavior of the gas production type curve.

The following equation defines the dimensionless peak water rate for horizontal wells in CBM reservoirs.

$$q_{(peak)WD} = \frac{q_{(peak)W} \times 162.6 \times \mu \times [\log(\frac{\sqrt{k_y \times k_z} \times t}{\mu \times c_t \times r_w^2}) - 3.23]}{\sqrt{k_y \times k_z} \times L_w \times (P_i - P_{wf})} \quad (11)$$

From this studies it was concluded that there is a linear relation between $q_{(peak)wd}$ and various reservoir parameters such as permeability (k), porosity (ϕ), critical desorption pressure ($P_{(matrix)}$), fracture pressure ($P_{(frac)}$), Langmuir pressure (P_L) and Langmuir volume (V_L).

3.5 Multiple Linear Regression Analysis

Linear regression analysis is a statistical analysis used for forecasting. Regression analysis estimates relationship between variables, so that a given variable can be predicted from one or more other variables. A correlation was developed to calculate dimensionless water rate using reservoir properties. This

correlation can be used to calculate dimensionless water rate in the absence of reservoir production data.

3.6 Validation

In the last stage in order to validate the accuracy of the production type curve that were constructed, the identification of the curve with the largest gap between the dimensionless curves and the average curve for each property was analyzed. Then the squares of Pearson and the errors between those curves were calculated by selecting the water rate at similar times. In that way, the maximum difference (error) was measured and evaluated for the Ten properties studied.

In addition to this, simulator runs were used to generate the production history for two cases. The inputs used were values within the range that characterize the Northern Appalachian Basin properties, but using a combination of inputs completely different than the ones used for the runs made before.

The production history simulated by CMG for the first 25 years of production was used to obtain dimensionless values in order to employ the type curve. Then, the prediction of future production rate from the type curve and the future rates generated by the numerical simulator were compared. This step was performed in order to guarantee the degree of uniqueness of the dimensionless group used in the construction of the CBM production type curve.

At the same time, evaluation of peak water rate was done in order to present an alternative procedure to predict CBM water production without having any production data. The impact of the reservoir properties (area, permeability, thickness, porosity, initial matrix pressure, initial fracture pressure, flowing bottomhole pressure, and differential pressure) on peak water rate was studied. Dimensionless group was presented (equation 11) based on Darcy's Law definition. Flow rate generally depends on thickness, time, porosity, well length, permeability and differential pressure. Therefore, these properties and peak

water rate were used as first approach to get the dimensionless group. These dimensionless flow rates were plotted against the reservoir properties studied before in order to scrutinize the impact of each property. The properties whose effect was not taken in account by the dimensionless group were identified. An evaluation of those properties and peak water rate behavior was performed.

$$q_{(peak)WD} = \frac{q_{(peak)W} \times 162.6 \times \mu \times [\log(\frac{\sqrt{k_y \times k_z \times t}}{\mu \times c_t \times r_w^2}) - 3.23]}{\sqrt{k_y \times k_z} \times L_w \times (P_i - P_{wf})} \quad (11)$$

This approach was conducted with the purpose of defining a correlation to estimate the value of q_{peak} . Then, knowing some of the reservoir properties Q_D value can be found from the correlation (equation 12) developed. Then, solving equation 11 for q_{peak} , the prediction of water production can be also estimated if there is not production data available. The value of peak water rate was compared with the maximum water rate obtained from the numerical simulator to complete the validation process.

Table 3.3: Case Study Inputs

PARAMETERS	Case 1	Case 2	Case 3
Fracture Permeability (md)	$K_x=7, K_y=2.3, K_z=1$	$K_x=12, K_y=4, K_z=1.3$	$K_x=17, K_y=5.6, K_z=1.8$
Fracture Porosity (%)	1.8	2.2	2.7
Thickness (ft)	8	12	18
Critical Desorption Pressure (psia)	350	450	550
Initial Fracture Pressure (psia)	525	425	325
Flowing Bottomhole Pressure (psia)	60	80	90
Langmuir Pressure (psia)	300	600	900
Langmuir Volume (Scf/ton)	250	500	750

Chapter IV

Results and Discussion

The purpose of this study has been to develop and evaluate a reliable method for predicting the production performance of the horizontal wells with out the need for costly and time-consuming computer simulations. The results of the impact of the various parameters studied are discussed below. Figure 4.1 shows the type curve for the base model.

Figure 4.1: Water Type Curve for Base Model (Horizontal Well)

The second set of simulations took into account the flowing BHP (Bottomhole Pressure). The BHP was changed to different values to determine its impact on the set of dimensionless equations. The BHP was run on values ranging from 50-

100 psia. As shown in Figure 4.2, it was concluded that bottomhole flowing pressure does not have effect on shape of the type curve.

Figure 4.2: Effect of Bottomhole Flowing Pressure on the Shape of the Type Curve.

The third set of simulations took into account the effect of porosity on the production from horizontal CBM wells. The porosity varied from 1.5% to 3%. At early stages, the time-water-peak and the late performance coincide with the average curve. By seeing the production behavior in log-log scale (Figure 4.3), the curves experience a small gap between them at the very early time of depletion. However, the curves converge right before and after the peak occur. The maximum error calculated between the curve with the largest gap and the average curve was less than 10%. It was concluded that fracture porosity does not have effect on shape of the type curve.

Figure 4.3: Effect of Fracture Porosity on the Shape of Type Curves.

The fourth set of simulations was performed to evaluate the influence of coal thickness in CBM reservoirs performance. The thickness varied from 6 to 15 ft. At early stages, the time-water-peak and the late performance coincide with the average curve. By seeing the production behavior in log-log scale (Figure 4.4), the curves experience a small gap between them at the very early time of depletion. However, the curves converge right before and after the peak occur. The maximum error calculated between the curve with the largest gap and the average curve was less than 10%. It was concluded that thickness does not have effect on shape of the type curve.

Figure 4.4: Effect of Reservoir Thickness on the Shape of Type Curve

The fifth set of simulations includes the variation of the critical desorption pressure. The impact of the pressure in the CBM production is considered critical and it needs to be tested to evaluate the behavior of the water depletion. The critical desorption pressure varied in a range of 300 to 600psi. As shown in Figure 4.5, it was concluded that critical desorption pressure does have effect on shape of the type curve.

The sixth set of simulations includes the variation of the fracture pressure. The fracture pressure varied in a range of 300 to 600 psi. As shown in Figure 4.6, it was concluded that fracture pressure does have effect on shape of the type curve.

Figure 4.5: Effect of Critical Desorption Pressure on the Shape of Type Curve.

Figure 4.6: Effect of Initial Reservoir Pressure on Shape of Type Curve

The curves for permeability converge at a later stage of the reservoir. As we can seen from the plot that even tough there is deflection in the type curves, the type started at a common point and ended tapered at the end. At early stages, By seeing the production behavior in log-log scale (Figure 4.7), the curves experience a small gap between them at the very early time of depletion. The maximum error calculated between the curve with the largest gap and the average curve was less 10%. For this case, the dimensionless groups generate a curve with reasonable results as far as sorption time is concerned. It was concluded that Permeability does have effect on shape of the type curve.

Figure 4.7: Effect of Permeability (k_x) on Shape of Type Curve.

The eight set of simulations considers the influence of Langmuir pressure on the CBM water production behavior. In this study, several Langmuir pressure were used. As shown in Figure 4.8, it was concluded that Langmuir Pressure does not have effect on shape of the type curve.

Figure 4.8: Effect of Langmuir Pressure on Shape of Type Curve

The ninth set of simulations considers the influence of Langmuir volume on the CBM water production behavior. As seen in Figure 4.9, type curves start at a common point and tapered to a common point, it was concluded that Langmuir Volume does not have effect on shape of the type curve.

In the Tenth set of simulations, the horizontal length is changed for all the different areas and this change is based on a constant ratio as given on table 3.2. As seen in Figure 4.10, it was concluded that change in horizontal well length to length of reservoir does not have effect on shape of the type curve.

The eleventh set of simulations corresponds to the variation of both initial desorption and reservoir pressure by the same value. Simulations were performed testing these properties for Desorption and reservoir pressures of 400 and 500psi.

As seen in Figure 4.11, it was concluded that variation of both initial desorption and reservoir pressure by the same value does not have effect on shape of the type curve.

Figure 4.9: Effect of Langmuir Volume on Shape of Type Curve

Figure 4.10: Effect of Ratio of Horizontal Length to Side of Reservoir on the Shape of the Type Curve

Figure 4.11: Effect of Changing both Initial Reservoir and Critical Desorption Pressure on the Shape of the Type Curve.

After all the parameters have been changed and an evaluation of their impact on the dimensionless equations has been made, average type curve was developed for combined effect of desorption pressure and reservoir pressure since they have a significant impact on the shape of the type curve. The average type curve is shown in Figure 4.12

4.2 Multiple Linear Regression Analysis

A linear regression analysis was done to develop a correlation. As first step all the parameters of interest were correlated in various combinations with an R^2 value of 0.86.

$$\begin{aligned}
 q_{(peak)WD} & h (4.4E - 02) \quad k (9.7E - 03) \quad Kx (2.5E - 03) \\
 & Ky (1.9E - 02) \quad A (3.3E - 04) \quad Lw (2.4E - 03) \\
 & Fp (2.3E - 03) \quad P_{wf} (2.9E - 04) \quad MP (1.2E - 03) \\
 & f (8.2E0) \quad VL (3.3E - 04) \quad PL (4.8E - 03) \quad 1.5
 \end{aligned} \tag{12}$$

Figure 4.12: Average Type Curve for Initial Reservoir and Critical Desorption Pressure for Range Employed in Study

4.3 Verification

By using the above dimensionless correlation (equation 12), and doing reverse calculation of equation 11, the peak water rate for any case in a coalbed methane reservoir can be calculated. With production type curves, an assumption that future production can easily determined with some thought and few calculations can be made. In order to estimate the future production from CBM wells in which no production data is available a new equation had to be adopted and a value of q_{peak} could be calculated just from knowing few parameters

This approach was validated by comparing the peak water rate from the correlation and from the simulated data for case one, two and three.

Table 4.1: Case Study

	Case 1	Case 2	Case 3
q_{peak} Value from simulator	1354.36	2091.59	3125.73
q_{peak} Value from back calculation	1462.70	1861.15	3052.26
Error % in q_{peak} calculation	7.4%	9%	3%

For case one, a peak water rate of 1354.36 Bbl/day was found by using the simulator and 1462.7 Bbl/day by applying the numerical simulator developed. For case two, a peak water rate of 2091.59 Bbl/day was found by using the simulator and 1861.15 Bbl/day by applying the numerical simulator. For case three, a peak water rate of 3125.73 Bbl/day was found by using the simulator and 3052.26 Bbl/day by applying the numerical simulator. As it can be seen, the correlation provides a reasonable estimation of peak water rate in order to be able to use the production type curves without starting the water production. This correlation allows the use of the type curve for water production forecast in order to evaluate the feasibility and economics between several projects to facilitate the decision-making.

Figure 4.13 Comparison of the Predicted Water Production (Case 1)

Case 2

Figure 4.14 Comparison of the Predicted Water Production (Case 2)

Case 3

Figure 4.15 Comparison of the Predicted Water Production (Case 3)

From the results, the predicted production rates from the type curves closely match those from the simulator. $Q_{(peak)D}$ Value was calculated for the case study by using the correlation equation developed and then the values of $q_{(peak)w}$ was computed using the calculated value of $Q_{(peak)D}$ in equation 11. The comparison of the calculated and estimated value of $Q_{(peak)W}$ for the case study, gave a maximum error of 8 percent and this leads to the conclusion that the correlation developed for $Q_{(peak)D}$ can provide reliable results.

Chapter V

Conclusions and Recommendation

The following conclusions and recommendations were made.

1. Average production type curves for water in horizontal CBM reservoirs were developed that could be used by the independent producers to evaluate and predict production data
2. Fracture pressure, and critical desorption pressure were found to have significant influence on the type curve.
3. A reliable correlation for predicting the peak water rate was developed that allowed the type curve to be used as a tool for predicting production.
4. The comparison of the model prediction and type curve prediction indicated an error of 8 percent, which is within reasonable engineering tolerance.

This study can be used in the development and implementation of new technology and growth in unconventional CBM gas reservoirs in the Northern Appalachian Basin.

Recommendations

Since relative permeability data is an important parameter for the water production from CBM wells, it is recommended to study this variable in detail in developing correlations for both gas and water prediction.

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Appendix

Langmuir Volume (V_L) and Langmuir Pressure (P_L) range employed in this study.

$$\frac{x}{453} \quad 379 \quad 2000 \quad V_L \quad \frac{1}{x} \quad P_L$$

V_L	X	P_L	X
100	0.0598	100	1.00E-02
200	0.1195	200	5.00E-03
300	0.1793	300	3.33E-03
400	0.2391	400	2.50E-03
476	0.2845	500	2.00E-03
500	0.2988	600	1.67E-03
600	0.3586	675.6	1.48E-03
700	0.4183	700	1.43E-03
800	0.4781	800	1.25E-03
900	0.5379	900	1.10E-03
1000	0.5976	1000	1.00E-03