Project Report

MODELING AND SIMULATION OF COALBED METHANE RESERVOIR FOR ITS OPTIMISED RECOVERY

Submitted for Partial Fulfillment of the requirement of
B-Tech. Degree
(APPLIED PETROEUM ENGINEERING)
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UNIVERSITY OF PETROLEUM AND ENERGY STUDIES
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UNIVERSITY OF PETROLEUM & ENERGY STUDIES

CERTIFICATE

This is to certify that the project work on ***"MODELING* AND SIMULATION OF COALBED METHANE RESERVOIR FOR ITS OPTIMISED RECOVERY"** submitted to University of Petroleum & Energy Studies, Dehradun, by **Mr. Abhishek Bhardwaj & Mr. Ruchir Srivastav**, in partial fulfillment of the requirement for the award of **Degree Of Bachelor Of Technology In Applied Petroleum Engineering** (Academic Session 2003 – 2007) is a bonafide work carried out by them under my supervision and guidance. This work has not been submitted anywhere else for any other degree or diploma.

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CHAPTER I

INTRODUCTION

1.1 Coalbed Methane Reservoirs

Coal bed methane is considered unconventional reservoirs in that methane gas is stored in micropores and bedding planes, as well as free gas within natural fractures or cleats. This Reservoir acts both as the source rock and storage reservoir for methane gas. Coal bed methane is peculiar in that methane is predominantly stored in a molecular adsorbed phase within micropores of the coal. High-cost natural gas produced from deep (greater than 15,000 feet) low permeability sands may also be termed unconventional, as may gas produced from geopressured (initial reservoir pressure exceeding 0.465 *psi/vertical foot of depth)* brines (greater than 10,000 *ppm* total dissolved solids). In comparison, conventional gas reservoirs contain gas molecules within interstitial pore-spaces, for example between sand grains in a sandstone reservoir, and in fractures. Gas trapped in a conventional reservoir generally is considered to have migrated from its place of genesis to a different geologic zone or horizon into the reservoir rock.

The ability of the coal bed methane reservoir to store methane is dependant upon numerous factors: reservoir pressure, composition and rank of the coal, micropores structure and its surface properties, the molecular properties of the adsorbed gas constituents, and reservoir temperature.

Coal beds are an attractive prospect for development because of their ability to
retain a higher amount of gas at shallow depths in comparison to conventional reservoirs at comparable depths and reservoir pressures. It has been estimated that during the formation of 1 *ton* of coal, gas is produced up to 46 *Mscf* Darton found that most mature coal contains between 20-100 *Mscf* of methane per *ton*.

Since methane gas is stored (adsorbed) on micropores of the coal, and storage is a function of pressure (the higher the pressure the greater the storage potential), production of gas is dependent upon reduction of pressure within the coal beds. Methane can be produced from the coal beds by reducing overall reservoir pressure or by reducing the partial pressure of the methane alone, while sustaining reservoir pressure. Pressure reduction frees the methane molecules from the coal and allows gas migration. A reduction of reservoir pressure is most often accomplished through formation water removal.

Water and gas separators used for conventional gas production were modified to accommodate copious amounts of produced water and associated coal fines. The produced water is often fresher (lower dissolved solids) than is characteristic of the relatively small amounts of produced water derived from conventional gas reservoirs. With hydrostatic pressure reduction at depth, methane gas is desorbed from the coal and is free to migrate through permeable strata, cleats and fractures to an area of lower pressure, ideally into the well bores that created the pressure reduction. In near-surface coal outcrops, hydrostatic pressure reduction may allow locally desorbed gas to migrate entrained with groundwater or rise vertically through porous soils to the surface.

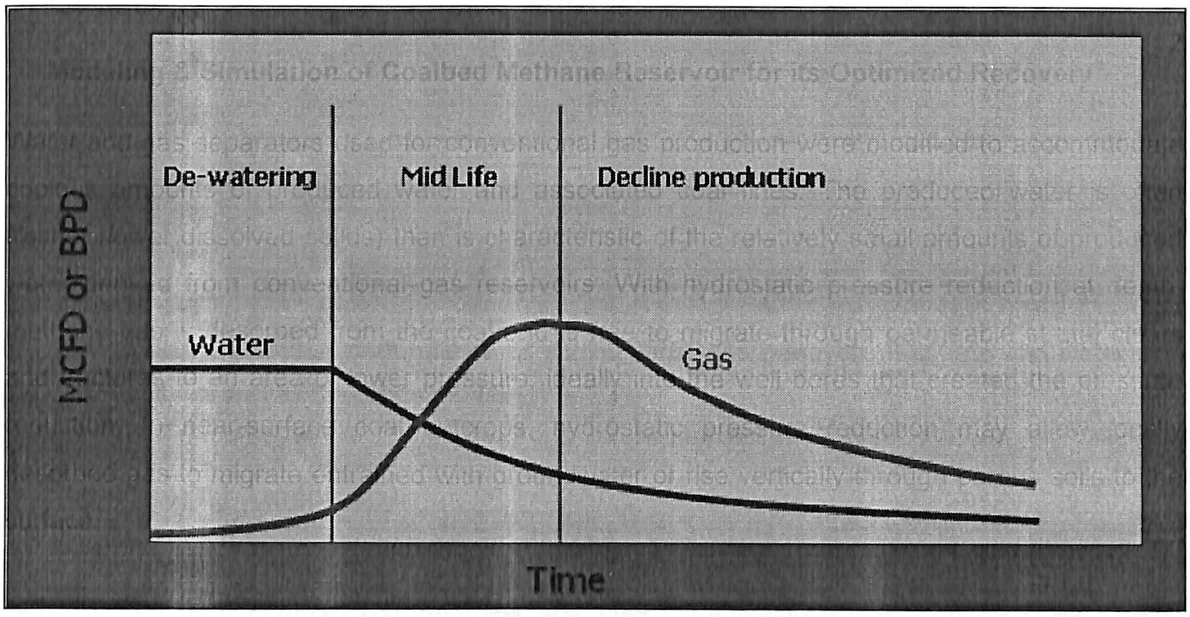

Fig. 1.1–Typical production performance of coal bed methane reservoir. First stage of production life is the dewatering stage, the second stage (mid-life) is the increasing of gas production rate (negative decline), and the third stage is the decline of gas production rate until the abandonment of production.

As coal bed water is withdrawn and formation pressure declines, the volume of gas produced tends to build from a low initial rate to a maximum rate several years after the onset of production (**Fig. 1.1**). The progressively increased gas production rate to a maximum flow years later is in direct contrast with conventional pressure-depletion reservoirs from which gas production rates tend to be greatest at the onset, then steadily decline over the life of the well (**Fig. 1.2**). While a reduction in reservoir pressure frees the methane from the coal, greatly reduced pressure may deprive the fluids of the energy needed to migrate efficiently to the well bore and enable desorption of increasing proportions of carbon dioxide. It is estimated that less than 50 percent of the coal bed methane in place can be economically recovered by reservoir pressure depletion strategy.

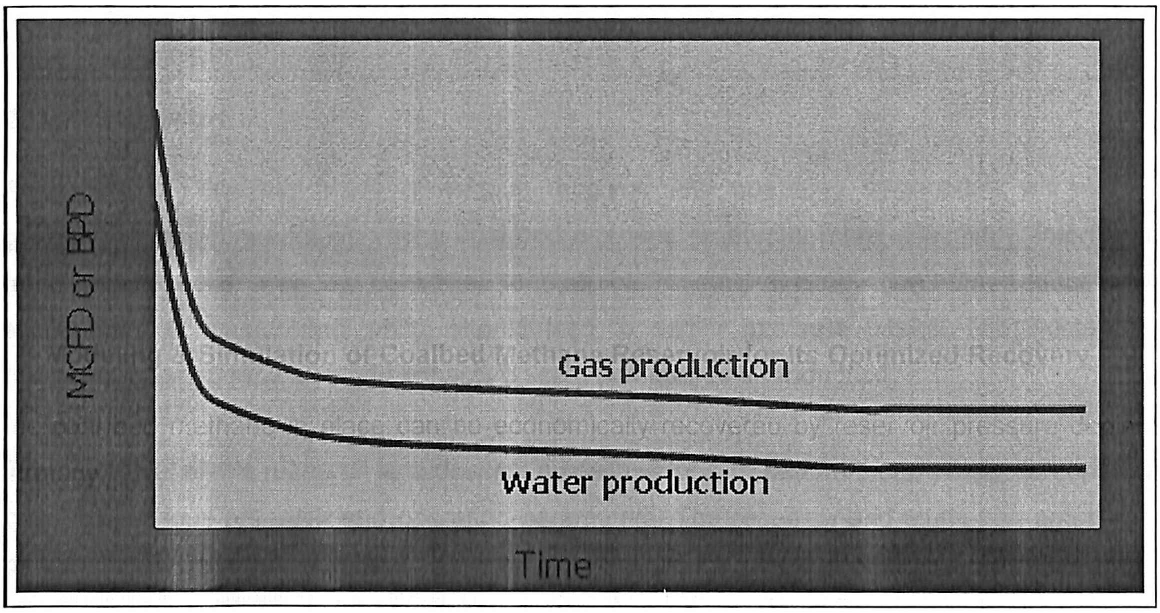

Fig. 1.2–Typical production performance of conventional gas reservoir. Gas rate and water rate decline directly as well as the production begins.

1.2 Permeability Anisotropy

Coal bed methane reservoir is considered as naturally fractured reservoir. Coal beds are characterized as a dual porosity reservoir, fractures (cleats) and matrix. The fractures (cleats) system is consisted of two major fractures system, the face cleat and butt cleat. The face cleat is long and continuous fractures throughout the coal seams and butt cleat is a short and discontinuous fractures perpendicular to the face cleat. The butt cleat is discontinuous because it is usually intersected by the face cleat. The face cleat has a larger contact area with the matrix compare to the butt cleat, therefore it is capable to drain larger area of coal seams and assumed as the maximum permeability direction. In some cases, this assumption may not be applicable (e.g. Bowen basin, Australia).

Coal matrix acts as the storage of gas but has very little permeability. As the pressure decreases, gas is desorbed from the surface of coal and diffuses into the fractures system. Once in the cleat system, gas will flow through the fractures into the wellbore. The fractures contribute to the formation permeability. The existence of face cleat and butt cleat develop permeability anisotropy.

This permeability anisotropy tends to create a preferential flow. In facts, the permeability has impacts on the coal bed methane production. One of the well known impacts is the drainage pattern shape.

1.3 Objectives

A systematic sensitivity study of various reservoir and operating parameters will result in generalized guidelines for operating coal bed methane reservoirs more effectively. Interference for adjacent wells may be beneficial to coal bed methane production. One effect is the acceleration of de-watering which should lead to earlier gas rate peaks. The existence of permeability anisotropy also has impacts on coal bed methane production.

The main goal of this research is to develop guidelines for coal bed methane production operation based on various reservoir and operating parameters. The research and study has emphasized on the following parameters: -

- **CBM Reservoir Modeling: -**

  This would include the following parameters as a part of the study.

  - Coals only or a mix of coals and sands;
  - Coal structure;
  - Porosity;
  - Permeability anisotropy;
  - Single or multi-component gas description (Methane, Carbon di-Oxide, Nitrogen);
  - Desorption characteristics;

- **Numerical simulation for coal bed methane recovery process: -**

  The two parameters that will form the foundation for numerical simulation will include:-

  - Multicomponent gas transport in in-situ bulk coal and
  - Changes of coal properties during methane production.

  The study will also include:-

  - Gas and water transport within coal matrix.
  - Factors influencing gas diffusion through coal matrix, such as pore structure, concentration and pressure, and water effects.

1.4 Organization of Project Work

The outline and organization of this project are as follows:

We begin this project report with the **INTRODUCTION, Chapter I**. It presents about the coal bed methane reservoirs, objectives, and organization of thesis.

Chapter II , presents the theories and fundamentals of coal bed methane reservoir engineering, coalbed methane modeling, and coalbed methane simulation.

Chapter III , presents the theory and background of modeling & simulation study.

Chapter IV discusses mathematical model and results from this project and research.

Chapter V , presents summary, conclusions, and limitations.

Finally, we present the nomenclature, reference, and some appendixes developed in this research.

CHAPTER II

RESERVOIR ENGINEERING AND MODELING OF COALBED METHANE RESERVOIR

2.1 Introduction

World demand on fossil energy, especially oil and gas, continuously increase. The ability of conventional oil to supply energy does no longer meet the demand. Therefore, the unconventional reservoir appears as an important player to supply the energy. Unconventional natural gas can be defined as gas produced from resources other than those historically exploited by the oil and gas industry17. Unconventional gas resources include tight gas formation, gas shales, coal bed methane, and geopressured aquifers.

Coal bed methane as the unconventional reservoir plays an important role on recently energy supply. Effective Development of coal bed methane reservoir needs a better understanding of coal bed methane reservoir. In order to deeply understand the behavior and performance of coal bed methane reservoir, the knowledge of coalbed methane reservoir engineering is the key points. Reservoir engineering of coalbed methane includes the phenomena and physical parameters of coal bed methane. This Chapter presents the fundamentals of coal bed methane reservoir and reservoir modeling of coal bed methane reservoir.

2.2 Reservoir Engineering of Coalbed Methane

2.2.1 Coalbed Methane Reservoir

Reservoir characteristic of coalbed methane is quite complicated. Coalbeds are naturally fractured and low pressure systems with gas adsorbed into the coal matrix. Coalbeds are characterized as a dual porosity reservoir, fractures (cleats) and matrix. The fractures (cleats) system is consisted of two major fractures system, the face cleat and butt cleat. The face cleat is long and continuous fractures throughout the coal seams and butt cleat is a short and discontinuous fractures perpendicular to the face cleat. The butt cleat is discontinuous because it is usually intersected by the face cleat. The matrix system is the part of the formation that exists between the fractures system. The face cleat has larger contact area with the matrix compare to the butt cleats, therefore it is capable to drain larger area of coal seams. The face cleats provide the main pathways for gas to flow into the wellbore (see **Fig. 2.1**).

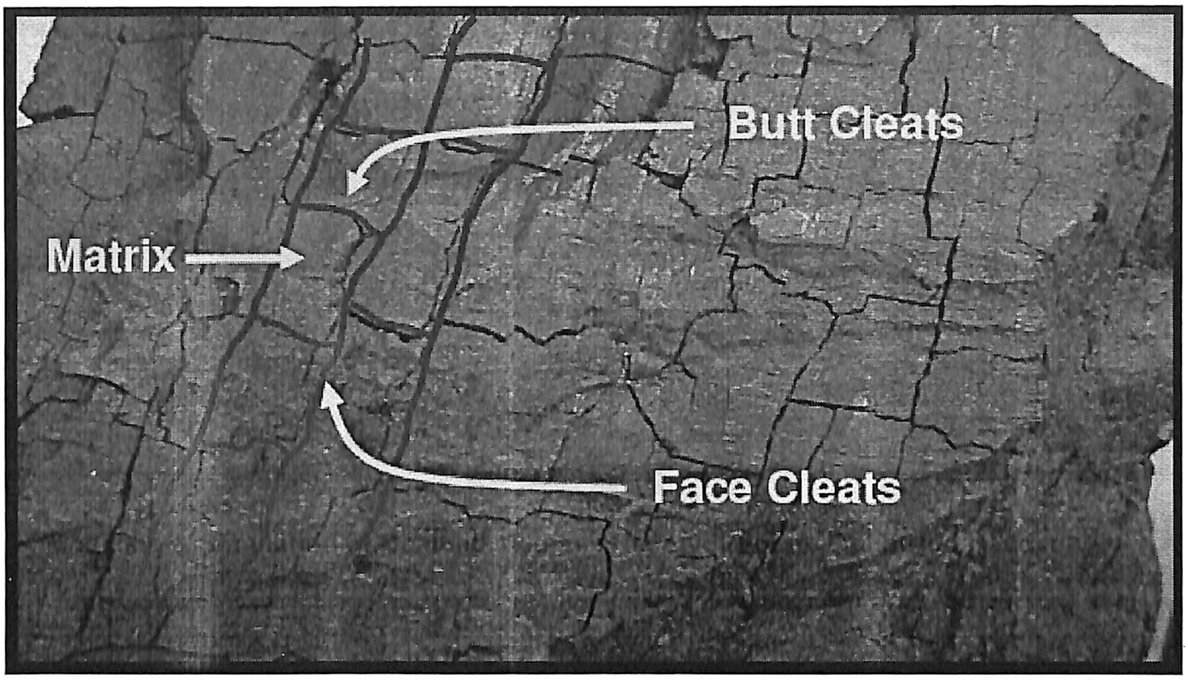

Fig. 2.1–Schematic of coal-seam cleat system. The red lines show the face cleats and butt cleat on a piece of coal. Face cleats are long and continues while butt cleats are short and discontinues (intersected by face cleats).

At the original conditions of reservoir, most of gas is stored in the matrix with a very little gas in the fractures, negligible. Fractures system is saturated with water. Gas is stored in the matrix in adsorption condition rather than stored as a free gas like in the conventional gas reservoirs. The majority of gas is adsorbed on the internal surface of the micropores of coal matrix.

Primary production of coalbed methane occurs by initially de-watering the naturally fractured system and hence reducing the pressure in the fracture system. The reduced pressure causes the desorption of gas from the surface of coal matrix and release of gas to the fractures. Gas diffuses from the surface of coal matrix towards the fracture system. Once in the fractures, gas flows throughout the fractures into the wellbore. The degasification of coalbed methane is consisted of three major processes:

1. Desorption process, the release of gas from the internal surface of micropores of the coal matrix.

2. Diffusion process, the desorbed gas flows throughout the coal matrix into the fractures system.

3. Gas flows throughout the fractures (cleats) into the wellbore.

(See Fig. 2.2)

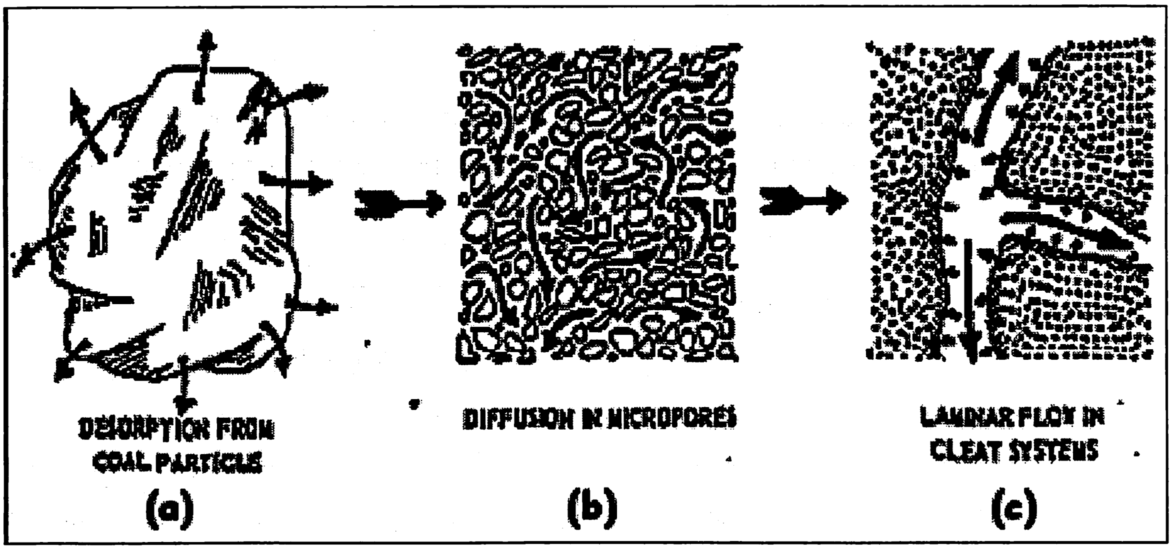

Fig. 2.2–Schematic of methane flow dynamics in coal-seam (After Remner *et.al*8). (a) Desorption process, the release of gas from the internal surface of micropores of the coal matrix. (b) Diffusion process, the desorbed gas flows throughout the coal matrix into the fractures system. (c) Gas flows throughout the fractures (cleats) into the wellbore.

2.2.2 Coal Porosity

Coal is both the source rock and reservoir rock for a coalbed methane well. Methane is stored in the same place where it is formed. As with conventional reservoirs, some barrier must be in place to prevent the gas from migrating out of the reservoir rock. Coal is solid substance separated by fractures or cleats. Like conventional reservoirs, some gas is stored in the space between the solid particles. However, the interstitial pore space represents a small portion of the overall available storage space within coal. Most of the gas is stored within the microscopic structure of the coal itself. The microscopic structure of coal creates a complex, intricate maze, providing a tremendous amount of surface area upon which the methane can attach.

Coal bed methane comprises three majors porosity:

1. Fractures, the face cleats and the butt cleats. It provides the path flow of gas from the coal matrix to the wellbore. At original reservoir condition, Fracture is almost a hundred percent saturated with water.

2. Macropores, interstitial pore spaces within the coal matrix that store the methane gas in the coalbed methane reservoir as a free gas. It is assumed as the porosity of the coal matrix.

3. Micropores, pore spaces within the coal matrix with very small size in diameter. Micropores store the methane gas in the coal bed methane reservoir as an adsorbed gas. These micropores are not considered as the porosity because of its very small size, but assumed as the internal surface area of coal matrix.

2.2.3 Gas Storage Properties

Coal is considered as a porous medium (reservoir rocks) because of its ability to store and flow the methane. However it has a remarkable difference from other conventional reservoirs in that the volume of gas, which it can store, is high beyond its pore volume capacity. In fact, the methane stored in coal reservoir is mainly adsorbed onto the internal micropores surface. Due to the very small size of individual micropores, typically $5 \times 10^{-10} - 10 \times 10^{-10}$ *m* in diameter, the internal micropores surface in coal can be very large. For some coals, the internal micropores surface area may reach several hundreds m^2 per gram of solid, thus making available large amount of surface adsorbing gas. Some authors concluded that the surface area of coals is mostly in the range of 2150 – 3150 ft^2/g. This also means that if 18 gram of coal is crushed its surface area can be a large as a 360 *ft* X 160 *ft* football field. This is illustrated in **Fig. 2.3**.

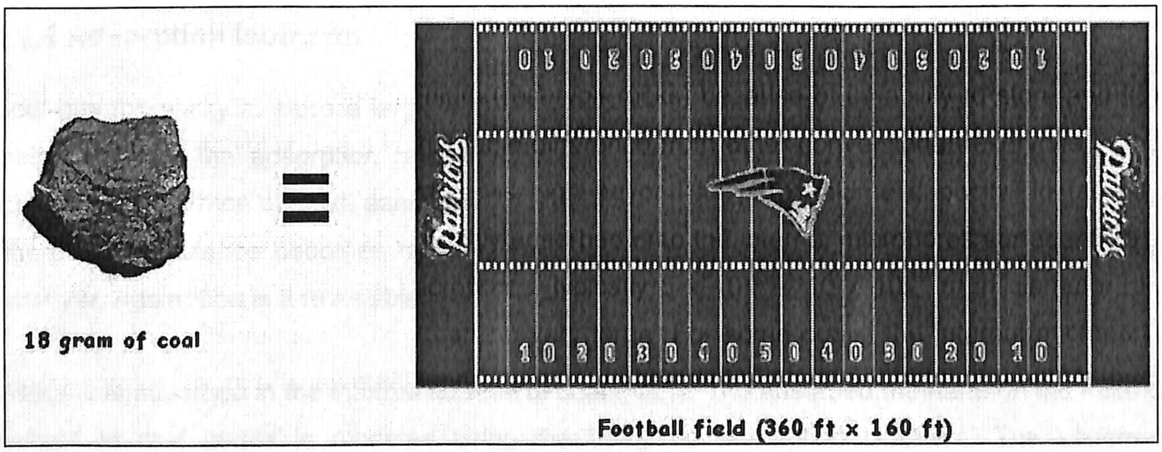

Fig. 2.3–Illustration of the large internal surface area possessed by coal particles. 18 gram of coal has internal surface are equals to a football field.

For a given coal, the amount of gas adsorbed in the surface of coal matrix is a function of the pressure within the pore volume only. The amount of adsorbed as is limited by the available free pore surface. The relationship of the amount (concentration) of adsorbed gas and pressure at a given temperature is well known as the Langmuir adsorption isotherm curve and is fundamental reservoir property of coal seam.

If we lower the coal seam pressure, gas will be released from the coal matrix until a new equilibrium condition between the new pressure and adsorbed gas is reached. The time required for the coal to reach a new equilibrium condition depends on the diffusion properties of coal. Reducing the pressure until zero absolute (0 *psia*) will cause the coal releasing all of the adsorbed gas.

For reservoir modeling purposes, the total amount of gas stored in the coal bed methane reservoir comprises the following category.

- Free gas, stored in the pore spaces follows normal gas law. The amount of this free gas can be calculated if the porosity and pressure are known. Free gas is very small compared to the adsorbed gas.
- Adsorbed gas, stored in the internal surface area of micropores by surface attraction forces. The relationship of the amount (concentration) of adsorbed gas and pressure at a given temperature is described by Langmuir Isotherm Curve. Adsorbed gas contributes most of the gas in the coal bed methane reservoir.

2.2.4 Adsorption Isotherm

Coal has the ability to store a large amount of gas. Methane (gas) is adsorbed in the coal bed methane under the adsorption mechanism. Adsorption can be described by imagining dust attached to a surface of solid, sand attached to surface of solid. This is different from absorption where one substance becomes trapped inside another, such as a sponge soaking up water. However, Adsorption is a reversible process because that involves weak attraction forces.

Methane is adsorbed in the internal surface of coal matrix. The adsorbed methane on the internal surface of coal matrix is modeled using the Langmuir adsorption isotherm. The Langmuir adsorption isotherm assumes that the gas attaches to the surface of the coal and covers the surface as a single layer of gas (monolayer). Nearly all of the gas stored by adsorption coal exists in a condensed, near liquid state. The following equation is the Langmuir equation that describes the amount of gas stored on the surface of coal matrix as a function of pressure:

$$C(p) = V_L * p / (p + p_L) \qquad (2.1)$$

Langmuir isotherm equation assumes that the concentration of methane adsorbed on the surface of coal matrix is a function of pressure only.

In the **Eqn. 2.1**, *C(p)* is the amount of adsorbed gas in *scf/ft*^{3}, V_L is the Langmuir volume constant in *scf/ft*^{3}, p_L is Langmuir pressure in *psia*, and *p* is instantaneous pressure in *psia*.

The Langmuir isotherm equation has 2 parameters:

Langmuir volume (*V_L*): is the maximum amount of methane adsorbed on the surface of the coal matrix when the pressure, *p*, reaches infinity. This value is asymptotically approached by the isotherm as the pressure increases. The following figure (**Fig. 2.4**) is of a typical isotherm and shows its relationship with V_L.

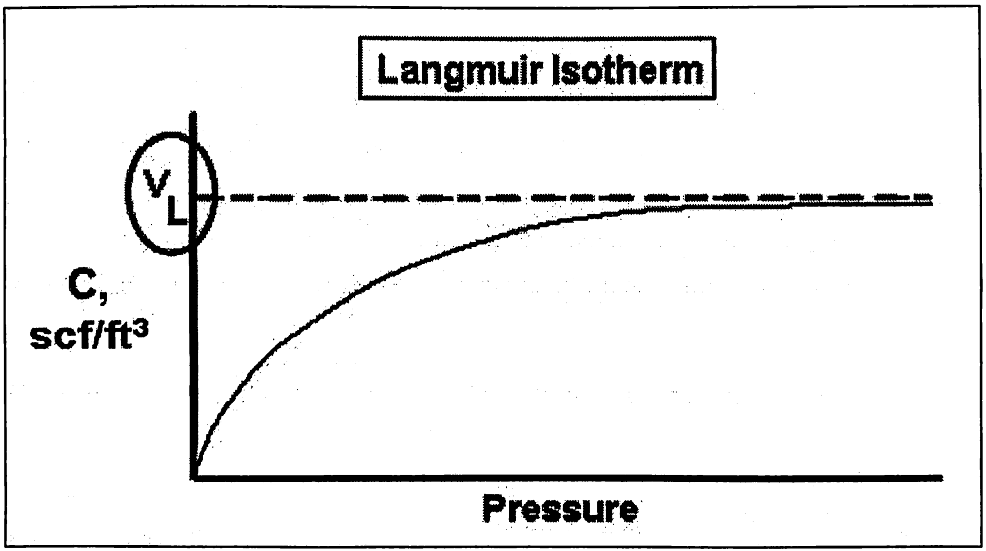

Fig. 2.4–Description of Langmuir volume (*VL*) on a typical Langmuir adsorption-desorption isotherm curve. The figure shows that *VL* is the maximum volume of adsorbed gas (methane).

Langmuir pressure (*P_L*): is the pressure where the amount of adsorbed methane is one half of its maximum amount, V_L, i.e. when $p = p_L$, $C = 0.5\ V_L$. This is illustrated in **Fig. 2.5**.

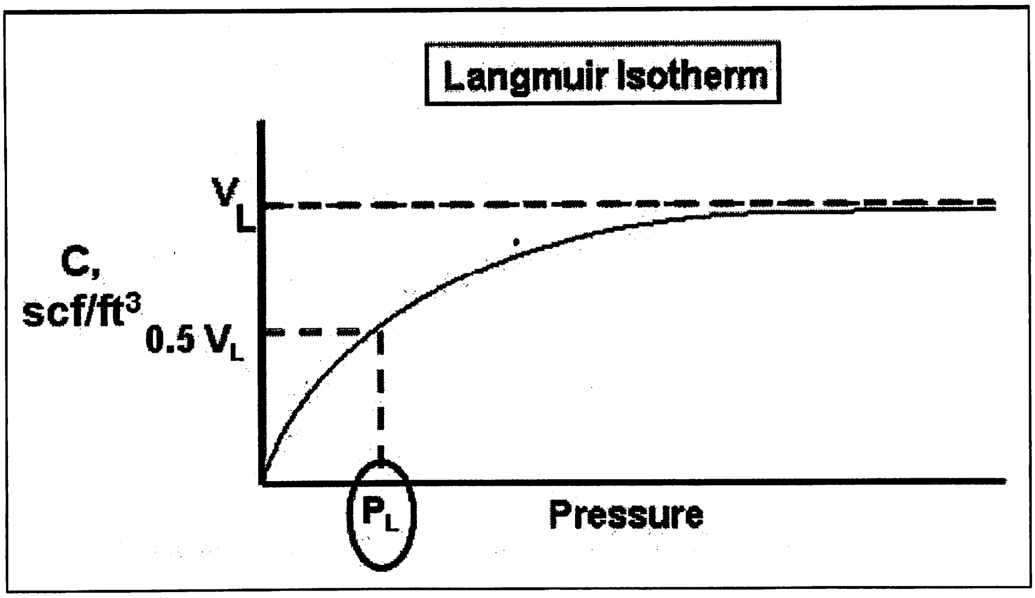

Fig. 2.5–Description of Langmuir pressure (p_L) on a typical Langmuir adsorption-desorption isotherm curve. The figure shows that pL is the presuure where the volume of the adsorbed gas is one half V_L.

Fig. 2.6 shows how Langmuir pressure, p_L, affects the shape of Langmuir isotherm curve. The higher the *pL* is the lower the curve is. However, eventually all of the curves will coincide at the same V_L.

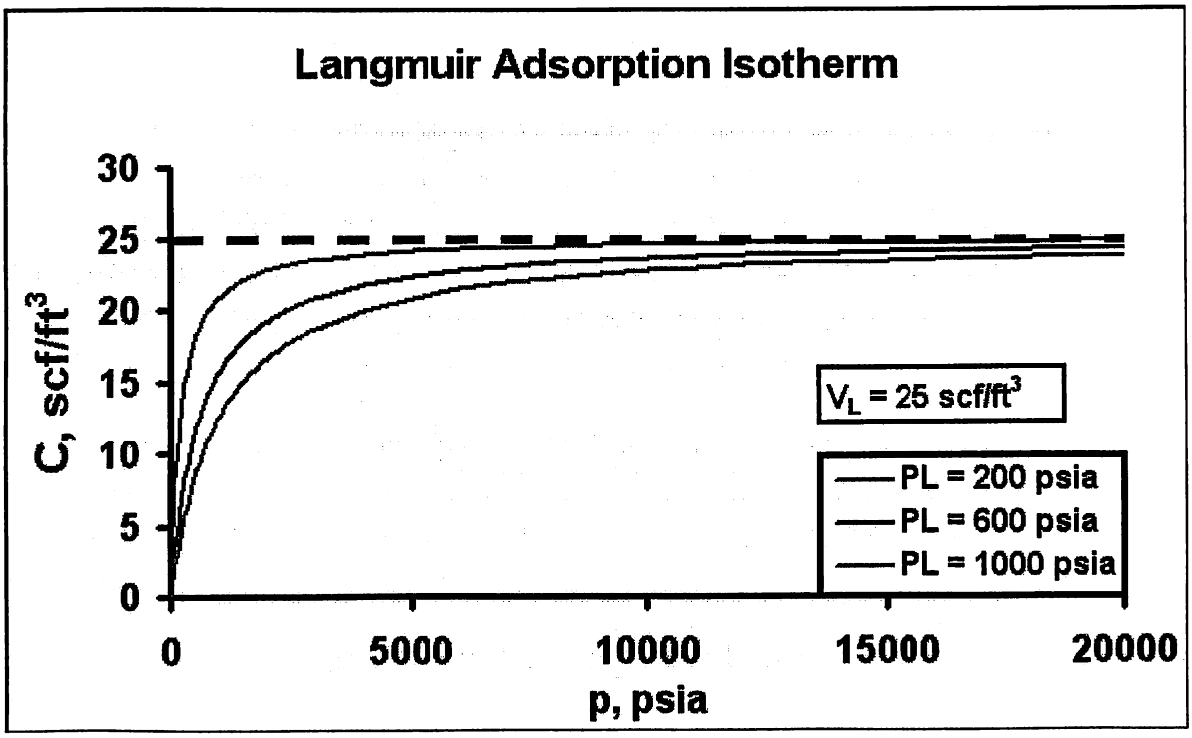

Fig. 2.6–Effect of Langmuir pressure (p_L) on Langmuir isotherm curve. The higher the p_L is the lower the curve is. However, eventually all of the curves will coincide at the same V_L.

The amount of adsorbed gas, (*C(p)*) mentioned in **Eqn. 3.1**, also can be stated in *scf/ton*. **Eqn. 3.2** determines the amount of adsorbed gas in *scf/ton*.

$$V = [Vm * (bP)] / (1 + bP) \qquad (2.2)$$

and

$$b = (1/P_L) \qquad (2.3)$$

Where *Vm* is the Langmuir isotherm constant in *scf/ton*, *b* is the Langmuir pressure constant constant in *psia-1*, and p is instantaneous pressure in *psia*. V_L is related to the *Vm* with the following equation:

$$V = 0.031214 V_L \, \rho_M \qquad (2.4)$$

Where ρ_B is bulk density of coal deposit in ***gram/cm***^{3}.

2.2.5 Methane Flow Properties of Coal

The ability of coalbed methane reservoir to transport the methane is measured by flow properties such as diffusivity and permeability. In the very small pores, such as micropores, gas is released from the internal micropores surface (desorption). The released gas is transported very slowly through the coal matrix into the fractures (cleats) with gradient of concentration as the driving force. In the fractures (cleats), gas released from the coal matrix flows throughout the fractures system into the wellbore with gradient of pressure as the driving force.

2.2.5.1 Gas Diffusion in Coalbed Methane Reservoir

Throughout the very small micropores in the coal matrix, the desorbed gas will flow in the diffusion state rather than flowing following Darcy's Law. The desorbed gas could not flow freely following Darcy's Law due to the very high drag force in the pathways of size micropores. This diffusion process is described using the Fick's Law:

$$Q_{gas} = -DA\,(dC/dL) \qquad (2.5)$$

where *D* **is the diffusion constant in** ***ft^2/day*** and ***A*** **is the surface area of matrix element,** ***ft^2***.

We can see that the driving force for the diffusion process is the gradient of concentration rather than gradient of pressure in Darcy's Law. However, the concentration of gas is a function of pressure as described by ***Langmuir Isotherm Theory.***

2.2.5.2 Gas Flow in Coalbed Methane Reservoir

The desorbed gas from the coal matrix system, gas flows throughout the fractures into the wellbore. The flow of gas throughout the fractures system is governed by Darcy's Law.

The following equation describes the Darcy's Law:

$$q = -\,(kA/\mu)(dP/dL) \qquad (2.6)$$

We can see clearly that the driving force for the flow of gas throughout the fractures system is the pressure gradient.

2.2.6 Permeability

Coal is a naturally fractured formation. It consists of fractures (face cleats and butt cleats) and the matrix. Most of the gas is stored inside the matrix system (on the surface of micropores). Gas is desorbed from the surface of matrix and flows throughout the matrix into the fractures by diffusion.

Fractures, initially, is saturated with water. Producing gas from coal bed methane reservoir is associated with dewatering the fractures. Dewatering the fractures decreases the reservoir pressure, therefore initiates gas to desorb from the surface of micropores. Gas diffuses throughout the coal matrix in to the fracture.

Fractures provide the pathway for water and gas to flow into the wellbore. Flow of fluids (water and gas) in the fractures follows the Darcy's Law. For CBM reservoir, permeability refers to the permeability of fractures system, not the permeability of the matrix system.

2.2.7 Saturation

Coal is a naturally fractured formation. It consists of fractures (face cleats and butt cleats) and the matrix. Fractures are almost a hundred percent saturated with water. The matrix consists of macropores and micropores. Macropores stores the gas as free gas, whereas micropores store the gas by adsorption.

For CBM production, saturation (*Sw* or *Sg*) refers to the saturation of the cleats and macropores, not the micropores in the matrix.

2.2.8 Effects of Cleat Compression and Matrix Shrinkage on Coalbed Methane Reservoir

Several authors have been reported from the laboratory experiments and field data that coal matrix shrinkage and the resulting change in cleat (fracture) system porosity can have a profound effect on the formation permeability and thus on production performance.

In the naturally fracture formation such as coal bed methane reservoir, the permeability is critically sensitive to changes in effective stress (pore pressure). During the drawdown, the desorption of methane from the coal matrix leads to matrix shrinkage. This matrix shrinkage has an impact to the formation permeability.

The following phenomena have been explained by Palmer and Mansoori that:

1. During drawdown of a reservoir by primary production, effective stress increases and permeability decreases due to cleats compression.

2. However, in coalbeds, drawdown leads to desorption of methane, and this is accompanied by matrix shrinkage which opens the cleats and leads to permeability increase.

2.2.8.1 Cleats Compression

As the reservoir pressure decreases, the overburden compresses the cleats thereby reducing the permeability. A schematic of this phenomenon is shown in the following figure (**Fig. 2.7**).

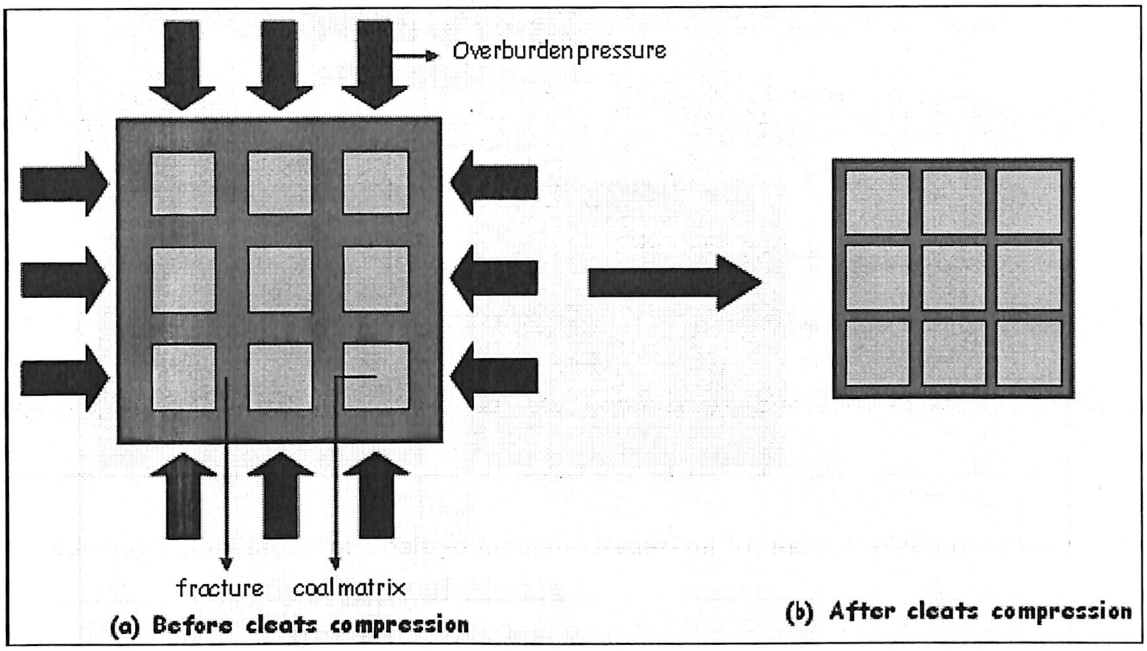

Fig. 2.7–Schematic of cleats compression phenomenon. (a) schematic of coal seam before cleats compression and (b) schematic of coal seam after cleats compression.

2.2.8.2 Matrix Shrinkage

Coal matrix adsorbs gas on the surface of micropores. The desorption of gas from the coal matrix leads to decrease the pressure exerted by the gas in these pores. This causes the volume of the coal matrix to reduce in size. A reduction in the matrix size simultaneously acts to widen the cleats thereby increasing permeability. This is illustrated in **Fig. 2.8**.

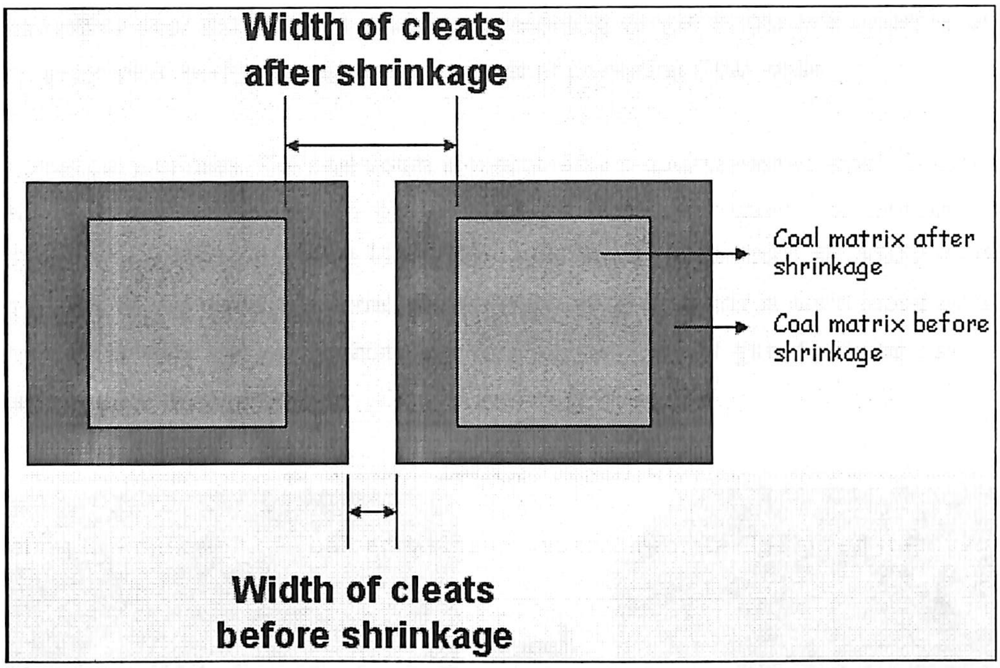

Fig.2.8–Schematic of matrix shrinkage phenomenon. The increasing of width of cleats is caused by the matrix shrinkage.

2.3 Reservoir Modeling of Coalbed Methane Reservoir

The easiest way to describe a coal bed methane reservoir is to think of a conventional reservoir in a dual-porosity mode. Usually a conventional dual-porosity simulator is used to model a system such as a fractured carbonate reservoir where there is a low permeability matrix coupled to a high-permeability fracture network. Each system has its own unique permeability and porosity, and a matrix/fracture transfer term governs the fluid flow from the matrix into the fractures.

In a CBM model, the fracture network represents the coal cleats. However, the matrix portion of the system has no effective permeability and porosity and is used only as a gas source with gas release controlled by a gas concentration vs. pressure relationship supplied as input data. While it is common to refer to CBM models as dual porosity models, they are really only single-porosity models with a pressure-dependent source term coupled to the reservoir.

If the system modeled is entirely coal, the simulation approach is straightforward. Coal properties must be supplied as input data as well as system permeability, porosity, initial pressure, and initial fluid saturations. As water is removed from the cleat system, the reservoir pressure declines, gas is desorbed from the coal into the cleats, and gas production begins. This approach has been used successfully over the years in models representing simple single-well systems as well as larger, more-complex models containing thousands of producing CBM wells.

For mathematical purposes, the coal-seam is modeled by a dual porosity model. The well known dual porosity model was proposed by Warren and Root and Kazemi to simulate naturally fractured reservoirs. **Fig. 2.9** shows idealization coal seam model from an actual model to an idealized model. In the idealized model, a systematic array of matrix is surrounded by fractures. The matrix has a very low permeability but very high storage of gas, fractures has very high permeability but low storage of gas.

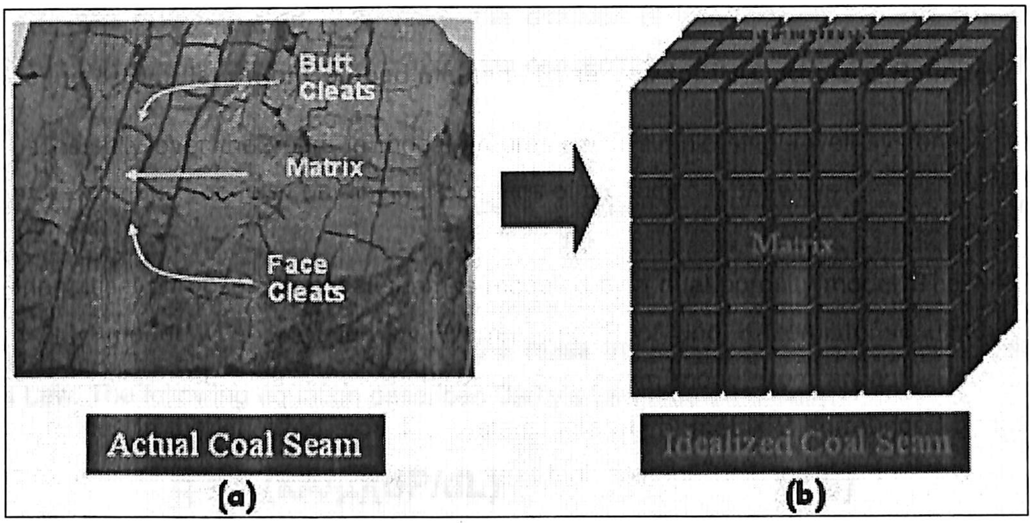

Fig. 2.9–Idealization coal seam model from an actual model to an idealized model (dual porosity modeling). (a) actual coal seam model and (b) idealized coal seam model.

Matrix system has very high storage ability compare to fractures system. Matrix system of coal seam has very large surface area. Darton4 found that most mature coal contains between 20 and 100 *scf* {0,566 and 2.832 *std.* m^3) of methane per ton. Gas is stored in the matrix as an adsorbed gas. The amount of gas stored in matrix is dependent to the reservoir pressure. The amount of gas (concentration of gas) as the function of pressure is described by Langmuir isotherm equation as follows:

$$C(p) = V_L * p / (p + p_L) \qquad (2.1)$$

As mentioned earlier, the coal matrix has very low permeability but it has very large surface area. Because coal matrix has very-very low permeability, mass transport through the matrix system is in diffusion state. Gas diffuses throughout the matrix rather than flows. The diffusion of gas through the matrix is described using the following equations:

$$Q_{gas}(P) = \text{Coef}\ (\bar{C} - C(P)) \qquad (2.7)$$

where

$$\text{Coef} = D\ (aN)\ N_e \qquad (2.8)$$

D is the diffusion constant in *ft²/day*, a shape factor in *ft⁻¹*, A is the surface area of a matrix *ft²*, and N_e is the number of matrix elements within a grid block.

As we can see from the **Eqn. 2.7** above, the diffusion of gas through the matrix system is proportional to the difference of the average gas concentration in the coal matrix, C and the gas at matrix-fracture (cleat) interface, $C(p)$.

$\bar{C}$ is calculated using the basic material balance. $C(p)$ is calculated from the Langmuir adsorption isotherm equation.

Once gas arrives in the fractures (cleats), the mass transport of gas is described using the Darcy's Law. The following equation describes Darcy's Law mathematically:

$$q = -(kA/\mu)(dP/dL) \qquad (2.6)$$

CHAPTER III

THEORY AND BACKGROUND OF MODELING & SIMULATION STUDY

3.1 INTRODUCTION

Coalbeds are naturally fractured, low pressure, water saturated gas reservoirs. While some free gas may exist in a coal deposit, the majority of the gas is sorbed on the surface of the coal matrix. When water is removed from the natural fractures of the coal, the pressure is reduced and gas is released from the matrix into the fractures. Once in the fractures, the gas flows to the wellbore. Thus coal degasification is a two-step process: desorption of gas from the coal matrix followed by flow through the fractures.

The slower of these two processes will control the rate of gas production from a coal. For engineering purposes, gas production can be approximated by mathematics which focuses on the dominant process. If the rata of gas desorption from the matrix is very slow compared to the rate of fluid transport in the fractures, diffusion equations need to be incorporated into a conventional simulator to describe gas production. If the release of gas from the matrix is very rapid compared to the time scale of fluid flow in cleats, gas production can be modeled by Darcy's Law only.

3.2 LANGMUIR ISOTHERM, APPARENT SORPTION COMPRESSIBILITY, AND PSUEDO-STEADYSTATE (COMPARISON WITH BLACK OIL MODEL)

The characteristic time for the flow of gas through the cleats, is the time required for a well to reach pseudo-steady state. Pseudo-steady state flow begins when the non-dimensional time is 0.1. for a gas well centered in a circular or square drainage area, the time to reach pseudo-steady state is given by:

$$(2.637\ (10)^{-4}\ k_g\ t)\ /\ (\phi\ (\mu_g\ C_t)_i\ A) = 0.1 \qquad (3.1)$$

where k_g **= effective gas permeability in md, t is time in hours,** ϕ **is cleat porosity in fraction, A is drainage area in** $ft^{2,}$ μ_g **is gas viscosity in cp,** C_t **is system compressibility in** psi^{-1}. Both gas viscosity and system compressibility are calculated at initial conditions. System compressibility is given by:

$$C_t = C_f + S_w C_w + S_g C_g + C_s \qquad (3.2)$$

where C_f **is cleat volume compressibility,** S_w **and** C_w **are the water saturations and compressibility respectively,** S_g **and** C_g **are the gas saturation and compressibility and** C_g **is the apparent sorption compressibility.**

The apparent sorption compressibility can be expressed as:-

$$C_s = (1.7525*10^{-4}\, B_g\, V_m\, \rho_B\, b) / [\phi(1+bp)^2] \qquad (3.3)$$

where **B is the gas formation volume factor in RB / MCF.**

Adsorption of gas on the coal surface increases system compressibility. The amount of gas stored on the coal is often described by Langmuir equation:

$$C = V_L\, (p/p + p_L) \qquad (2.1)$$

Because the amount of gas sorbed depends on the mass of coal, not on the volume, a more useful form of the Langmuir equation is :

$$V = V_m\, [bp / (1+bp)] \qquad (2.2)$$

3.2.1 Flow in Micropore System

The equilibrium value of gas physically adsorbed in the micropore structure of the coal matrix is described by Langmuir Isotherm, which is,

$$V_E = (V_L\, Pg) / (P_L + P_g) \qquad (3.4)$$

where

V_L = Langmuir Volume Constant, scf/ton
P_L = Langmuir Pressure Constant, psia
P_g = Macropore Gas Pressure, psia
V_E = equilibrium Sorption isotherm, scf/cuft

The gas in micropore close to fracture is in equilibrium with free gas, to account for the adsorbed gas in the micropores, a first order kinetic model (quasisteady state model) has been used.

$$dV_i / dt = (1/\tau)\,[VE\,(P_{ag}) - Vi] \qquad (3.5)$$

$$Q_{des} = -\,F_G\, dV_i / dt \qquad (3.6)$$

where
F_G = dimensionless geometry dependent pre-factor dependent on the shape of the matrix elements. F_G = 6, treating micropore elements as spheres.
τ = quasi – steady state time constant
$V_i = V_E\,(P_{lag})$

From eqn. (3.5), assuming that the gas in equilibrium is a constant during the timestep (evaluated at automatic average), we can integrate eqn. (3.5), over the time interval n to n+1, to get,

$$V_E^{n+1/2} - V_i^{n+1} / V_E^{n+1/2} - V_i^{n} = \exp[-\Delta t / \tau] \qquad (3.7)$$

Therefore, the average desorption rate is given by

$$Q_{des} = -\,F_G\,(V_i^{n+1} - V_i^{n}) / \Delta t \qquad (3.8)$$

From above equations

$$Q_{des} = (-\,F_G / \Delta t)\,\{V_{in}\,\{\exp(-\Delta t / \tau)^{-1}\} + \{(V_E^{n+1} + V_E^{n})/2\} * \{1 - \exp\{-\Delta t / \tau\}\}\} \qquad (3.9)$$

3.3 PHYSICAL AND MATHEMATICAL MODEL

3.3.1 Assumptions

To simply the mathematics of fluid transport in coalbed reservoir and be convenient to solve it, the following assumptions were made:

- The coalbed contains two-phase, gas and water.
- Porosity in coal micropore and macropore system is unchanged with pressure.
- The temperature remains constant.
- Fractures are uniformly distributed.
- Gas volume desorbed from the coal surface is estimated from available Sorption isotherm.
- Gas transport through coal matrix system is a diffusion process, while gas and water flow to the wellbore via the cleat network obey Darcy's law.
- Gas is not soluble in water.

3.3.2 Physical Model

The differential equations describing two-phase flow in the coal macropore system are based on the conventional combination of Darcy's law for each phase and phase continuity equations. The following equations for gas phase (referenced by a subscript g) and water (referenced by a subscript w) are presented:

Gas equation (Refer Appendix A)

$$\nabla[(\rho_g\, k\, k_{rg}/\mu_g)\,(\nabla p_{gf} - \rho_g\, g\, \nabla D)] - q_{gf} + q_{gmf} = (\partial/\partial t)\,(\phi_g\, \rho_g\, S_{gf}) \qquad (3.10)$$

Water equation

$$\nabla[(\rho_w\, k\, k_{rw}/\mu_w)\,(\nabla p_{wf} - \rho_w\, g\, \nabla D)] - q_{wf} + q_{wmf} = (\partial/\partial t)\,(\phi_w\, \rho_w\, S_{wf}) \qquad (3.11)$$

Drainage wells are treated as effective sinks or source. In regions of the coal seam without wells the gas and water phase volumetric source term: q_{gf} and q_{wf} are zero. The corresponding gas and water phase term, q_{gmf} and q_{wmf}, represents gas and water volume per unit volume per unit time from the coal micropores which enters the macropore system.

In the above equations there are six unknowns (P_{gf}, P_{wf}, S_g, S_w, q_{gmf} and q_{wmf}). if wells produce gas and water at constant well bottomhole pressures, there are extra two unknowns (q_{gf} and q_{wf}). In order to complete the set of equations and render the problem well-defined, four or six more equations are needed. Two of these are provided by macropore auxiliary relationships which are capillary pressure and phase saturation. They are:

$$P_{cgwf}(S_g) = p_{gf} - p_{wf} \qquad (3.12)$$

And

$$S_{gf} + S_{wf} = 1 \qquad (3.13)$$

The saturation must also satisfy the following relations:

$$S_{gcf} <= S_{gf} <= 1-S_{wcf} \qquad (3.14)$$

$$S_{wcf} <= S_{wf} <= 1-S_{gcf} \qquad (3.15)$$

The other additional equations are a set of formulation which expresses gas and water volume from micropores in the coal matrix which enters the macropore system and/or the gas and water flow rate in fractures. They are described below in detail.

3.3.3 Gas Exchange between the Coal Macropores and Micropores (Refer Appendix B)

Gas transport in coal seams with generally low-permeability is described by two different mechanisms. In this kind of multi-mechanism approach gas transport through macropores is described by laminar flow which is directly proportional pressure gradient and obeys Darcy's law whereas the coal matrix diameter as the same order as magnitude with free path of gas molecule is so small that gas transport through micropores is dominated by diffusional flow which is directly proportional to concentration gradient.

The mass of gas desorbed from the coal surface which enters the micropore system is looked upon as the gas mass inflow across the control volume surface whereas the mass of gas transport from the coal micropores which enters the macropore system, i.e. gas exchange between the coal macropores and micropores, is regarded as the gas mass outflow across the control volume surface. The difference between inflow and outflow must be equal to the sum of accumulation of free gas mass within the control volume in the coal micropores. Based on the above views, we now have

$$q_{gmf} = [\bar{\rho}_g (p_m) \{C (p_{m0}) - C (p_m)\} / \Delta t_0] + [p_m \phi_m S_{gm} (p_m) M / Z (p_m) RT\Delta t_0] - [p_{m0} V_b \phi_m S_{gm} (p_{m0}) M / Z (p_{mo}) RT\Delta t_0] \qquad (3.16)$$

3.3.4 Water Exchange between the Coal Macropores and Micropores

Water mass exchange between the coal macropores and micropores is distinctly different from gas mass exchange. It is similar to water exchange between the fracture and matrix system in conventional dual medium reservoirs. Formulation of the water mass exchange between the coal macropores and micropores per unit volume is described as following.

$$q_{wmf} = \delta (\rho_w k_m k_{mrw}/\mu_w) (p_{wm} - p_{wf}) \qquad (3.17)$$

where

$$\delta = 4(1/Lx^2) \qquad (3.18)$$

3.3.5 The Gas and Water Flow Rate in the Coal Macropores

The Gas-Water flow in the coal macropores obeys the Darcy' Law, the equations of gas and water flow rate are

$$q_{lf} = \sum_k wfrac_k \left[\{(2\Pi k\, k_{rl}\, h / \mu_1)_k\, (p_{1,k} - p_{bh})\} / \{\ln (r_e/r_w) - .75 + s\}\right] \qquad (3.19)$$

where

$$r_e = 0.208\, \Delta x$$

3.3.6 The Gas Saturation and Pressure in the Coal Micropores

The gas saturation S_{gm} and P_m are variable parameters which can be obtained by solving the equations given below. The formulation is the mass conversation equation in the coal micropores.

$$q_{gmf} = \partial(\rho_g\, \phi_m\, S_{gm}) / \partial t \qquad (3.20)$$

$$q_{wmf} = - \partial(\rho_w\, \phi_m\, S_{gm}) / \partial t \qquad (3.21)$$

CHAPTER IV

MATHEMATICAL MODEL AND RESULTS

4.1 MATHEMATICAL MODEL

The model developed in this study is for a one-dimensional, two-phase (gas-water) flow coalbed-methane (CBM) numerical reservoir simulator. The grid systems used in this model is a block-distributed system.

We Substituted Eqns. 3.16, 3.17,and 3.19 into Eq.3.10 and Eq.3.11, then multiplied both sides by Δx_i, Now the finite-difference approximations to Eqs.1 and 2 by the discreting method and have the form

(Refer Appendix C)

$$T^{n}_{lxi+1/2}\,\varphi^{n+1}_{lfi+1} + T^{n}_{lxi-1/2,j,k}\,\varphi^{n+1}_{lfi-1,j,k} - (T^{n}_{lxi+1/2,j,k} + T^{n}_{lxi-1/2,j,k})\,\varphi^{n+1}_{lfi} - Q^{n}_{lf} + Q^{n+1}_{lmf} = \alpha_1\{(\varphi^{n+1}_{lfi} - \varphi^{n1}_{lfi}) / \Delta t_n\} + \phi_f\rho_g\{(S^{n+1}_{lfi} - S^{n1}_{lfi}) / \Delta t_n\} \quad (4.1)$$

where

$\alpha = \rho_1\,\phi_1\,S^{n+1}_{li}\,(c_f+c_1)$

$T^{n}_{lxi} = 2(\rho_1 k k_{rl}/\mu_1)^{n+1}{}_{i}{}^{+}{}_{-1/2} / \Delta x_i + \Delta x_{i(+/-)1}$

$Q_{lf} = \Delta x q_{lf}$

$Q_{lmf} = \Delta x q_{lmf}$

$\varphi_1 = p_1 - \rho_1 g D$

$l = g,w$

In the finite-difference equation, all the parameters were explicitly dealt with; to acquire the parameters and the amount of mass exchange of the coal matix-cleat system.

4.2 COMPUTER MODEL

The program source code can be written to solve the set of equations of the numerical model by modifying a conventional black oil model. The computing flow diagram is presented below: -

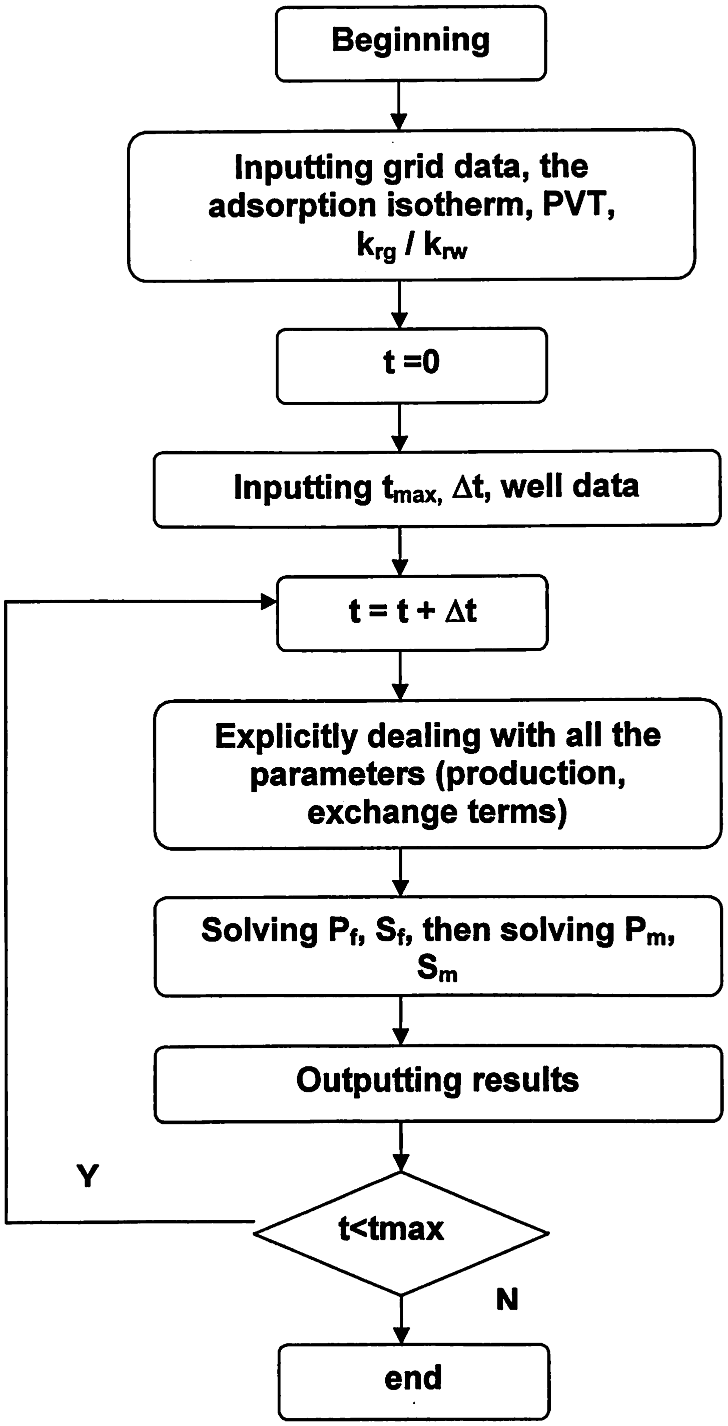

Fig 4.1:- The Flow Chart of Simulator Calculation

4.3 INPUT PARAMETERS USED IN EXAMPLE SIMULATION ONE

Arial extent of the reservoir, acre	50
Thickness of coal, ft	30
Cavity Radius at well bore, ft	.329
Outer boundary radius, ft	3280
Initial fluid pressure, psia	1305
Coal seam temperature, °R	605
Cleat Porosity, fraction	.0395
Cleat permeability, md	6.5
Micropores porosity, fraction	0.08
Micropores permeability, fraction	1.34
Coal seam compressibility at standard conditions, $psia^{-1}$	3×10^{-4}
Cleat connate water saturation, fraction	0.82
Micropores connate water saturation, fraction	0.2
Viscosity of gas, cp	0.020
Langmuir gas constant, scf/ton	660
Langmuir pressure constant, psia	57
Bulk density of coal, g/cm^3	1.3
Langmuir volume constant, scf/ft^3	30.3

Table 4.1

From the program the time taken for the gas to flow through the cleat structure into the well bore is: 715.955 days.

The corresponding adsorption isotherm for the above mentioned data is shown below to determine the amount of gas content available in coal seams.

Pressure (psia)	Gas content(scf/ton)
1355	29.0768
1345	29.0681
1335	29.0593
1325	29.0503
1315	29.0412
1305	29.0319

1295	29.0226
1285	29.013
1275	29.0034
1265	28.9936
1255	28.9836
1245	28.9735
1235	28.9632
1225	28.9528
1215	28.9422
1205	28.9315
1195	28.9205
1185	28.9094
1175	28.8981
1165	28.8867
1155	28.875
1145	28.8631
1135	28.8511
1125	28.8388
1115	28.8264
1105	28.8137
1095	28.8008
1085	28.7877
1075	28.7743
1065	28.7607
1055	28.7469
1045	28.7328
1035	28.7184
1025	28.7038
1015	28.6889
1005	28.6737
995	28.6583
985	28.6425
975	28.6265
965	28.6101
955	28.5934
945	28.5763
935	28.559
925	28.5412
915	28.5231
905	28.5047
895	28.4858
885	28.4666
875	28.4469
865	28.4268
855	28.4062
845	28.3853

835	28.3638
825	28.3418
815	28.3194
805	28.2964
795	28.2729
785	28.2488
775	28.2242
765	28.1989
755	28.173
745	28.1465
735	28.1193
725	28.0914
715	28.0628
705	28.0335
695	28.0033
685	27.9724
675	27.9406
665	27.9079
655	27.8743
645	27.8397
635	27.8042
625	27.7676
615	27.7299
605	27.6911
595	27.6511
585	27.6098
575	27.5672
565	27.5233
555	27.4779
545	27.4311
535	27.3826
525	27.3325
515	27.2806
505	27.2269
495	27.1712
485	27.1135
475	27.0536
465	26.9914
455	26.9268
445	26.8596
435	26.7896
425	26.7168
415	26.6409
405	26.5617
395	26.479
385	26.3925

375	26.3021
365	26.2073
355	26.108
345	26.0037
335	25.8941
325	25.7788
315	25.6573
305	25.529
295	25.3935
285	25.25
275	25.0979
265	24.9363
255	24.7644
245	24.5811
235	24.3853
225	24.1755
215	23.9504
205	23.708
195	23.4464
185	23.1632
175	22.8556
165	22.5203
155	22.1533
145	21.75
135	21.3047
125	20.8104
115	20.2587
105	19.6389
95	18.9375
85	18.1373
75	17.2159
65	16.1434
55	14.8795
45	13.3676
35	11.5272
25	9.2378
15	6.3125

Table 4.2

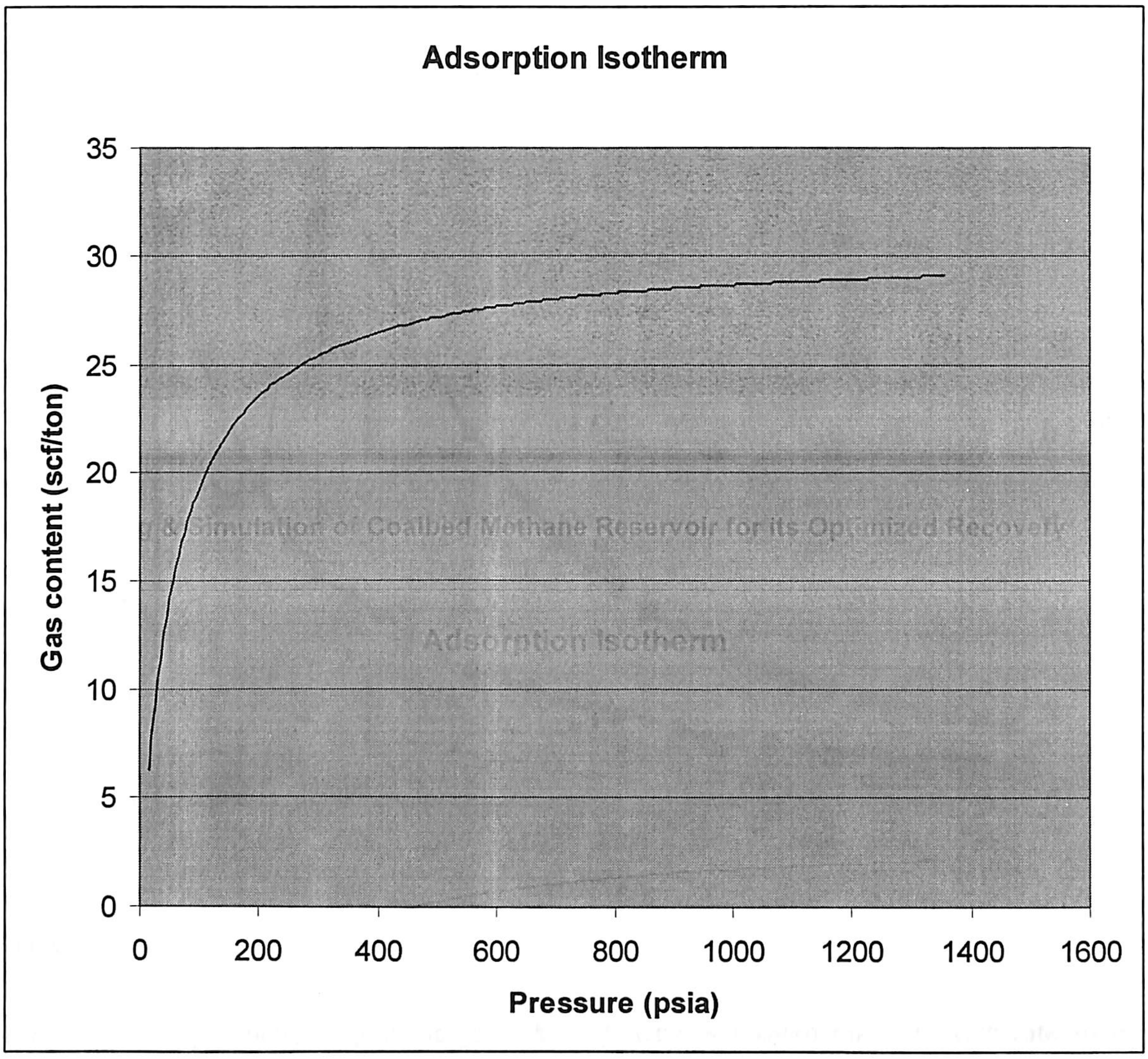

Fig. 4.2

The PVT laboratory data considered for the following simulation is given below:-

P (MPa)	$Bg(m^3/m^3)$	µg (MPa.s)	Z_g (fraction)
1	.1147	.0130	.9869
2.6	.0450	.0131	.9680
4	.0276	.0134	.9501
6.51	.0165	.0139	.9234
8	.0132	.0142	.9096
9	.0116	.0145	.9015
9.5	.0110	.0146	.8977

Table 4.3

On substitution of the following data to the simulator (refer reference 1), the following results were obtained.

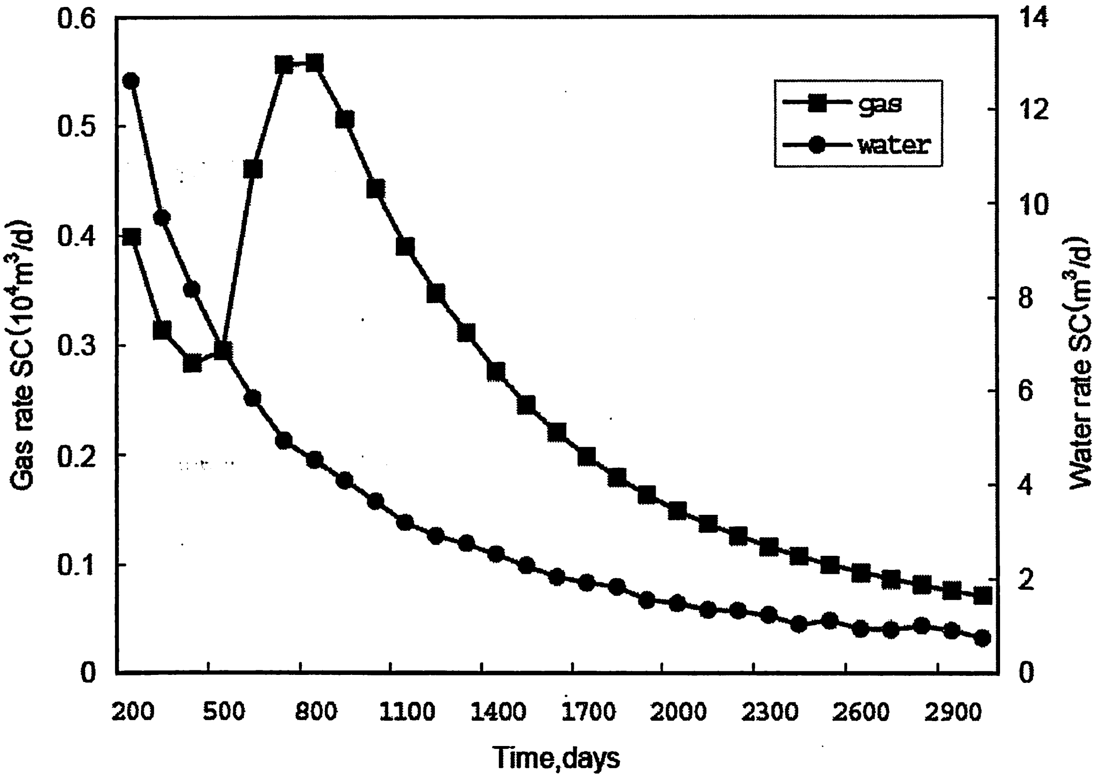

Fig. 4.3

The water and production equations (3.10 & 3.11) were simulated manually with reference to pressure drop corresponding to number of production days. The initial reservoir pressure taken for the simulation is 1305 psia at production of 0 days. The simulation yielded the following results.

time (days)	gas rate (10^4 m3/d)	water production(10^4 m3/d)
100	0.3	0.55
200	0.25	0.51
300	0.22	0.46
400	0.2	0.43
500	0.18	0.4
600	0.16	0.38
700	0.15	0.37
800	0.14	0.35
900	0.16	0.33
1000	0.19	0.32

1100	0.21	0.31
1200	0.24	0.31
1300	0.28	0.29
1400	0.3	0.28
1500	0.33	0.26
1600	0.36	0.24
1700	0.38	0.23
1800	0.43	0.22
1900	0.47	0.21
2000	0.5	0.2
2100	0.53	0.19
2200	0.58	0.18
2300	0.62	0.17
2400	0.65	0.165
2500	0.65	0.162
2600	0.65	0.158
2700	0.63	0.144
2800	0.57	0.14
2900	0.54	0.138
3000	0.49	0.12
3100	0.44	0.116
3200	0.42	0.111
3300	0.38	0.104
3400	0.35	0.1
3500	0.31	0.097
3600	0.28	0.083
3700	0.25	0.077
3800	0.21	0.075
3900	0.18	0.069
4000	0.14	0.061
4100	0.1	0.058
4200	0.08	0.05

Table 4.4

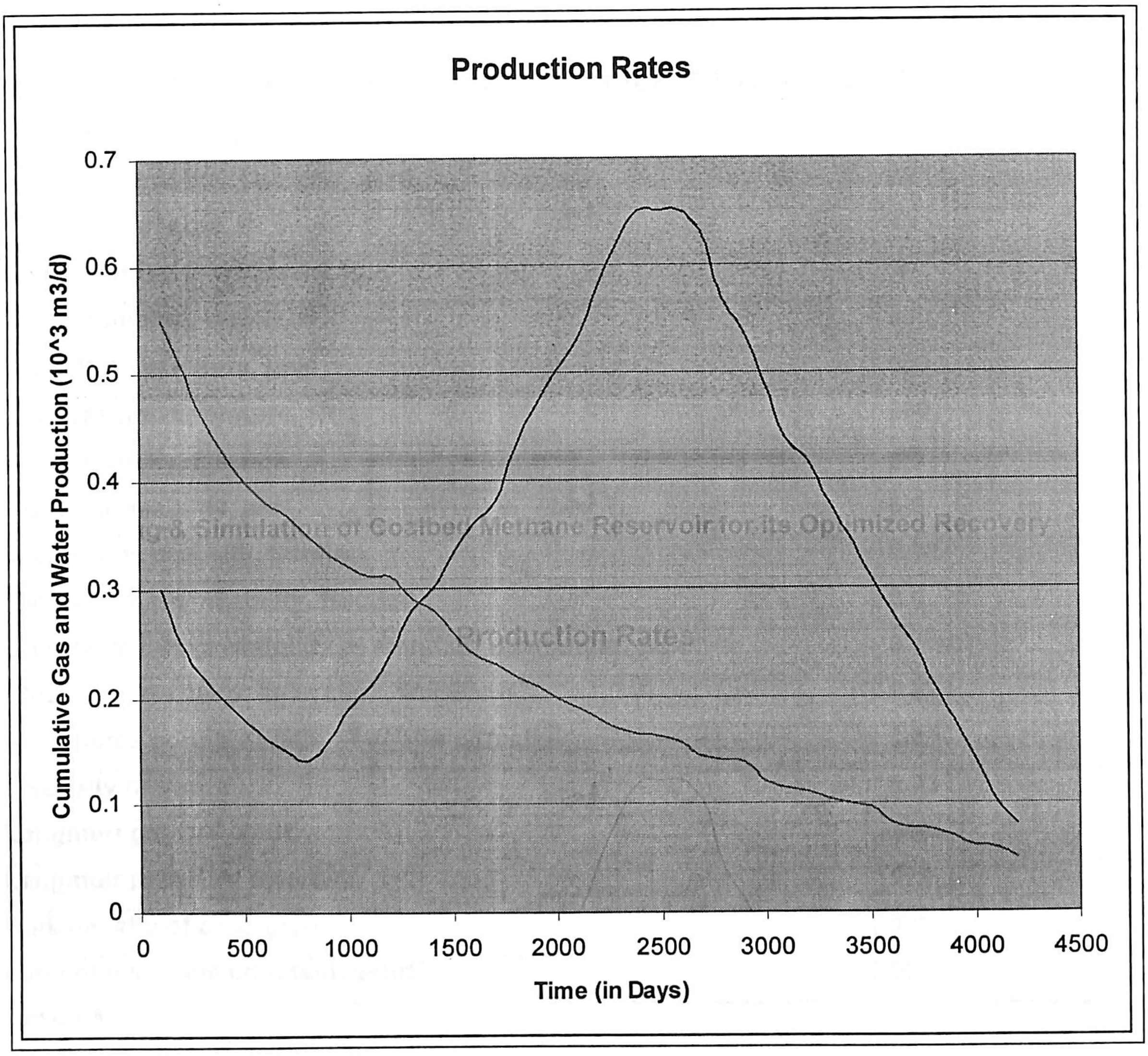
Production Rates
Cumulative Gas and Water Production (10^3 m3/d)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Time (in Days)

Fig. 4.4

4.4 INPUT PARAMETERS USED IN EXAMPLE SIMULATION TWO

(Assumption: - no permeability variation)

Arial extent of the reservoir, acre	**25**
Thickness of coal, ft	**10**
Cavity Radius at well bore, ft	**.5**
Outer boundary radius, ft	**250**
Initial fluid pressure, psia	**550**
Coal seam temperature, °R	**580**
Cleat Porosity, fraction	**.25**
Cleat permeability, md	**5.0**
Micropores porosity, fraction	**0.08**
Micropores permeability, fraction	**5.0**
Coal seam compressibility at standard conditions, psia^{-1}	**3×10^{-4}**
Cleat connate water saturation, fraction	**0.82**
Micropores connate water saturation, fraction	**0.05**
Viscosity of gas, cp	**0.83**
Langmuir gas constant, scf/ton	**440**
Langmuir pressure constant, psia	**176**
Bulk density of coal, g/cm^3	**1.3**
Langmuir volume constant, scf/ft^3	**20**

Table 4.5

From the program the time taken for the gas to flow through the cleat structure into the well bore is: 68390.7 hours.

The corresponding adsorption isotherm for the above mentioned data is shown below to determine the amount of gas content available in coal seams.

Pressure (psia)	gas content (scf/ton)
600	15.4639
590	15.4047
580	15.3439
570	15.2815
560	15.2174
550	15.1515

540	15.0838
530	15.0142
520	14.9425
510	14.8688
500	14.7929
490	14.7147
480	14.6341
470	14.5511
460	14.4654
450	14.377
440	14.2857
430	14.1914
420	14.094
410	13.9932
400	13.8889
390	13.7809
380	13.6691
370	13.5531
360	13.4328
350	13.308
340	13.1783
330	13.0435
320	12.9032
310	12.7572
300	12.605
290	12.4464
280	12.2807
270	12.1076
260	11.9266
250	11.7371
240	11.5385
230	11.33
220	11.1111
210	10.8808
200	10.6383
190	10.3825
180	10.1124
170	9.82659
160	9.52381
150	9.20245
140	8.86076
130	8.49673
120	8.10811
110	7.69231
100	7.24638
90	6.76692

80	6.25
70	5.69106
60	5.08475
50	4.42478
40	3.7037
30	2.91262
20	2.04082
10	1.07527

Table 4.5

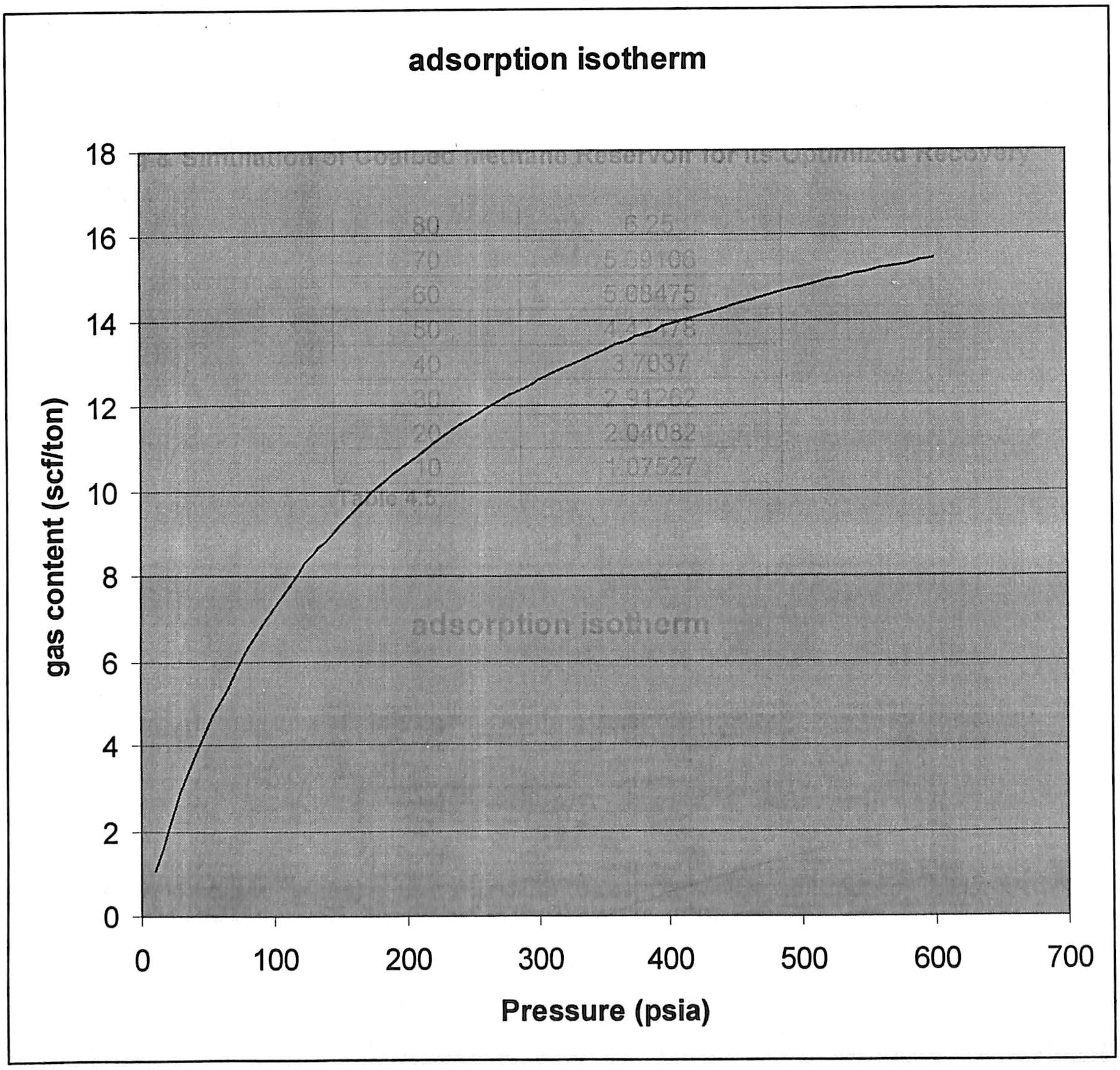

Fig. 4.5

Due to the unavailability of PVT data (as in simulation example1) for the following presumed simulation, the results could not produced and compared any further.

CHAPTER V

LIMITATIONS

5.1 LIMITATIONS

- The entire model has been developed for one-dimension rather than three-dimension. Coal been highly anisotropic, the parameters change in all the three dimensions (x,y,z axes) .
- Several parameters were to be dealt with implicitly but have been dealt explicitly as the program code (C++) has the constraint for the same.
- The effects of matrix shrinkage and stresses have not been discussed in the course of the study.
- The simulation work has been incomplete and to verify the results is done manually.

CHAPTER VI

CONCLUSION

6.1 CONCLUSION

- One dimensional, two-phase (gas-water) flow coalbed-methane (CBM) numerical reservoir simulator is developed for simulating methane gas producing process.

- In our new model, because the volume of gas released from the coal can be predicted by a sorption isotherm which is obtained from experiments or calculations, the condition of achieving equilibrium is not considered.

- The new model also permits to precisely describe the phenomena occurring within the fractures and the coal micropores, and to be better understanding the production mechanisms of coalbed reservoir.

NOMENCLATURE

C = The gas concentration, m^3/t

D = Depth, m

g = The gravity acceleration=9.81 g/ ($cm.s^2$)

h = Thickness, m

k = Absolute permeability, md

k_{rg} = Relative permeability to gas

k_{rw} = Relative permeability to water

Lx = The fracture spacings in the x direction, m

M = Molecular weight, kg/mol

m = Mass, kg

p = pressure, atm

p_c = Capillary pressure, atm

p_{bh} = Bottom hole pressure, atm

q_g = Gas flow rate, m^3/day

q_w = Water flow rate, m^3/day

r_e = Effective drainage radius, m

r_w = Well bore radius, m

R =Universal gas constant=8.3145 ($kPa.m^3$)/(kmol.k)

s = Skin effect

S_w = Water saturation

S_{wc}=Connate water saturation

S_g = Gas saturation

S_{gc}=Critical gas saturation

t = Time, day

T = Temperature,

V_b = Bulk volume, m^3

Wfrac= Well fraction

Z = Gas deviation factor

μ = Viscosity, cp

φ = Porosity

ρ = Density, kg/m^3

V_L = Langmuir Volume Constant, scf/ton

P_L = Langmuir Pressure Constant, psia

P_g = Macropore Gas Pressure, psia

V_E = equilibrium Sorption isotherm, scf/cuft

$\alpha = \rho_1 \phi_1 S^{n+1}{}_{ll} (c_f + c_1)$

$T^n{}_{lxl} = 2(\rho_1 k k_{rl}/\mu_1)^{n+1}{}_{l}{}^{+}{}_{-1/2} / \Delta x_l + \Delta x_{l(+/-)1}$

$Q_{lf} = \Delta x q_{lf}$

$Q_{lmf} = \Delta x q_{lmf}$

$\varphi_1 = p_1 - \rho_1 g D$

$l = g, w$

Subscripts

g = Gas

w = Water

m = The coal matrix system

f = The coal fracture system

REFERENCES

- Xiao Guo, Zhimin Du, Shilun Li, “Computer Modeling and Simulation Of Coal Bed Methane Reservoir”, Southwest Petro Institute And The CNPC Key Lab For Special Gas Reservoir Development

- Kissell N. Fred, Edwards C. John, “Two – Phase Flow in Coalbeds”

- Darton, N. H.: “Occurrence of Explosive Gases in Coal Mines,” *United States Bureau of Mines Bulletin* (1915) 10, No.101, 72.

- Seidle, J. P. and Arri, L. E., Use of Conventional Reservoir Models for Coalbed Methane Simulation,” paper SPE 21599 presented at the International Technical Meeting IM/SPE, Calgary, Canada, 10-13 June 1990.

- Palmer, I. and Mansoori, J.: “How Permeability Depends on Stress and Pore Pressure in Coalbeds: A New Model,” paper SPE 36737 presented at the Annual Technical Conference and Exhibition, Denver, Colorado, 6-9 October 1996.

- Warren, J. E. and Root, P. S.: “The Behavior of Naturally Fractured Reservoirs,“ paper SPE 426 presented at the Fall Meeting of Society of the Petroleum Engineers, Los Angeles, California, 7-10 October 1965.

- Earlougher,R. C., Advances in Well Test Analysis, Society of Petroleum Engineers, Dallas, TX 1977.

- Bumb, A. C., and McKee, C. R., “Gas-Well Testing in the Presence of Desorption for Coalbed Methane and Devonian Shale,” SPE 1S277, presented at the Unconventional Gas Technology Symposium, Louisville, KY, May 18-21, 1986.

- Kissell, Fred N. Methane Migration Characteristics of the Pocahontas No. 3 Coalbed. Bureau of Mines R I 7649, 1972, 13 pp.

- Moffat, D. H., and R. W. Weale. Sorption by Coal of Methane a t High Pressure. Fuel, v. 34, 1955, p. 449.

- Price, H. S . , and A . A. Abdalla. A Mathematical Model Simulating Flow of Methane and Water in Coal. Bureau of Mines OFR 10-72, 1972, 39 pp. ; available from National Technical Information Service, Springfield, Va. , PB 209 273. Cards are available from F. N. Kissell, Bureau of Mines, 4800 Forbes Ave.,Pittsburgh, Pa. 15213.

- Smith and Williams "Diffusional Effects in the Recovery of Methane From Coalbeds" paper SPE 10821, presented at the 1982 SPE/DOE Symposium on Unconventional Gas recovery held in Pittsburgh, May.16-18, 1980.

- Arri et al. "Modeling Coalbed Methane Production With Binary Gas Sorption" paper SPE 24363, presented at the SPE Rocky Mountain Regional Meeting held in Casper, Wyoming, May 18-21, 1992.

- Lie Hui Zhang et al. " Application of Black Oil Model to Coalbed Methane Reservoir", Journal of Southwest Petroleum Institute (Nov.2001), Vol.23, No.5, 26-28

- David et al., " A Parametric Study of the Effects of Coal Seam Properties on Gas Drainage Efficiency", paper SPE 13366, presented at the 1984 SPE Eastern Regional Meeting held in Charieston, WV, Oct.31-Nov.2

- Sawyer, W.K.; Paul, G.W.; Schraufnagel, R. A., "Development and Application of a 3D Coalbed Simulator", CIM/SPE 90-119, International CIM/SPE Technical Meeting, Calgary, (June 10- 13, 1989).

- Young, Genevieve B.C.; Paul, George W., "A Simulation-Based Approach To Evaluating Coalbed Methane Reservoir Producibility and Operating Practices", Case Studies in Coalbed Methane Reservoir Simulation, International Coalbed Methane Extraction Conference, London (January 24-25, 1994).

- Arri, L.E.; Yee, Dan; Morgan, W.D.; Jeansonne, M.W., "Modeling Coalbed Methane Production With Binary Gas Sorption", SPE 24363, SPE Rocky Mountain Regional Meeting, Casper, (May 18-21, 1992).

APPENDIX A

Continuous Gas-Transport equation

Taking differential mass balance,

$$\nabla(\rho_g \nu_{Tg}) + m_{fi} = \frac{\delta}{\delta t}(\Phi_f \rho_g s_{gf}) \ldots\ldots\ldots\ldots\ldots(1)$$

Now,

$$\nu_{Tg} = \nu_{\Delta g} + \nu_{sg}$$

$$\nu_{Tg} = -[\frac{k_{rg}\, k\propto}{\mu_g}(\nabla P_{fg} - \rho_g\, g\, \nabla\, D)]$$

(1) becomes,

$$\nabla[\rho_g \frac{k_{rg}\, k\propto}{\mu_g}(\nabla P_{fg} - \rho_g\, g\, \nabla\, D)] + m_{fi} = \frac{\delta}{\delta t}(\Phi_f \rho_g s_{gf}) \ldots\ldots\ldots\ldots(2)$$

But,

$$m_{fi} = q_{gmf} - q_{gf}$$

(2) Becomes,

$$\nabla[\rho_g \frac{k_{rg}\, k\propto}{\mu_g}(\nabla P_{fg} - \rho_g\, g\, \nabla\, D)] + q_{gmf} - q_{gf} = \frac{\delta}{\delta t}\, \Phi_f \rho_g s_{gf}) \qquad (3)$$

Similarly for water,

$$\nabla[\,\rho_w \frac{k_{rw}\, k\propto}{\mu_w} (\nabla P_{wf} - \rho_w g \nabla D)] + q_{wmf} - q_{wf} = \frac{\delta}{\delta t} (\Phi_f \rho_w s_{wf})$$

where,

m_{fi} = mass flow rate of fractures
$\nu_{\Delta g}$ = viscous diffusion flux
ν_{sg} = Knudsen diffusion flux
ν_{Tg} = Total gas flux
q_{gmf} = gas flow rate from micropores to macropores
q_{gf} = gas flow rate from coal fracture system

APPENDIX B

Derivation of gas exchange between micropores and macropores

Consider the gas transport in the coal single micropore and single macropore as shown in the figure:-

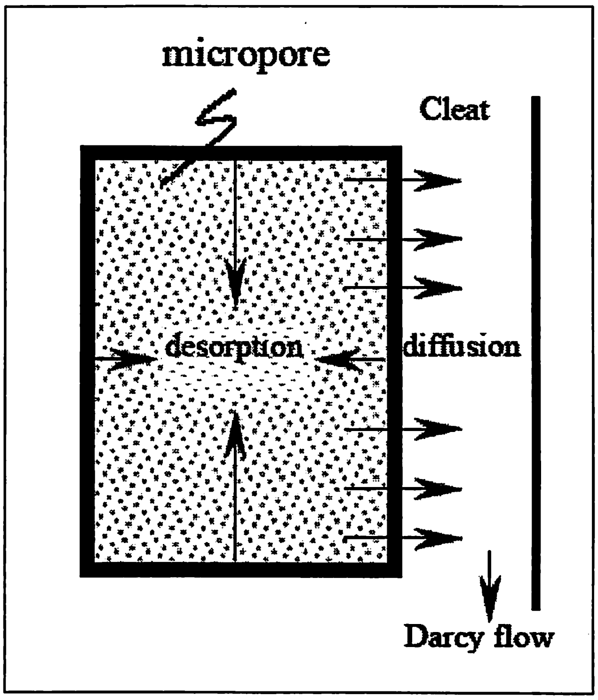

Fig. A.B.1

Within the control volume in the coal micropores, the difference between inflow and outflow must be equal to the sum of mass accumulation of free gas. The gas mass inflow across the control volume surface is equal to the mass of gas desorbed from the coal surface which enters the micropore system, whereas the gas mass outflow is equal to gas mass exchange between the coal macropores and micropores, i.e. the mass of gas transport from the coal micropores which enters the macropore system.

Mass of desorbed gas – mass of diffusion gas = the sum of mass accumulation of free gas

The volume of gas released from the coal can be predicted by a sorption isotherm which relates the gas storage capacity of a coal sample to pressure. When the coalbed reservoir pressure descends from level P_{m0} to level P_m over a time interval Δt_0, the difference between t and t_0, the mass of gas desorbed from the coal surface per unit mass of coal per unit time is

$$q_{des} = (\rho_g (\bar{p}_m) [C(p_{m0}) - C(p_m)] / \Delta t_0$$

where $\bar{p} = 0.5 (p_m + p_{m0})$

The real gas law to describe the density of the free gas contained in the micropore pore space is expressed

$$m (p_m) = [p_m V_b \phi S_{gm}(p_m) M] / Z(p_m) RT$$

The sum of mass accumulation of gas within the control volume in the coal micropores per unit volume per unit time is described

$$[m (p_{m0}) - m (p_m)] / V_b \Delta t_0 = [(p_{mo} \phi S_{gm}(p_{m0}) M) / Z(p_{mo}) RT \Delta t_0] - [(p_m \phi S_{gm}(p_m) M) / Z(p_m) RT \Delta t_0]$$

According to principle that the difference between inflow and outflow must be equal to the sum of mass accumulation of free gas. We now have

$$q_{gmf} = [\rho_g (p_m) \{C (p_{m0}) - C (p_m)\} / \Delta t_0] + [p_m \phi_m S_{gm} (p_m) M / Z (p_m) RT \Delta t_0] - [p_{m0} V_b \phi_m S_{gm} (p_{m0}) M / Z (p_{mo}) RT \Delta t_0]$$

APPENDIX C

Difference Form of the Macropore Transport Equation

The development of discretizing the macropore transport equation by the finite-difference method is presented as following.

The partial differential equation that describes the transport of methane gas in the coal macropore system is given in continuous form by

$$\nabla[(\rho_l\, k\, k_{rl} / \mu_l)\ \nabla \varphi_{lf}] - q_{lf} + q_{lmf} = (\partial / \partial t)\ (\phi_f\, \rho_l\, S_{lf}) \qquad (C.1)$$

For 1-dimensional flow the left hand side can be expanded as

$$(\partial/\partial x)\ [(\rho_l\, k\, k_{rl} / \mu_l)\ \nabla \varphi_{lf}] - q_{lf} + q_{lmf} \qquad (C.2)$$

Furthermore, the central difference operator is derived by expanding the potential at the current time around half-nodes of x direction. Then eqn. (C.2) is given as

$$(\partial/\partial x)\ [(\rho_l\, k\, k_{rl} / \mu_l)\ (\partial/\partial x)\varphi_{lf}] = [\{(\rho_l\, k\, k_{rl} / \mu_l)\ (\partial/\partial x)\varphi_{lf}\}_{i+1/2} - \{(\rho_l\, k\, k_{rl} / \mu_l)\ (\partial/\partial x)\varphi_{lf}\}_{i-1/2}]\ /\ [x_{i+1/2} - x_{i-1/2}]$$

The above equation can further be simplified as

$$(\rho_l\, k\, k_{rl} / \mu_l)_{i+1/2}\{(\varphi_{lfi+1} - \varphi_{lfi})/0.5(\Delta x_i - \Delta x_{i+1}))\}\ /\ \Delta x_i - (\rho_l\, k\, k_{rl} / \mu_l)_{i-1/2}\{(\varphi_{lfi-1} - \varphi_{lfi})/0.5(\Delta x_i - \Delta x_{i-1}))\}\ /\ \Delta x_i \qquad (C.3)$$

The time backward difference approximation of the right-hand side of Eqn. C.1 is given by

$$(\partial / \partial t)\ (\phi_f\, \rho_l\, S_{lf}) = \phi_f\, \rho_l\, (\partial S_{lf} / \partial t) + \phi_f\, S_{lf}[(\partial \rho_l / \partial \varphi_l)\ (\partial \varphi_l / \partial t)] + \rho_l\, S_{lf}\ [(\partial \phi_f / \partial \varphi_l)\ (\partial \varphi_l / \partial t)]$$

The above equation can further be simplified as

$$\phi_f \rho_l (\partial S_{lf} / \partial t) + \phi_f S_{lf} \rho_l C_l (\partial \varphi_l / \partial t) + \rho_l S_{lf} \phi_f C_\phi (\partial \varphi_l / \partial t)]$$

Further the eqn. can be written as

$$\phi_f \rho_l (S^{n+1}{}_{lfi} - S^n{}_{lfi}) / \Delta t + \rho_l S_{lf} \phi_f (C_l + C_\phi) (\varphi^{n+1}{}_{lfi} - \varphi^n{}_{lfi}) / \Delta t$$

Considering the following parameters

$\alpha = \quad \rho_1 \phi_1 S^{n+1}{}_{li} (c_f + c_1)$

$T^n{}_{lxi} = 2(\rho_1 k k_{rl} / \mu_1)^{n+1}{}_{i}^{+}{}_{-1/2} / \; \Delta x_i + \Delta x_{i(+/-)1}$

$Q_{lf} = \Delta x q_{lf}$

$Q_{lmf} = \Delta x q_{lmf}$

$\varphi_1 = p_1 - \rho_1 g D$

$l = g, w$

The difference form so obtained is:

$$T^n{}_{lxi+1/2} \varphi^{n+1}{}_{lfi+1} + T^n{}_{lxi-1/2,j,k} \varphi^{n+1}{}_{lfi-1,j,k} - (T^n{}_{lxi+1/2,j,k} + T^n{}_{lxi-1/2,j,k}) \varphi^{n+1}{}_{lfi} - Q^n{}_{lf}$$
$$+ Q^{n+1}{}_{lmf} = \alpha_1 \{(\varphi^{n+1}{}_{lfi} - \varphi^{n1}{}_{lfi}) / \Delta t_n\} + \phi_f \rho_g \{(S^{n+1}{}_{lfi} - S^{n1}{}_{lfi}) / \Delta t_n\}$$

APPENDIX D

D.1 Program code for adsorption isotherm and pseudo-steady state.

```
# include<iostream.h>
# include<conio.h>
# include<math.h>
# include<stdio.h>
float isotherm (float P, float V)
{
 float Pl,Vl,C,i;
 clrscr();
 cout<< "\n enter the value of langmuir pressure constant in psi";
 cin>>Pl;
 cout<< "\n enter the value of langmuir volume constant in scf/ft3";
 cin>>Vl;
 cout<<"\n Pressure        \t\t"<<"gas content";
 for (i=(P+50);i>=10;i-=10)
 {
  C = (Vl*i)/(i+Pl);
  cout<<"\n    "<<i<<"         \t\t"<<C;
 }
}
float sorption_compressibility(float P, float V, float T, float porosity)
{
 float constant,b,Bg,bd,cs,Z,R,Vm,Pl;
 cout<< "\n enter the value of bulk density in g/cm3";
 cin>>bd;
 cout<< "\n enter the value of langmuir pressure same as enetered for claculation
of volume";
```

```
 cin>>Pl;
 b= 1/Pl;
 Vm = V*(1+(b*P))/(b*P);
 Z = 0.92;
 R = 10.732;
 Bg = (R*T*Z)/(P*V);
 cout<<" formation volume factor of gas is = "<<Bg<<" RB/MCF";
 constant = 1.7525*pow(10,-4);
 float x = (1+(b*P));
 cs = (constant*Bg*Vm*bd*b)/(porosity*pow(x,2));
 return (cs);
}
float volume(float P,float T,float porosity)
{
 float Vm,b,vol,Pl,Pr,Te,Po;
 cout<< "\n enter the value of langmuir gas constant in scf/ton";
 cin>>Vm;
 cout<< "\n enter the value of langmuir pressure constant in psi";
 cin>>Pl;
 Pr=P;
 Te=T;
 Po=porosity;
 b = 1/Pl;
 vol = (Vm*(b*P))/(1+(b*P));
 return(vol);
}
void main()
{
 float
choice,con,kgx,kgy,kg,t,td,porosity,mu,ct,cf,Sw,cg,Sg,cw,cs,A,P,T,V,Tr,h,iso;
```

```
cout<< "\n enter the initial reservoir pressure in psia";
cin>>P;
cout<< "\n enter the initial reservoir temperture in degree farenhite";
cin>>T;
Tr = T+460;
cout<< "\n enter the cleat porosity in fraction";
cin>>porosity;
cout<< "\n enter the effective gas permeability in x-direction in milli darcy";
cin>>kgx;
cout<< "\n enter the effective gas permeability in y-direction in milli darcy";
cin>>kgy;
kg = pow((kgx*kgy),0.5);
cout<< "\n enter the areal reservoir extent in acres";
cin>>A;
cout<< "\n enter the seam thickness in feet";
cin>>h;
cout<< "\n enter the viscosity in centipoise";
cin>>mu;
td = 0.1;
V = volume(P,T,porosity);
cf= 8.6*pow(10,-6);
cout<< "\n enter the value of water saturation";
cin>>Sw;
Sg = (1-Sw);
cg = (1/P);
cs = sorption_compressibility(P,T,V,porosity);
ct = cf+(Sw*cw)+(Sg*cg)+cs;
con = 2.637*pow(10,-6);
t = ((td*porosity*mu*ct*A)/(con*kg))*1000;
clrscr();
```

```
cout<< "\n the initial reservoir pressure is = "<<P<<" psia";
cout<< "\n the initial reservoir temperature is = "<<Tr<<" degree rankine";
cout<< "\n the volume if gas is = "<<V<<" scf/ton";
cout<< "\n the porosity of the cleat system is = "<<(porosity*100)<<" %";
cout<< "\n the effective gas permeability is = "<<kg<<" md";
cout<< "\n ariel extent of the reservoir is = "<<A<<" Acres";
cout<< "\n the seam thickness of the seam is = "<<h<<" Feet";
cout<< "\n the viscosity of gas is = "<<mu<<" centi poise";
cout<< "\n the compressibility of the system is = "<<ct<<" /psi";
cout<< "\n time taken by the gas to flow thru the cleat structure is = "<<t<<"
hours";
isotherm(P,V);
getch();
}
```