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MODIFICATION OF A CURRENT COALBED METHANE PERMEABILITY MODEL FOR HORIZONTAL STRAIN ONLY

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MODIFICATION OF A CURRENT COALBED METHANE PERMEABILITY MODEL FOR HORIZONTAL STRAIN ONLY

By

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MAJOR PROFESSOR: **Dr. Satya Harpalani**

Cleat permeability of coal is the most critical parameter affecting the amount of production from a coalbed methane (CBM) reservoir. As a result, there have been many studies about how cleat permeability changes over the life of a reservoir, leading to the development over time of several different permeability models. Most permeability models used today consider volumetric strain as an input parameter; however, permeability is impacted primarily by the increase in cleat aperture, resulting from matrix shrinkage in the horizontal direction. Recent work has shown that coal exhibits transverse isotropy, with total strain in the vertical direction being significantly higher than either horizontal direction. Hence, the inclusion of vertical strain through use of the volumetric strain parameter could be predicting inaccurate permeability variation results. The objective of this study was to determine the difference in permeability modeling with volumetric strain compared to permeability modeling with only horizontal strain, and assess the degree to which different parameters affect results from modeling using only horizontal strain.

Experimental results showed that matrix strain remained consistent with transversely isotropic results of previous works. When included into the Palmer and Mansoori (P&M) permeability model, modeling results showed that permeability with horizontal strain is significantly lower than that with volumetric strain. The three unmeasured parameters in the Palmer and Mansoori permeability model have a major effect on the final results and need to be history matched in order to improve the level of accuracy in their estimation.

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CHAPTER 1

INTRODUCTION

1.1 COALBED METHANE PRODUCTION

Methane is a naturally occurring gas in coal and is generated during formation of coal. In the long history of coal mining, methane explosions have been one of the most feared hazards in underground operations. In recent years, however, coalbed methane (CBM) has become a steady source of unconventional natural gas with ~1.3 trillion cubic feet (TCF) produced in the United States (US) alone in 2015 (EIA, 2016). Four major CBM producing countries today are the US, Australia, China, and India. In the US, the majority of production comes from three basins: Black Warrior (Alabama), San Juan (New Mexico and Colorado), and Powder River (Wyoming). However, there are other areas where it is produced in relatively smaller quantities. Major CBM production in the US began in the early 1980s in the Black Warrior basin; however, the Black Warrior basin was quickly surpassed by the San Juan basin as the major producer (Moore, 2012). Production of CBM grew substantially from 1989, with 91 billion cubic feet produced, to its peak in 2008 with 1,966 billion cubic feet produced. Production has since declined each year to 1,269 billion cubic feet produced in 2015 (EIA, 2016). Coalbed methane is an ideal source of natural gas production because reservoirs are self-sourced, meaning the gas is produced and then trapped in the same area. This makes coal deposits a low-risk exploration target with the major risk being the ability to produce a commercial amount of gas from a well (Liu, 2012).

Methane is stored in coal mostly in an adsorbed state. The adsorbed gas can be found at high densities along internal surfaces of the coal's micropore system. This system is made up of tiny blocks of coal known as the coal matrix, which are separated by larger fractures known as cleats (Gray, 1987). The macropore system (cleats) stores small amounts of free gas with quantities dependent on unique coal properties and environmental conditions such as coal rank, ash content, organic composition, gas composition, seam temperature, and initial pressure (Yee et al., 1993). Migration of gas stored in coal begins with desorption of gas from micropores. As the adsorbed gas becomes free gas, a concentration gradient is established between the coal matrix and the coal cleats, which causes the newly-freed gas to diffuse towards the cleats (Harpalani and Chen, 1997). Gas flow through coal cleats is controlled by permeability, and cleats function as the main pathway for coalbed gas to escape.

Coalbed methane is primarily produced by pressure depletion of a reservoir. Most reservoirs in the US are initially water-saturated and, in order to reduce seam pressure, water must be pumped out. This leads to initial production of large quantities of water from a reservoir, while almost no gas is produced. When pressure lowers below the desorption pressure, gas begins to desorb and flow out of the system. As the reservoir pressure decreases, gas/water saturation in cleats changes, producing a fluid permeability change in the cleat system (McKee et al., 1987). The rate at which gas leaves a coal seam is observed to increase to a peak rate as pressure is lowered and water production decreases. After reaching this peak production rate, gas flow starts to decline steadily over the life of the well until it becomes uneconomical to continue production.

1.2 PROBLEM STATEMENT

The most important parameter when predicting the performance of a CBM reservoir over a long period of time is coal permeability, or the ability of a gas to flow through coal. Permeability changes over the life of a reservoir and is affected by multiple parameters, such as reservoir pressure, effective stress, and matrix shrinkage effects. When a combination of parameters are considered together, permeability can be modeled and predicted for long-term simulation. However, even if one parameter is inaccurate, it can lead to misinterpretations in the simulation. Therefore, it is important to understand coal permeability and all parameters associated with it.

When a CBM reservoir is in production, gas leaves coal micropores by diffusion and begins free-flowing horizontally through vertical cleats – a process which is governed by the coal's permeability (Harpalani and Chen, 1997). Over time, permeability increases due to matrix shrinkage, which results in opening of the cleat aperture, thereby facilitating the flow of gas (Gray, 1987). The cleat aperture is measured horizontally, that is in the x- and y-directions. The z-direction, or height of a coal matrix, is affected more than the x- and y-directions during matrix shrinkage; however, it has the least effect on changes in permeability. Most permeability models consider volumetric strain of the coal matrix in a uniaxial-strain based coal reservoir, meaning that lateral boundaries are confined while the vertical boundary is free to move (Palmer and Mansoori, 1998; Shi and Durucan, 2003; Cui and Bustin, 2005). This type of confinement accounts for matrix shrinkage and opening of cleat apertures in the horizontal direction.

In most permeability models, volumetric strain, or sum of strains in three orthogonal directions, is a critical parameter. However, when exposed to a sorbing gas and with change in pressure, the volume of solid coal has been shown to shrink/swell with similar values in the x- and y- directions, but with strong anisotropy in the vertical z-direction (Levine, 1996; Larsen et al., 1997; Day et al., 2008). This means that volumetric strain is disproportionately affected by the vertical strain when predicting the permeability increase due to matrix shrinkage. In recent years, published research studies have added an anisotropy parameter to some previous models and significant differences have been found when considering average volumetric strain compared to anisotropic strain (Pan and Connell, 2011; Moore et al., 2015).

The hypothesis of this study is that inclusion of the vertical direction in the volumetric strain calculation may be an unnecessary step, even when anisotropy is considered. Thus, “volumetric strain” can actually be replaced with “horizontal strain.” Only considering change in area in the x- and y- directions provides a different result for permeability predictions. This is because the two horizontal directions are the only ones where the matrix shrinkage is relevant. Change in the vertical direction is larger in comparison to that in the x- and y- directions, but should still be ignored. When using volumetric strain, anisotropic behavior in the z-direction significantly skews the true horizontal shrinkage value when modeling permeability changes. Modeled differences in permeability when using volumetric strain versus horizontal strain needed to be investigated to assess effects, if any, on permeability changes over the life of a CBM reservoir.

1.3 RESEARCH OBJECTIVE

The objective of the work completed for this thesis was to conduct matrix shrinkage/swelling experiments under unconstrained conditions and analyze results for three orthogonal directions. Differences in permeability modelling results were assessed when using volumetric strain versus using only horizontal strain as the shrinkage parameter. In order to attain this overall objective, the following specific objectives were pursued:

1. Determination of strain in three orthogonal directions with depletion of helium, methane, and carbon dioxide as pore fluids under unconstrained condition;
2. Analysis of strain in both vertical and horizontal orthogonal directions in order to determine magnitudes of horizontal and volumetric strains;
3. Modeling of coal permeability with volumetric strain and horizontal strain using the Palmer and Mansoori (1998) permeability model;
4. Comparison of modeling results obtained using volumetric and horizontal strain parameters and proposal of appropriate modifications to modeling criteria.
5. Analysis of different modeling parameters that affect horizontal strain.

1.4 THESIS ORGANIZATION

This thesis contains seven chapters. Chapter 2 is a background section, provides a basic understanding of the subject matter by presenting the fundamentals of coalbed reservoirs. The chapter includes coalbed reservoir characteristics and gas storage and transport in reservoirs. The literature review in Chapter 3 presents a summary of past studies, both experimental and theoretical, on matrix shrinkage, coal permeability, and the effects of coal anisotropy on permeability. This literature review provides the background knowledge and groundwork that is essential to the formation of this thesis.

Chapter 4 presents the experimental work. In it, the experimental plan and procedure are discussed along with the sample preparation process. Chapter 5 discusses results of the experimental work and an illustrative analysis of the data. Chapter 6 presents results from permeability modeling of the experimental data including an analysis of the hypothesis and a discussion on the differences in permeability modeling based on multiple parameters.

Chapter 7 closes the thesis with several concluding remarks about experimental and modeling results and provides recommendations for continued work in the future.

CHAPTER 2

BACKGROUND

2.1 INTRODUCTION

Although dangerous to mine, coal has been an indispensable energy resource due to its unique properties. Throughout the history of coal mining, explosions due to ignition of coal mine methane have been one of the deadliest hazards. The same properties that have made coal so dangerous in the past are today being utilized as a resource through the production of coalbed methane (CBM). During CBM production, methane is safely removed from coal through depressurization of a coal seam, allowing the gas to escape via coal's natural fractures. This section will discuss the origin of these gases, how they are stored, and the processes that lead to their migration in the coal seam.

2.2 COALBED RESERVOIR CHARACTERISTICS

2.2.1 Origin of Methane and Other Gases in Coal

For production purposes, the most important gas naturally found in coal is methane; however, there are several other gases found naturally in coal as well, such as, carbon dioxide, ethane and nitrogen. These gases are formed from two distinct processes: biogenic and thermogenic (Rice 1993). The primary biogenic gases, methane and carbon dioxide, are produced from decomposition of organic matter by microorganisms (microbes), in places such as peat swamps (Kim and Douglas, 1972). In order to generate economically significant amounts of biogenic gas, the environment must contain low amounts of dissolved oxygen, must be low in sulfate concentration, should be at low temperatures, have abundant organic matter, adequate pore space, and rapid sedimentation (Rice and Claypool, 1981; Zhang and Chen, 1985; Rice, 1992). Under ideal conditions, it is possible for microbes to break down enough organic matter to create several thousand cubic feet of gas per ton of coal formed in the early stages of coalification (Patching, 1970).

In higher rank coals with a large vitrinite reflectance, thermogenic gas begins to form due to higher heat and pressure over time. Similar to biogenic processes, thermogenic processes form methane and carbon dioxide in coal, but also nitrogen and hydrogen sulfide from devolatilization (Whiticar, 1994). These coals generally, but not always, contain a greater quantity of total gas than coalbeds where strictly biogenic gas has formed (Behar et al., 1995). Figure 2.1 shows the amount of methane formed based on biogenic and thermogenic processes in different types of coals. It should be noted that moisture content is one of the most significant factors in determining the amount of gas formed and the process by which it is formed (Moore, 2012).

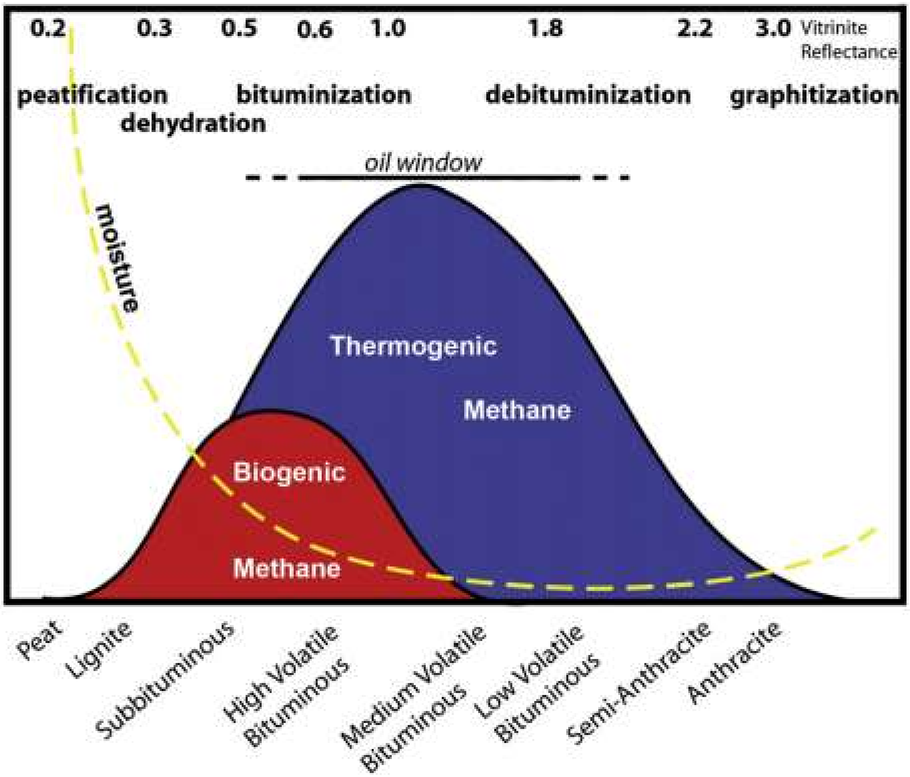

Figure 2.1 - Biogenic and thermogenic gas generation in relation to rank, moisture, vitrinite reflectance, and coalification stages (Moore, 2012)

2.2.2 Physical Structure of Coal

Coal is considered a dual porosity rock. Macropores are large aperture, natural fractures called cleats. Cleats can be spaced anywhere from 0.1 to 1 inch apart and are formed during the coalification process due to tectonic stresses (Thakur et al., 2014). These cleats usually occur in two sets that are both perpendicular to the bedding plane as seen in Figure 2.2. The set of cleats formed first and the larger of the two sets are called face cleats. The smaller set of cleats that intersect face cleats are called butt cleats (Laubach and Tremain, 1991; Kulander and Dean, 1993). These two cleat sets are the primary pathways for coalbed gas and water to flow through the system. The formation of cleats and their spacing is known to vary with coal type and ash content (Spears and Caswell, 1986). Coals with high vitrain (bright lithotype) have smaller cleat spacing than do durain coals (dull lithotype). Similarly, low ash content in coal has been observed to be correlated with smaller cleat spacing (Kendall and Briggs, 1934; Stach et al., 1982).

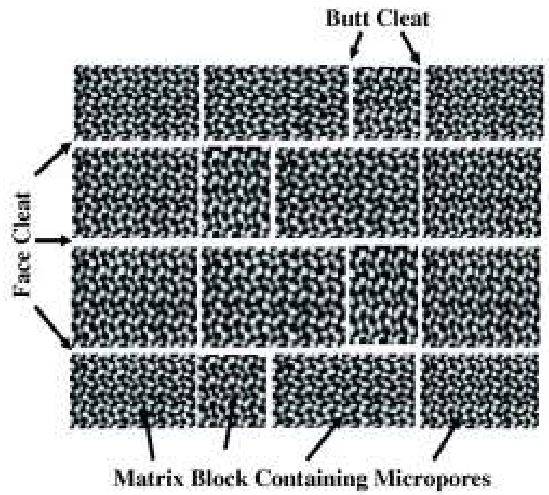

Figure 2.2 - Physical structure of face and butt cleats (Mitra et al., 2012)

The second type of pore that makes coal a dual porosity system is called a micropore. These pores are much smaller in size than macropores, usually 0.5-1 nm, and make up the coal matrix, a critical parameter of CBM production (Krevelen, 1961). Micropores are the primary storage system for gas in coal, containing up to 95% of the gas in the adsorbed and free states (Gray, 1987). Macropores and micropores function together making coal a dual porosity system.

2.3 GAS STORAGE IN COALBED RESERVOIRS

The vast majority of gas in coal is methane, but there are small amounts of carbon dioxide, nitrogen, and other gases as well. Gas stored in coal is mainly due to adsorption into pores, which accounts for roughly 95% of the total. The remaining small quantity of gas in coal seams is either free or dissolved, which, though only a fraction of the total, is still important. This section summarizes the different ways coal gas is stored as a basis for an understanding how gas can be removed during production.

2.3.1 Free Gas

Free gas is that which is not adsorbed and is allowed to move around in the coal voids freely. The amount of free gas is partially dependent on the temperature and the amount of adsorbed gas, which will be discussed later.

2.3.2 Dissolved Gas

Dissolved, or absorbed gas, is that which is dissolved within the molecular structure of coal, changing its physical structure, properties, and behavior. This happens when gas fills sub-micropores smaller than the sorbate molecule, causing small amounts of swelling. In the case of methane, very little absorption occurs, although carbon dioxide has been shown to dissolve at a much higher rate (Milewska-Duda et al., 2000).

2.3.3 Adsorbed Gas

The vast majority of gas in coal is stored as adsorbed gas. This means that gas molecules attach themselves to the surface of a coal pore in a physical state. Coal is naturally a very porous material containing up to $3m^3$ of surface area in just a $1cm^3$ piece of coal (Radlinski et al., 2004). When there is a large body of coal, such as a seam, the potential for adsorbed gas storage is extremely high, making coal a valuable gas resource. Although methane is the primary gas in coal, carbon dioxide is sorbed preferentially over methane, meaning that the greater the amount of CO_2 present, the smaller will be the amount of adsorbed methane (Harpalani et al., 2006).

There are several factors that play a role in the amount of adsorbed gas in coal. One of the most prominent adsorption retardants is the presence of moisture. Coals that contain a higher moisture content show reductions in pore sizes due to swelling of coal (Yee et al., 1993). This is partially why high-moisture, low-rank coals contain small concentrations of methane. On the other hand, coals with increasing vitrinite content have been reported to have an increasing sorption capacity, suggesting that maceral content plays an important role in adsorption (Laxminarayana and Crosdale, 1999). A third major factor for gas sorption is temperature. Higher temperatures have been found to have a negative effect on the amount of gas stored in coal, showing that there is higher concentrations of free gas instead (Bustin and Clarkson, 1998). These three factors, along with pressure, coal rank, gas composition, and lithological properties play a role in the amount of gas sorbed in coal, meaning that each coal needs to be studied on a case by case basis (Levy et al., 1997).

The most common way to estimate the gas retention capacity of a reservoir is through a sorption isotherm. The isotherm is a quantitative measure of the amount of adsorbed gas as a function of reservoir pressure at the in situ temperature (Harpalani et al., 2006). The isotherm is a critical parameter in CBM modeling, and must be accurate to ensure the validity of the CBM production decision-making process.

2.3.4 Langmuir Isotherm

The Langmuir model is the most commonly used isotherm model for adsorption of gases on solids. This model is based on five assumptions: (i) One gas molecule is adsorbed at a single adsorption site, (ii) an adsorbed molecule does not affect the molecule on the neighboring sites, (iii) sites are indistinguishable by gas molecules, (iv) adsorption is on an open surface, and (v) there is no resistance to gas access by adsorption sites (Daniels & Alberty, 1957). It is also assumed that adsorption is restricted to a single monolayer (Gregg and Sing, 1982). The common form of the Langmuir isotherm is given as:

$$\frac{V}{V_L} = \frac{P}{P+P_L} \qquad (2\text{-}1)$$

where V is the adsorbed volume of gas at equilibrium pressure and V_L is the maximum monolayer adsorption capacity, or the Langmuir volume. Once a coal seam reaches a high enough pressure, all adsorption sites (pores) become full, meaning there is no more room for additional gas molecules to adsorb. This maximum pressure, known as the saturation pressure corresponds with the Langmuir volume. In the equation above, P_L is the value for reservoir pressure when half the amount of gas at infinite pressure is sorbed. This is referred to as the Langmuir pressure.

The Langmuir isotherm model is the one most widely used because the simple equation correctly expresses adsorption behavior for wide ranges of pressures. The pressure constant known as $1/P_L$ measures isotherm curvature. A large value of this constant corresponds to a greater initial slope of the isotherm (Harpalani et al., 2006). The shape of the isotherm describes the behavior of gas release in the reservoir when exposed to changes in pressure, a steeper slope meaning significantly more gas will flow out of the coal seam at lower pressures. V_L and P_L are the two critical parameters for determining the sorption isotherm in coal, which, in turn, determines the economic viability of a reservoir. The measured Langmuir volume is the maximum amount of gas possible based on the Langmuir curve, and the Langmuir pressure corresponds to how much gas would have to be removed for 50% recovery of that gas. It should be noted, however, that most coals do not contain the maximum amount of gas possible at in situ conditions. In most new wells, the pressure needs to be reduced by dewatering so that the gas content in the seam matches the corresponding pressure on the isotherm model. Once pressure and gas volume are in equilibrium with the isotherm, gas will start desorbing from pores to be transported out of the seam (Moore, 2012).

2.3.5 Gas Mixtures in Coal

As has been stated previously, gas in coal seams is a mixture of multiple gases. There are only three, however, that are sorbing gases: carbon dioxide, methane, and nitrogen. It has also been stated that carbon dioxide has a higher adsorption preference in coal than does methane, while nitrogen has the lowest preference due to differences in the molecular structure of these gases (Arri et al., 1992). This means that if all three gases are present, carbon dioxide is the preferred gas to be completely adsorbed in coal, followed by methane. If adsorbed methane saturates the coal, no nitrogen will be adsorbed. However, if the coal seam is undersaturated after adsorption of methane, it will adsorb nitrogen to fill vacant areas. The different sorption properties of these gases cannot be considered using the simple Langmuir model because they have different Langmuir pressures and volumes in coal. Kapoor et al. (1990) presented a new extended Langmuir (EL) model for adsorption of gas mixtures given as:

$$V_i = \frac{(V_{max,i})B_i P_i}{1+\sum_{j=1}^{n} B_j P_j} \tag{2-2}$$

where V_i is the gas volume of component i adsorbed at partial pressure P_i, $V_{max,i}$ is the monolayer volumetric capacity of component i in standard cubic feet per ton (scft), n is the number of gas components in the mixture, and B_i is the reciprocal of Langmuir pressure for component i (Rogers, 1994). This model allows for the calculation of gas content for multiple gases using their respective partial pressures, but since the vast majority of gas in a coal seam is methane, it is only slightly more accurate than the Langmuir isotherm.

2.4 GAS TRANSPORT IN COALBED RESERVOIRS

Section 2.3 discussed three ways that gas is stored in coal. This section discusses three processes that govern gas flow in coal: (i) desorption of gas from internal coal pores, (ii) gas diffusion through the micropore structure, or coal matrix, due to a concentration gradient, and (iii) free flow (Darcian flow) through the cleat system in response to a pressure gradient (King and Ertekin, 1989; Harpalani and Schraufnagel, 1990b). All three flow systems function together throughout all parts of the complex coal structure to form many flow paths for gas to be transported out of coal for production. Figure 2.3 shows these desorption, diffusion, and free flow processes.

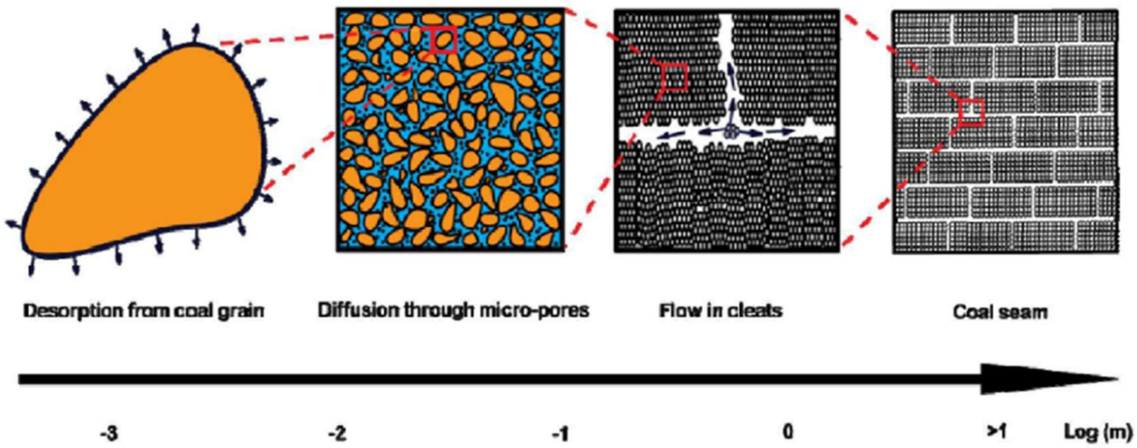

Figure 2.3 - Gas flow through the coal cleat system (Srivastava, 2005)

2.4.1 Desorption

The first process which initiates gas transport of stored gas in coal is desorption. This is a physical process where gas molecules attached to coal pores detach, or desorb, and become free gas. Desorption can be caused by a variety of factors, but for production purposes it is induced by a lowering of reservoir pressure (thus lowering pressure in coal cleats). When this happens, the coal becomes less capable of storing gas molecules, which begin to detach at a rate that follows the adsorption isotherm. The lower the pressure in a reservoir becomes through removal of water and gas, the more gas desorbs, thus facilitating concentration and pressure gradients in the next two gas flow processes.

2.4.2 Diffusion

Once methane has desorbed and becomes free gas, it enters into the coal microstructure known as the coal matrix. In the coal matrix, the pressure is constant, but the release of methane creates a concentration gradient across the matrix to the lower pressure cleats. Due to micropore diameters being so small compared to free paths for gas molecules, the migration of gas molecules is due to diffusion rather than the difference in pressure between the matrix and cleats (Harpalani and Chen, 1997).

This type of diffusion where the mean free path of gas molecules is smaller than the actual pore diameter is known as bulk diffusion. It is the primary diffusion occurring in the coal matrix. Resistance to bulk diffusion comes primarily from gas molecules colliding with other gas molecules (Collins, 1991). Although this is the primary type of diffusion (especially at higher pressures), Knudsen and surface diffusion also play small roles in gas transport through the matrix (Shi and Durucan, 2003). Usually occurring at lower pressures, Knudsen diffusion is the opposite of bulk diffusion because the mean free path of gas molecules is larger than the molecule diameter. This allows gas molecules to collide more frequently with flow path walls rather than with each other (Thorstenson and Pollock, 1989). Surface diffusion occurs as transport through a physically adsorbed gas layer moving along micropore surfaces like a liquid, but it is usually a very small, almost negligible amount (Collins, 1991; Pillalamarry et al., 2011).

In CBM production, the combination of these three diffusion processes is considered as a single process, which is explained by Fick's Second Law of Diffusion, stating that the rate of diffusion of concentration of a gas is directly proportional to the concentration gradient in the direction of flow. In mathematical terms, it is given as:

$$m = -D\nabla C \tag{2-3}$$

where m is the mass flowrate, D is the diffusion coefficient, and ∇C is the concentration gradient (Harpalani and Chen, 1997).

2.4.3 Darcian Flow in Cleats

Once gas flow reaches a cleat due to diffusion, free flow occurs. Free flow is controlled by the permeability of the coal. This is considered to be a laminar flow process governed by Darcy's law, given as:

$$m = -\frac{kP_m\rho_m}{\mu P_0}\nabla P \quad (2\text{-}4)$$

where *m* is the mass flow rate per unit area, *k* is the apparent permeability, P_m is the mean gas pressure ($(P_i+P_0)/2$), P_i is the inlet gas pressure, P_0 is the outlet pressure, ρ_m is the mean density, μ is the viscosity of the gas, and ∇P is the pressure gradient vector (Singh, 2012). This flow is pressure driven through cleats, and the mass flow rate is strongly dependent on permeability.

2.4.4 Stages of Gas Flow in Coalbed Methane Reservoirs

Over the life of a CBM reservoir, there are likely to be multiple stages of gas production. The three recognized by McKee and Bumb (1987) are: (i) saturated water flow with no gas phase, (ii) unsaturated water flow with an immobile gas phase, and (iii) two-phase flow of gas and water.

Saturated water flow with no gas phase occurs when a CBM reservoir is water-saturated at the beginning of production, with a pressure higher than the desorption pressure of the gases present. When production from this type of well first starts, water will be the only fluid coming out of the reservoir until the pressure is lowered enough to allow for desorption to take place.

The second stage of gas production is unsaturated water flow with immobile gas. Once enough water is removed from a well for gas molecules to desorb, gas bubbles begin to form in the water, partially blocking pore spaces that are still saturated with water. When these gas bubbles block a portion of the previously unrestricted flow path for water, the relative permeability of coal to water decreases. Although some gas has desorbed, gas molecules remain immobile as bubbles because there is still no flow path for them to take into the cleat system. Although there is both water and gas present in this stage, there is still no gas production and only the water is mobile.

When the reservoir pressure is lowered enough for the desorbing, immobile gas bubbles to form a continuous path to cleats and out the well, two-phase flow of gas and water begins. This means that the relative permeability of gas is now non-zero. As production continues and water saturation declines, the relative permeability of gas continues to increase at the expense of the relative permeability of water (McKee and Bumb, 1987).

These three phases of gas flow occur assuming the reservoir is fully saturated with gas. However, it is not common for a CBM reservoir to be fully gas saturated and under-saturated reservoirs must be discussed as well. When a reservoir is under-saturated, significant pressure drawdown must occur before any gas can begin to desorb. Similar to saturated water flow with no gas, under-saturated reservoirs will produce large quantities of water before any gas desorbs, sometimes making a well uneconomical from a production standpoint. Figure 2.4 compares the difference between a well with 50% gas saturation and a well with 85% gas saturation (100% gas saturation would follow the curve of the isotherm). When a coal seam is under-saturated with gas, the pressure must be lowered until it meets the point on the isotherm curve corresponding to the amount of gas in the coal seam. Only at that time will gas begin to flow out of the reservoir. If a coal seam is heavily under-saturated, it may not be economical to produce due to the large amount of time it would take to lower the pressure significantly with no production. Once gas flow begins, production can continue for years while gas continuously flows out of the coal seam. It will usually reach a point of peak production due to matrix shrinkage, then slowly decrease until the well is no longer viable to keep producing.

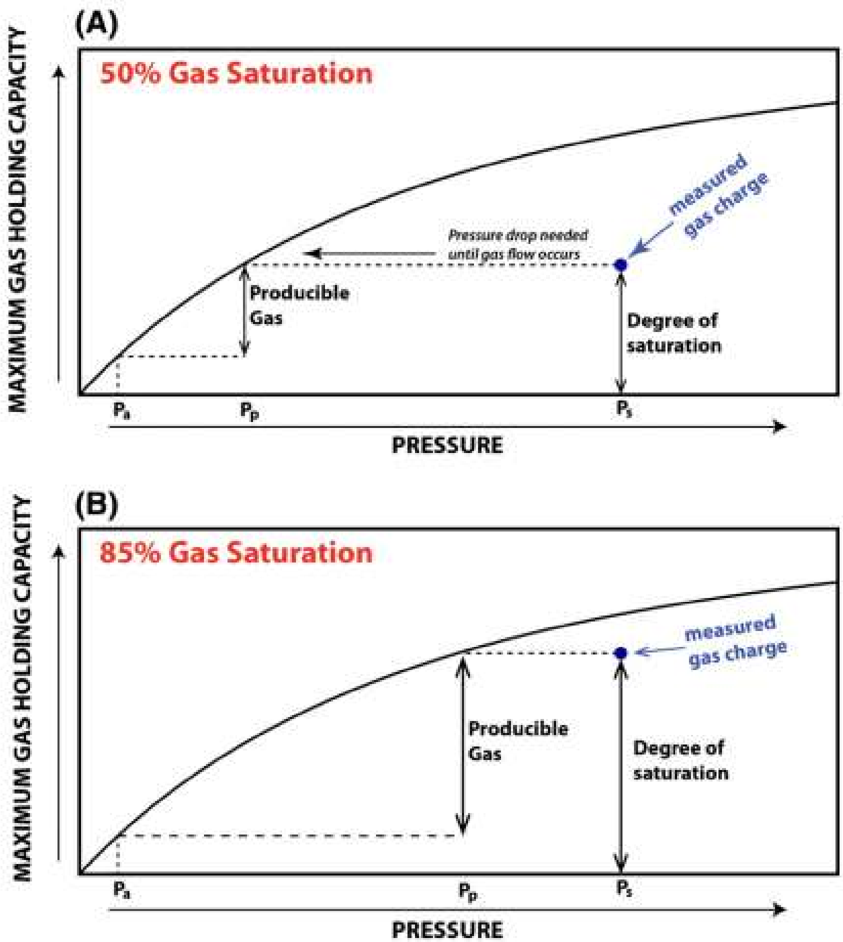

Figure 2.4 - Comparison of two different gas saturations and ultimate gas production. (A) 50% gas saturation and (B) 85% gas saturation (Moore, 2012)

2.5 CHAPTER SUMMARY

This chapter has introduced the way gas is formed in coal, how it is stored, and the processes by which it is transported during CBM production. These concepts have been used for decades, allowing for further research to increase coalbed methane production and what modern science knows about it. The concepts in this chapter will continue to be built upon as this thesis continues. The next step in the journey is to perform a literature review that introduces the more advanced concepts that this thesis will utilize.

CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

The primary recovery process for coalbed methane reservoirs is through pressure depletion at a well. This first requires large amounts of water to be pumped out of the well to reduce the pressure so that gas can begin to desorb from micropores and travel out to the cleat system. This system of openings determines the permeability of coal, and tends to change during the life of a reservoir (Levine, 1996). Permeability is perhaps the most important parameter to understand and estimate in order to predict how a CBM reservoir will behave over time, and has therefore been studied extensively over the last forty years.

Coal permeability is affected by many different factors, such as cleat aperture, orientation of the coal seam relative to stress, and more, but the three main parameters are reservoir pressure, change in effective stress, and matrix shrinkage effects. The volumetric shrinkage/swelling of coal in response to pressure and stress variations helps to summarize these three permeability parameters. A decrease in reservoir pressure brings about a pressure difference between the reservoir and surrounding rock, creating an increase in external stress. This increase is effectively counteracted by shrinkage of the coal matrix, which allows for the opening of cleat aperture and the increase of permeability.

Changes in permeability due to different factors have been extensively studied through laboratory experiments and theoretical models during the time that CBM has grown into a valuable resource. This chapter discusses previous literature on matrix shrinkage and experimental and theoretical models of permeability. Lastly, it presents newer research on anisotropy of coal and why it is an important parameter when considering permeability models.

3.2 LITERATURE REVIEW OF MATRIX SHRINKAGE

3.2.1 Background

Due to coal being a dual-porosity rock, it has a complex geometry of macropores and micropores. Macropores contain blocks of coal between them that house micropores. Each individual block of coal is considered to be a "coal matrix." Figure 3.1(a) shows the coal matrix and its geometry with face cleats and butt cleats. Figure 3.1(b) shows the "bundle of matchsticks" geometry, which is considered to best represent the coal matrix for modeling purposes. The coal matrix is what initially houses gas molecules adsorbed in coal before they migrate to cleats (macropores). When these gas molecules desorb from pores and leave the coal matrix, a process known as matrix shrinkage occurs. This section will discuss past studies of matrix shrinkage/swelling and how it is critical to CBM production.

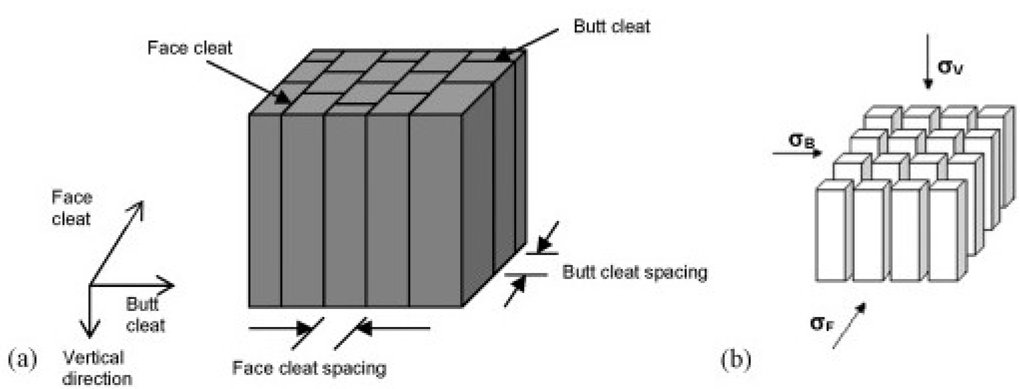

Figure 3.1 - Anisotropy of coal: (a) A coal fracture system; and (b) matchstick geometry showing anisotropic stresses (An et al., 2015)

3.2.2 Matrix Shrinkage Studies

It is well known that sorption of gas or immersion in a liquid causes dilation of a porous body (Scherer, 1986). There have been many studies throughout the last century that have analyzed the effects of shrinkage/swelling in coal with the first one reported by Briggs (1933). This was the first study to report the swelling of coal due to adsorption of methane and carbon dioxide. Briggs's breakthrough paved the way for Moffat and Weale (1955) to introduce isotherms for shrinkage/swelling due to adsorption of methane in coal. Their study reported a volume increase ranging from 0.2% to 1.6% when coal samples were pressurized up to 2200psi, but for anything above that pressure the coal sample's volume either decreased or remained constant. This study concluded that sorption of gas results in a change in coal volume.

In 1986, Reucroft and Patel carried out a study to determine how surface area and pore structure of coal are altered, concluding that carbon dioxide changed the length of samples by 0.36 to 1.31%. This study also showed a negligible change in length under the same temperature and pressure conditions when less sorptive nitrogen and helium gases were used. In another swelling study, they measured the change in specimen length to estimate the change in volume and concluded that swelling of coal through adsorption of carbon dioxide increases between 0.75% and 4.18% with increasing pressure up to 217psi (Reucroft and Sethuraman, 1987).

The first study to hypothesize that matrix shrinkage from desorption resulted in the opening of coal cleats was by Gray (1987). This idea meant that if coal cleats actually did become wider as a result of matrix shrinkage, coal permeability would increase significantly depending on each individual coal's in situ stress conditions and shrinkage characteristics. Harpalani and Schraufnagel (1990b) confirmed this idea of increasing permeability with their study a few years later. Their results showed that when a coal sample is subjected to an increase in pressure with helium, a non-sorbing gas, the coal matrix volume decreased due to mechanical compression of the solid coal matrix. However, for methane, coal samples were found to swell about 0.5% with increasing pressure up to 1000psi. Their study also concluded that samples shrink with decreasing pressure, thereby increasing permeability significantly, which will be discussed in detail in Section 3.3 (Harpalani and Schraufnagel, 1990b).

Seidle and Huitt (1995) found eight studies on coal matrix swelling due to gas sorption and reported that shrinkage coefficients were in the range of 1 to 10 E^{-6} psi^{-1}, but very few details from any of their studies provided information on coal rank and mineral matter. This study set to determine the swelling coefficient for methane pressured up to 2000psi and carbon dioxide at 900psi, which was found to be 0.86 µs-ton/scf and 0.78 µs-ton/scf, respectively. Matrix shrinkage during this experiment was also found to correlate with gas content rather than pressure.

The first study to relate sorption-induced strain to the Langmuir model was by Levine (1996). This study observed that strain had a very steep slope at low pressures, but leveled off at higher pressures. The following Langmuir-type equation was used to fit the curve:

$$\varepsilon_s = \varepsilon_\infty \frac{p}{p+P_\varepsilon} \tag{3-1}$$

where ε_s is sorption-induced volumetric strain at pressure, p, ε_∞ is the maximum strain achieved at infinite pressure, and P_ε is the pressure at which coal attains 50% of its maximum strain. This study also showed a linear swelling ratio for carbon dioxide of 0.41% at 450psi and 0.18% for methane at 750psi.

In a more recent study, Harpalani and Mitra (2010) measured coal matrix volumetric strain for two different US basins. Illinois basin coal swelled roughly 0.6% from methane at 800psi. The matrix volume of San Juan basin coal increased by 0.64% with methane at 1015psi.

In an effort to quantify some of the studies described previously, Pan and Connell (2007) developed a model for sorption-induced coal swelling at adsorption and strain equilibrium. A major assumption of this model is that the surface energy change caused by adsorption is equal to the elastic energy change of the coal solid. The model is as follows:

$$\varepsilon = RT * \ln(1 + BP)\frac{\rho_s}{E_s}f(x, v_s) - \frac{P}{E_s}(1 - 2v_s) \tag{3-2}$$

where Ɛ is linear strain, R is the universal gas constant (8.314 J mol^{-1} K^{-1}), T is temperature (K), B is the Langmuir constant (inverse of Langmuir pressure), ρ_s is density (kg/m^3) of the solid adsorbent, E_s is Young's modulus for the solid phase, P is the solid-phase stress, v_s is the coal-solid phase Poisson's ratio, and the function $f(x, v_s)$ is the parameter provided by Scherer (1986) relating change in surface energy and elastic energy. This model is able to describe the difference in swelling behavior with respect to gas type at high pressures and can be used to describe mixed-gas adsorption induced coal swelling (Pan and Connell, 2007).

3.3 LITERATURE REVIEW OF PERMEABILITY STUDIES

3.3.1 Background

Permeability is an intrinsic property of a porous medium that defines the level of transportability of a fluid within it. There are two types of permeability in coal, matrix and fracture, and together they play an important role in determining the gas production profile of a well (Levine, 1996; Moore, 2012). Simply put, matrix permeability is the permeability of the coal itself without accounting for natural fractures that are found throughout coal. This part of coal permeability comes from the pore system within the coal matrix. Fracture or cleat permeability can be orders of magnitude higher than matrix permeability. Therefore, it plays a much more significant role in determining overall permeability (Moore, 2012).

Cleat permeability changes with production in two basic ways, according to Gray (1987). The first is phase-relative permeability effects where the degree of saturation affects gas and water relative permeability of coals. The second, and more important, is a change in the difference between total stress and seam fluid pressure, known as effective stress. With continued production, pore pressure within the coal decreases, resulting in an increased effective stress across cleat surfaces. This increased effective stress forces cleats to close, thereby reducing permeability (Gray, 1987). It is known from Section 3.2 that the coal matrix shrinks with continued production due to desorption of gas from coal pores. Gray (1987) hypothesized that this matrix shrinkage counteracts and outweighs the increase in effective stress across cleats by causing a larger decrease in effective horizontal stress, thus leading to the widening of the cleat aperture and significantly increasing permeability. There have been multiple attempts to predict the change in cleat permeability over the life of a well through modeling exercises. Both empirical/experimental and theoretical/numerical approaches have been used to predict permeability, with the most focus in recent years being on numerical methods.

3.3.2 Experimental Studies

Many studies have been performed over the last sixty years providing a good understanding of the cleat permeability behavior of coalbeds (Patching, 1965; Gunther, 1965; Dabbous *et al*., 1974; Somerton *et al*., 1975; Harpalani and McPherson, 1985; Durucan and Edwards, 1986; Harpalani and Schraufnagel, 1990a, b; Harpalani and Chen, 1997; Robertson, 2005; Singh, 2008; Mitra, 2010; Pan *et al*., 2010; Liu, 2012). Both Patching (1965) and Gunther (1965) recorded a permeability decrease of three orders of magnitude when coal was placed under variable confining stresses. Dabbous et al. (1974) observed considerable hysteresis when measuring gas and water permeability of coal, concluding that overburden pressure had the most significant effect on single-phase permeability.

Somerton et al. (1975) used methane and nitrogen to perform permeability measurements on three different bituminous coals as a function of applied stress by flooding coal cores with each respective gas. Results of this study showed that permeability is highly stress-dependent. High-permeability samples showed a decrease in permeability by an order of magnitude with stress increasing from 250psi to 2000psi, while low permeability samples decreased by two orders. For this experiment, the loading sequence and direction of application of the maximum principal stress did not have much of an effect on the observed reduction in permeability. Based on the study results, the following empirical stress-permeability relationship was developed:

$$k = k_0(\exp\left(-3 \times 10^3 \sigma {k_0}^{-0.1}\right) + 2 \times 10^{-4} \sigma^{1/3} {k_0}^{1/3} \tag{3-3}$$

where k is permeability under stress (md), k_0 is permeability under zero stress (md), and σ is mean stress (psi). Finally, this study compared permeability reductions for methane and nitrogen finding that methane was only about 20% to 40% of the measured reduction for nitrogen. The observed discrepancy was attributed to the difference in molecular diameters and sorption of methane on coal.

Harpalani and McPherson (1985) conducted multiple experiments testing the permeability variation of coal with respect to different stress conditions. Their samples were subjected to multiple cycles of loading and unloading under triaxial stress conditions at constant pressure while permeability was estimated throughout the test. Results from repeated unloading and loading showed strong hysteresis and a consistent reduction in permeability, which was attributed to failure of macerals during loading. When stressed hydrostatically, however, coal behaved elastically, showing linear results between hydrostatic stress and the logarithm of permeability. This led to the development of the following stress-permeability empirical relationship:

$$k = Ae^{B\sigma} \tag{3-4}$$

where k is permeability (md), A is a constant indicative of coal's theoretical permeability at zero stress, σ is hydrostatic stress (psi), and B is a constant for the rate at which ln(k) changes with respect to hydrostatic stress.

Durucan and Edwards (1986) used nitrogen as the flowing fluid to understand the effect of stress on permeability for high-volatile bituminous coals. Their experiment found permeability to be highly stress-dependent, decreasing as stress increased. This led to the suggestion that the change in permeability of coal subjected to stress is caused by compression of pores and changes in flow, or by compression and microfracturing. Their study resulted in development of the following stress-permeability empirical relationship for coal under triaxial stress:

$$k = (1.12 - 0.03\sigma_3)k_i \times \exp[-(1.12 - 0.03\sigma_3)C\sigma_3] \tag{3-5}$$

where k is permeability (m^2) at the applied radial stress σ_3 (MPa), k_i is a constant defining the relative incidence of existing fissures and fractures in coal, and C is the compressibility of coal for a particular seam. This study concluded that the variation in permeability of coal due to stress is dependent on coal compressibility, and that microfracturing significantly affects permeability only after stress relief and relaxation of coal.

Harpalani and Schraufnagel (1990b) developed pressure-permeability relationships for coal specimens subjected to triaxial stress conditions using methane and helium. Results showed a decrease in permeability when gas pressure was reduced from 1000psi to 400psi using methane. When pressure was lowered below 400psi, however, permeability increased significantly. Based on this result, it was hypothesized that permeability increases only after significant desorption has occurred. They confirmed this result by performing the test again using helium, a non-sorbing gas, as the pore fluid. Helium exhibited a continuous decrease in permeability with lowered gas pressure, even after 400psi. In another study the same year, Harpalani and Schraufnagel (1990a), performed a similar test using carbon dioxide. Results showed that permeability increased by almost five times when the gas pressure was reduced from 600psi to 50psi. Reaching the same conclusion as the other experiment, this change was also attributed to desorption.

Harpalani and Chen (1997) performed laboratory tests on San Juan basin coal to determine the effects of effective stress, gas slippage, and matrix volumetric strain on coal permeability. Gas slippage explains the concept of permeability variation of a gas to coal based on the molecular weight of the gas and the applied pressure. This study concluded that matrix shrinkage and gas slippage both play a role in the permeability increase of coal with reduced pressure. At pressures above 250psi, matrix shrinkage has a much larger effect on coal permeability than gas slippage. However, at pressures below 250psi, both gas slippage and matrix shrinkage effects become significant factors in the permeability increase. A second conclusion of this study was that the change in permeability due to matrix shrinkage is linearly dependent on the amount of gas desorbed from coal. Based on these conclusions, the following theoretical model was developed to model the effect of matrix shrinkage on cleat permeability:

$$\frac{k_{new}}{k_{old}} = \frac{\left(1+\frac{2l_m^* \Delta p}{\phi_0}\right)^3}{1-l_m^* \Delta p} \tag{3-6}$$

where k_{new} is permeability (md) at pressure p, k_{old} is virgin permeability (md), l_m* is the change in the dimension of the coal matrix block in the horizontal direction with pressure, Δp is the change in reservoir pressure, and ϕ_0 is the virgin porosity.

Robertson (2005) performed a series of methane permeability experiments on the Unita-Piceance basin coal. Similar to past studies, depletion results from 800psi down to 100psi showed an initial decrease in methane permeability, followed by an increase at lower pressures. This study made the important conclusion that, at higher pressures, the stress effect is more dominant than matrix shrinkage, resulting in a decrease in permeability. However, at a certain point with continued depletion, the matrix shrinkage effect begins to dominate the stress effect, resulting in the observed permeability increase.

Singh (2008) attempted to model the relationship between permeability variation and changes in pore pressure. Using Illinois and San Juan basin coals, the following empirical relationship was developed:

$$k = aP^2 - bP + c \quad (3\text{-}7)$$

where k is permeability (md); P is gas pressure (psi); and a, b, and c are constants depending on in situ stress conditions and coal type. For Illinois basin coal samples, permeability remained almost constant at higher pressures while an increase in permeability was observed for gas pressures below 450psi. For San Juan basin coal samples, however, the permeability decreased initially and then increased after gas pressures reduced below 400psi.

Mitra (2010) was the first to perform a study to understand pressure-dependent permeability under in situ stress conditions for San Juan and Illinois basin coals. This study assumed that changes in stress can only induce strain in the vertical direction, also known as uniaxial strain conditions. This is what most theoretical models consider to be the fundamental strain condition when modeling permeability due to the fact that CBM reservoirs are confined laterally. Results from this study showed a permeability increase of roughly thirteen times for San Juan basin coal when pressure was depleted from 900psi to 70psi. It also showed an increase in permeability for Illinois basin coals. These increases in permeability for both types of coal were attributed to desorption-induced strain, resulting in the opening of the coal cleat aperture and loss of horizontal stress.

Pan et al. (2010) used Australian coal samples to conduct permeability tests for helium, methane, and carbon dioxide as pore fluids. This study reported a decrease in permeability under a constant pressure difference with increasing pore pressure and confining stress for methane and carbon dioxide and attributed it to three factors: (i) the Klinkenberg effect (gas permeability is a linear function of pressure), especially at low pressures, (ii) matrix swelling, and (iii) an increase in effective stress due to the constant pressure difference. The permeability for carbon dioxide decreased less than that for methane due to the Klinkenberg effect and because larger CO_2 molecules have a higher swelling effect when adsorbed in coal.

Liu (2012) performed experiments on San Juan basin coal in an attempt to estimate different coal compressibilities. During this experiment, uniaxial strain conditions were maintained and a permeability increase was measured during pressure depletion. This study reported a consistent increase in permeability during depletion starting at 1100psi, but the increase was not significant until after 500psi. The sorption-induced volumetric strain was found to have a direct relationship with the permeability increase, with both having significantly higher increases at lower pore pressures. Finally, horizontal stress under uniaxial strain showed a significant decrease with depletion, signifying an opening of the cleat aperture.

The studies discussed in this section show that coal permeability is stress-dependent and highly affected by matrix shrinkage/swelling properties. There have been many studies that provide data matching the theories discussed in this section. The next section will discuss attempts at “validating” the experimental data obtained. It will present the theory behind modeling and then introduce the primary theoretical/numerical model that will be used for this thesis. A few other models that are currently used in the industry will also be reviewed.

3.3.3 Theoretical Models

In order to understand the progression of coalbed methane production over time, theoretical models must be introduced. Theoretical modeling of permeability variation is a fairly complicated process that is hard to accurately perform due to major variations in coal across an individual seam, but also in different coal types around the world. Therefore, there are many different models that have been proposed over the years, with some working better in specific parts of the world than others. Modeling of permeability allows predictions of how a CBM reservoir will react over time and provides an estimation of reservoir output. If performed improperly, it can lead to errors in decision-making. Over the last 20 years, permeability modeling has come to incorporate rock mechanics, uniaxial strain conditions, matrix shrinkage, stress effects, and sorption-induced strain in order to improve older, more heuristic models.

One of the first basic CBM reservoir permeability models was proposed by McKee et al. (1987). Assuming incompressible solid grains and using pore compressibility as a primary parameter, the following equation for variation of porosity with depletion was developed:

$$\phi = \phi_0 \frac{e^{-\bar{C}_p \Delta\sigma}}{1-\phi_0(1-e^{-\bar{C}_p \Delta\sigma})} \tag{3-8}$$

where ϕ is formation porosity, ϕ_0 is initial formation porosity, $\bar{C}_p$ is pore volume compressibility, and Δσ is the change in effective stress. Assuming the Carman-Kozeny equation to be valid, the following equation was derived to predict permeability of coal:

$$k = k_0 e^{-3\bar{C}_p \Delta\sigma} \tag{3-9}$$

where k is permeability and k_0 is permeability at initial conditions. This permeability equation was used to fit stress-permeability data obtained from laboratory experiments using coal from Piceance, San Juan, and Black Warrior basins in the western US. Most of the coals tested were found to have a reasonable fit to the proposed model when a constant pore compressibility value was used, although some needed an additional variable, pore volume compressibility.

A permeability model proposed by Sawyer et al. (1990) accounted for both pore compressibility and shrinkage/swelling factors. The variation in porosity was expressed as:

$$\phi = \phi_i\left[1 + C_p(P + P_i)\right] - C_m(1 - \phi_i)\left(\frac{\Delta P_i}{\Delta C_i}\right)(C - C_i) \tag{3-10}$$

where ϕ and ϕ_i are fracture porosity and porosity at initial conditions respectively, C_p is pore volume compressibility (psi^{-1}), C_m is matrix shrinkage compressibility (psi^{-1}), C and C_i are average matrix gas concentration and initial matrix gas concentration (scf/ft^3), respectively. Furthermore, ΔP_i and ΔC_i are maximum pressure and concentration changes based on the following equation for initial desorption pressure:

$$\frac{\Delta P_i}{\Delta C_i} = \frac{P_{di} - 14.7}{C(P_{di}) - 1\;\;.7} \tag{3-11}$$

where P_{di} and $C(P_{di})$ are initial desorption pressure (psi) and concentration at initial desorption pressure (scf/ft^3).

The model proposed by Seidle et al. (1992) aimed to predict coal permeability based on the "bundle of matchstick" geometry. The result was the following derived relationship between permeability and stress:

$$\frac{k_{f2}}{k_{f1}} = \exp[-3C_f(\sigma_{h2} - \sigma_{h1})] \tag{3-12}$$

where k_f is cleat permeability, with k_{f1} being initial and k_{f2} being dynamic (md), C_f is cleat volume compressibility (psi^{-1}), and σ_h is hydrostatic stress (psi). Alongside this equation, Seidle et al. (1992) derived the following model to quantify the permeability increase due to matrix shrinkage:

$$\frac{k_{f2}}{k_{f1}} = \frac{\left(1+\frac{2C_x\Delta p}{\phi_{f1}}\right)^3}{1-C_x\Delta p} \tag{3-13}$$

where C_x is the shrinkage coefficient (psi), Δp is the pressure change (psi), and ϕ_{f1} is cleat porosity.

Seidle and Huitt (1995) proposed another permeability model to study permeability changes caused solely by sorption-induced strain. The following model expresses permeability as a function of initial porosity, Langmuir strain constants, and pressure:

$$\frac{k}{k_0} = \left[1 + \left(1 + \frac{2}{\phi_0}\right) C_m V_m \left(\frac{\beta p_0}{1+\beta p_0} - \frac{\beta p}{1+\beta p}\right)\right]^3 \tag{3-14}$$

where k is the permeability, ϕ_0 is the initial porosity, C_m is the matrix swelling coefficient, V_m is the maximum amount of adsorption at infinite pressure, and β is the Langmuir constant (Pa^{-1}).

There are three assumptions behind this model. The first is that the coalbed is represented by a matchstick geometry. Second, swelling is proportional to the amount of gas adsorbed:

$$\varepsilon = C_m V_{ads} \tag{3-15}$$

where ε is the strain due to matrix swelling. Finally, adsorbed gas is related to pressure by the Langmuir equation:

$$V_{ads} = \frac{V_m Bp}{1+Bp} \tag{3-16}$$

Palmer and Mansoori (1998) developed a new geomechanics-based analytical permeability model that is still heavily used in the industry, although with a few modifications. This model is based on fundamental rock mechanics principles under uniaxial strain condition and matrix shrinkage. The model quantitatively describes cleat compression due to pore pressure fall-off and opening of cleats due to matrix shrinkage, which results in permeability changes over time. Permeability is described as a function of Young's modulus, Poisson's ratio, net strain, initial porosity, Langmuir strain constants, and pressure. The model is as follows:

$$\frac{k}{k_0} = \left[1 + \frac{C_m}{\phi_0}(p - p_0) + \frac{\varepsilon_\infty}{\phi_0}\left(\frac{K}{M} - 1\right)\left(\frac{\beta p}{1+\beta p} - \frac{\beta p_0}{1+\beta p_0}\right)\right]^3 \tag{3-17}$$

where k and k_0 are permeability and permeability at initial reservoir conditions (md), ϕ_0 is initial porosity at virgin reservoir pressure, K and M are bulk modulus and constrained axial modulus (psi), p and p_0 are reservoir pressure and initial reservoir pressure (psi), and ε_∞ (dimensionless) and β (psi^{-1}) are Langmuir-type parameters. The term C_m in the model describes mechanical strain due to changes in pressure, which is equal to:

$$C_m = \frac{1}{M} - \left(\frac{K}{M} + f - 1\right)\gamma \qquad (3\text{-}18)$$

where γ is grain compressibility (psi^{-1}) of coal and f is a fraction (0 to 1). The 1998 Palmer and Mansoori (P&M) model had one flaw, which was that field permeability could not always be matched without neglecting the permeability loss associated with effective stress increases (Palmer and Vaziri, 2004). Therefore, C_m (please note that this is different from eq. 3.15) was modified by Palmer et al. (2007) replacing "1" with the new g term, which compensated for this permeability loss as follows:

$$C_m = \frac{g}{M} - \left(\frac{K}{M} + f - 1\right)\gamma \qquad (3\text{-}19)$$

The last term in equation (3-17) defines the effect of sorption-induced strain. A part of the last term is defined as the change in volumetric strain as follows:

$$\Delta\varepsilon_v = \varepsilon_\infty\left(\frac{\beta p}{1+\beta p} - \frac{\beta p_0}{1+\beta p_0}\right) \qquad (3\text{-}20)$$

where $\Delta\varepsilon_v$ is the change in volumetric strain. This substitution allows for a more general form of the model (Clarkson et al., 2008), which is written as:

$$\frac{k}{k_0} = \left[1 + \frac{C_m}{\phi_0}(p - p_0) + \frac{1}{\phi_0}\left(\frac{K}{M} - 1\right)(\Delta\varepsilon_v)\right]^3 \qquad (3\text{-}21)$$

Shi and Durucan (2003) presented another complex permeability model for both stress-dependent permeability and matrix shrinkage terms under uniaxial strain conditions. This model states that changes in pore pressure are a function of changes in the effective horizontal stresses, given as:

$$\sigma - \sigma_0 = -\frac{v}{1-v}(p - p_0) + \left(\frac{E}{3(1-v)}\right)\varepsilon_\infty\left(\frac{p}{p+P_\varepsilon} - \frac{p_0}{p_0+P_\varepsilon}\right) \qquad (3\text{-}22)$$

where σ is the effective horizontal stress, v is Poisson's ratio, p is the reservoir pressure (psi), E is Young's modulus (psi), and ε_∞ (dimensionless) and P_ε (psi) are Langmuir-type shrinkage constants. Any parameter with a "0" subscript represents the corresponding parameter's value at initial reservoir conditions. With an established relationship for changes in horizontal stresses and pore pressure, the model can be related to a permeability change through the following:

$$\frac{k}{k_0} = \exp\left[-3C_f(\sigma - \sigma_0)\right] \tag{3-23}$$

where k is permeability, σ is effective horizontal stress, and C_f is cleat volume compressibility. After successfully matching the model to field data, Shi and Durucan (2003) claimed that if the initial reservoir pressure is high, the permeability should exhibit a rebound; however, if the starting pressure is lower, then permeability would increase from the start of production.

In order to create a new uniaxial strain permeability model, Cui and Bustin (2005) assumed that volumetric strain is a linear function of sorbed gas volume, rate of reservoir loading remains constant, and that the coal matrix is stiffer than bulk coal. The equation describes permeability variation with pressure drawdown for a CBM reservoir as follows:

$$\frac{k}{k_0} = exp\left\{\frac{3}{K_p}\left[\frac{(1+v)}{3(1+v)}(p - p_0) - \frac{2E}{9(1-v)}(\varepsilon_v - \varepsilon_{v0})\right]\right\} \tag{3-24}$$

where k is permeability, K_p is the modulus of pore volume (Pa), and ε_v and ε_{v0} describe the change in sorption-induced volumetric strain. The rest of the variables are the same as described by Shi and Durucan (2003).

A newer model by Ma et al. (2011) considers the volumetric balance between bulk coal, solid grain (matrix), and cleat pores. Whereas other models discussed so far have been based on the uniaxial strain concept, this one uses the constant volume assumption, first proposed by Massarotto et al. (2009). The fundamental concept for this model is that grain/matrix volume changes dynamically with reservoir depletion due to mechanical compression and sorption-induced strain. The variation in cleat aperture is calculated as a function of reservoir pressure using the grain/matrix volumetric variation, and the permeability variation is calculated based on matchstick geometry. The matchstick strain resulting from matrix shrinkage as reservoir pressure decreases is as follows:

$$\frac{\Delta a}{a} = -1 + \sqrt{1 + \varepsilon_1 \left(\frac{p_0}{P_L + p_0} - \frac{p}{P_L + p}\right)} + \frac{1 - v}{E}(p - p_0) \tag{3-25}$$

where $\frac{\Delta a}{a}$ is the horizontal strain in a single matchstick. The permeability change is calculated using the model from Harpalani and Chen (1997), which was listed earlier as equation (3-6). This model emphasizes the grain volume change and converts it to cleat volume, assuming that total volume remains constant.

Theoretical models discussed in this section have been presented as background on changes in CBM permeability modeling over time. This thesis will only be focusing on the 1998 P&M model since it is still the most commonly used model in the San Juan basin. However, it is important to present other models because they are commonly used in other geologic regions. All identified models provide a rough understanding of permeability changes over time for a CBM reservoir. Due to variability in coal geology, some models work better than others depending on coal type. Also, these models can be changed slightly to better fit specific needs of an individual reservoir.

3.4 LITERATURE REVIEW OF COAL ANISOTROPY

The first study to use volumetric strain for coal when talking about matrix shrinkage was Harpalani and Schraufnagel (1990b). They argued that volumetric strain decrease took place in the coal matrix, thus increasing the volume of voids. This study set the standard for matrix shrinkage/swelling experiments to use volumetric strain, which is still being used in many publications (Liu and Harpalani, 2014). It was a few years after this study that strain in orthogonal directions was measured in a laboratory setting, finding coal to swell anisotropically. It was not until recent years, however, that researchers have considered how this anisotropy can affect permeability modeling (Pan and Connell, 2011). This section presents studies on coal anisotropy and work that has been completed in recent years to consider how it affects permeability differently when considered over simple volumetric strain.

The first study finding coal to swell anisotropically was by Ceglarska-Stefańska and Czapliński (1993). They presented results for three Polish coals swelling more in the direction perpendicular to bedding than in the direction parallel to bedding. In the next few years, Levine (1996), and Larsen et al. (1997) both found swelling to be significantly greater in the perpendicular direction than in the direction parallel to bedding, with the first using methane as a sorbate and the latter using the chemical chlorobenzene. Similarly, Day et al. (2008) performed a shrinkage/swelling study on coal using carbon dioxide and found that swelling in the plane perpendicular to bedding was always substantially higher than in the plane parallel to bedding. Using coals from the Hunter Valley, Bowen, and Illawarra basins in Australia, this study found swelling in the perpendicular direction to be about 70% higher than in the parallel direction for Hunter Valley and Bowen basins and 30% higher in the Illawarra basin. The Hunter

Valley and Bowen basins are significantly lower in rank than the Illawarra basin, indicating that lower rank coals tend to show stronger anisotropic swelling.

The first modeling analysis performed specifically to account for anisotropy was by Pan and Connell (2011). The model developed in this study is an anisotropic swelling model based on Pan and Connell (2007). It was able to match coal swelling induced by nitrogen, methane, and carbon dioxide. The model is as follows:

$$\Delta\varepsilon_i = \frac{\Delta\sigma_i}{E_i} - \sum_{j=x,j\neq i}^{z}\left[\nu_{ij}\frac{\Delta\sigma_j}{E_j}\right] + \Delta\varepsilon_i^s + \alpha_i\Delta T \qquad i = x, y, z \tag{3-26}$$

where ε is strain; σ is stress (Pa); E is the elastic modulus (Pa); ν is Poisson's ratio; α is the Biot coefficient; T is temperature (K); superscript *s* is the solid phase; and x, y, and z are orthogonal directions.

This swelling model was found to be in close agreement with experimental swelling data for multiple gases. Furthermore, when anisotropic swelling was applied to a permeability model, the permeability prediction over the life of a well tended to vary significantly with the averaged swelling strain model, overestimating that of the anisotropic swelling model. The permeability model used for this study was the one developed by Shi and Durucan (2004), which was adapted as:

$$\Delta\sigma_x = \Delta\sigma_y = \frac{E_x}{E_z}\frac{\nu}{1-\nu}(-\Delta\alpha P) - \frac{E_x\Delta\varepsilon_x^S}{(1-\nu)} \tag{3-27}$$

where P is pressure (Pa) and all other variables are as defined above. In this model, stress is related to permeability by:

$$k_i = k_{i,0} e^{-3C_f(\sigma_i - \sigma_{i,0})} \tag{3-28}$$

where k is permeability (md) and C_f is the cleat compressibility (Pa^{-1}). It should be noted that in the end of the Pan and Connell (2011) study, permeability was significantly different when anisotropic strain was considered; however, the magnitude of the permeability difference when using the two methods to describe swelling strain may also depend on the permeability model used (Pan and Connell, 2011).

A second model was developed recently by Moore et al. (2015), which added anisotropy as an extension to the 1998 P&M model. This model was able to match the strong permeability increases in CBM wells documented in the San Juan basin for primary depletion. This study states that the two horizontal x and y directions in coal have similar elastic properties, which are less stiff than the vertical z direction due to the presence of coal cleats. This type of material is described by the transversely isotropic elastic model as follows:

$$\Delta\phi = \left\{\frac{1}{M} - (1-\phi) f \beta_g - \left[\frac{K}{M} - (1-\phi)\right]\beta_g + \left[\frac{K}{M} - (1-\phi)\right]\frac{\varepsilon_\infty P_\varepsilon}{(P_\varepsilon + P)^2}\right\}\Delta P \tag{3-29}$$

where ϕ is cleat porosity, M is constrained vertical modulus (psi), f is an empirical factor ranging from zero to one, β_g is grain compressibility (psi^{-1}), K is bulk modulus (psi), ε_∞ is the Langmuir strain parameter for matrix swelling/shrinkage at infinity, P_ε (P_L in other models) is the Langmuir pressure parameter for matrix swelling/shrinkage (psi), and P is reservoir pressure (psi). While this model is similar to the original P&M model on sight, the difference stems from the K and M components of the equation which have been altered to include two measured Young's moduli and three measured Poisson's ratios.

3.5 CHAPTER SUMMARY

Chapter 2 introduced the basic concepts of coalbed methane. This chapter has summarized how those basic concepts were used to develop empirical and theoretical models explaining the flow of coalbed methane in various locations and under varying conditions. Understanding matrix shrinkage, permeability modeling, and coal anisotropy modeling is critical in comprehending the need for a horizontal strain comparison to volumetric strain in permeability modeling. At this point, all of the background knowledge has been presented. The remainder of this thesis will focus on new content and steps taken to attain proper conclusions starting with a discussion of the experimental work presented in Chapter 4.

CHAPTER 4

EXPERIMENTAL WORK

4.1 INTRODUCTION

The coal used in this study was taken from the San Juan basin, outside the fairway – the most prolific area in the basin. This coal type had never been used in previous laboratory experiments of the type performed for this thesis making this work an exploratory process. In order to determine permeability modeling parameters for this coal type, an experimental study was required to measure strains in orthogonal x-, y-, and z-directions. The unconstrained shrinkage/swelling test was imperative to measure three parameters used in the P&M model, grain compressibility of coal (γ), maximum strain given infinite time (ε_∞), and Langmuir-type pressure (P_ε). By continuously monitoring the response of coal in a controlled environment with changes in pressure, large amounts of data were gathered to provide insight into the hypothesis of this thesis. This chapter highlights the processes that made obtaining data for the experiment a possibility, including the experimental equipment, testing techniques, and testing procedures.

4.2 MATRIX STRAIN (UNCONSTRAINED CONDITION)

4.2.1 Experimental Setup

The setup for an unconstrained matrix strain test is designed to measure mechanical compression of coal due to high pressure and shrinkage/swelling due to desorption/adsorption. This test allows for multiple samples to be tested concurrently, as shown in Figure 4.1. The primary equipment needed for this experiment are high pressure vessels and a pressure and strain monitoring and recording system. After some time into the experiment, it was noted that pressure and subsequent shrinkage/swelling were strongly dependent on temperature and samples were placed in a water bath to keep temperatures constant.

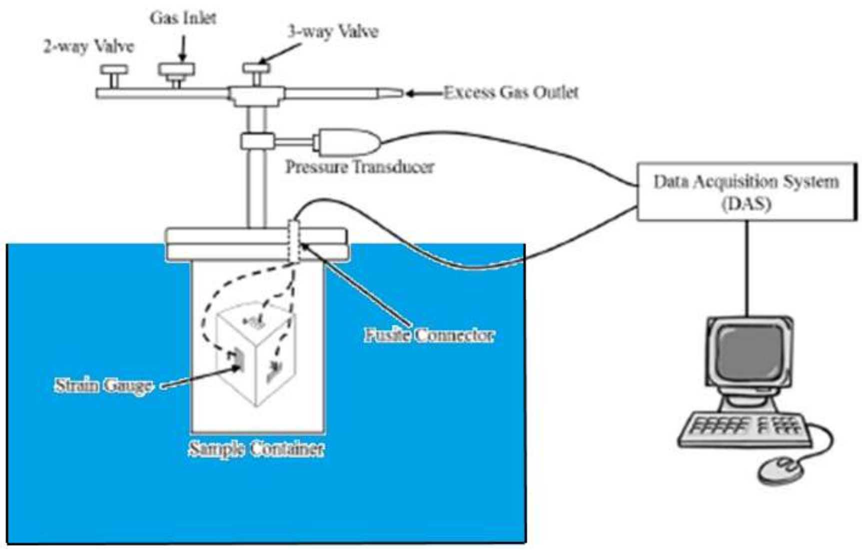

Figure 4.1 - Experimental setup for unconstrained matrix shrinkage test

4.2.2 Sample Preparation

Samples for this experiment were cut from cores drilled from outside the fairway in the San Juan basin as part of an exploratory test. Cores were trimmed into multiple samples using a saw and the best four samples were selected. These samples were picked based on low impurities, such as shale, a small number of large fractures, and overall size of the sample. Samples were then prepared to first determine the grain compressibility of the coal using helium, followed by shrinkage/swelling of the coal matrix with sorption of methane and carbon dioxide. After samples were cut, they were washed and polished to create smooth surfaces on sample faces. To measure strain, three strain gauges were affixed to each sample in the three orthogonal directions. Each strain gauge had to be on a flat and polished surface, free from any large cracks in the coal sample to ensure accurate results. Figure 4.2(a) shows a schematic of a typical coal sample with attached strain gauges, and Figure 4.2(b) shows the four samples used in this experiment.

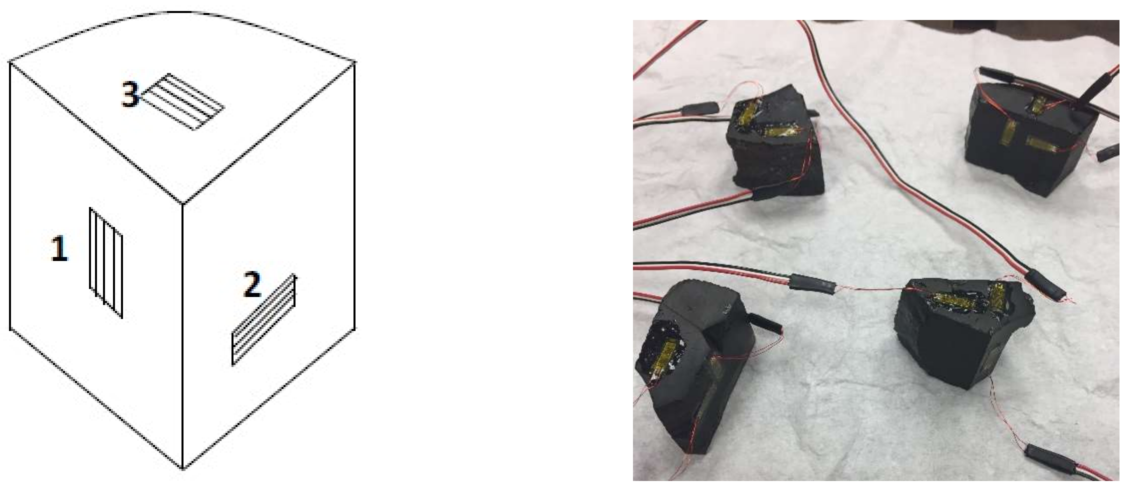

Figure 4.2 - Shrinkage swelling experiment sample: (a) schematic of a coal sample; and (b) actual samples used in experiment

4.2.3 Experimental Procedure

The first step of this experiment was to flood these samples with helium to determine grain compressibility, or change in volume of solid grains as a result of changes in external pressure. This was done by starting at lower pressure and increasing pressure in steps up to 1200psi for helium. Once equilibrium was attained at the final pressure step, samples were allowed to decompress by lowering pressure in steps while recording results at each step. Once a value for mechanical compression of samples had been attained, helium was completely bled out and three samples were flooded with methane, while one was flooded with carbon dioxide. Using a similar pressure step procedure as for helium, methane pressure was increased to

1100psi while carbon dioxide pressure was increased to 800psi. Then samples were allowed to swell until they reached equilibrium, or 100% gas sorption. Pressure was then lowered and the resulting shrinkage strain was recorded to attain desired data. Using measured strain data, volumetric and horizontal strain were calculated for each sample.

4.3 SUMMARY OF EXPERIMENTAL WORK

After experiments were completed, it was time to review and analyze measured data. The first step of this process was data reduction in order to turn tens of thousands of data points into a scaled-down, but representative, dataset of roughly twenty points for each experiment. This chapter has highlighted the experimental setup, sample preparation, and experimental procedure. The next chapter will present results of the experimental study and an analysis of those results.

CHAPTER 5

EXPERIMENTAL RESULTS AND ANALYSIS

5.1 INTRODUCTION

This chapter provides results obtained from the experimental work described in the previous chapter. The outcome of helium, methane, and carbon dioxide depletion tests are discussed as well as an assessment of the effect of methane shrinkage on vertical and horizontal strain. The results presented show the transversely isotropic behavior of the coal type tested, confirming the need for modifying permeability modeling, which is presented in Chapter 6.

5.2 MATRIX STRAIN RESULTS – UNCONSTRAINED CONDITION

5.2.1 Helium Depletion Results

The experimental phase involving helium was performed first in order to determine grain compressibility of coal. Grain compressibility is a critical parameter when doing a shrinkage experiment as it is needed to determine “true” shrinkage, or the amount a sample would shrink/swell if mechanical compression was not affecting it. Four samples were placed in high pressure vessels and flooded with helium in gradual steps up to 1200psi. When samples reached equilibrium at the final pressure, helium was bled out in a step-wise manner. Samples were considered to be in equilibrium when strain remained stable for more than 12 hours. Each step took roughly one to two days to complete, which, for the coal type tested, was a fairly fast process compared to subsequent experiments with methane and carbon dioxide. This can be attributed to helium being a non-sorbing gas with small molecular diameter and weight in comparison to other gases.

Three strain gauges attached to each sample in orthogonal directions allowed for calculation of volumetric strain throughout each experiment. As expected, the coal matrix volume increased with each step of depletion. Strain measured from helium depletion was due strictly to mechanical decompression of the coal matrix since helium is a non-sorbing gas. Results for two samples can be seen in Figure 5.1.

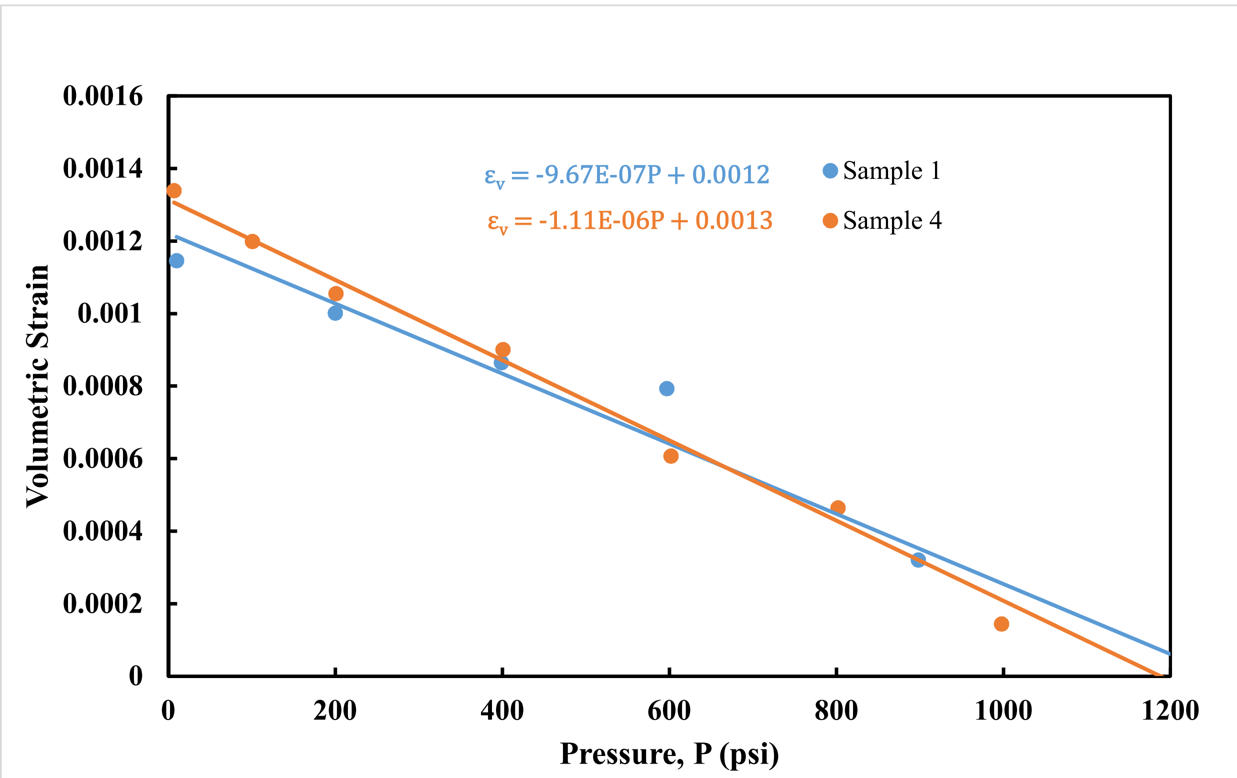

Figure 5.1 - Measured volumetric strain with helium depletion

Grain compressibility (C_g) is defined as the change in volume of solid grains as a result of changes in external pressure (P). Mathematically, grain compressibility is defined as:

$$C_g = \frac{1}{V_m}\left(\frac{dV_m}{dP}\right) \qquad (5\text{-}1)$$

where V_m is the volume for solid coal and dP is the change in pressure. Grain compressibility for the coal type tested was determined to be approximately -1.05E-6 psi^{-1} by averaging two sets of measured values. Results were fairly close for both samples.

5.2.2 Methane Depletion Results

The bulk of the experimental phase consisted of performing the matrix shrinkage procedure using methane as the sorbing gas. To do this, methane was injected into each sample canister in steps up to 1100psi. Once each sample reached equilibrium at that pressure, methane was depleted and resulting strains were measured. This phase took significantly longer than any of the other phases and resulted in the Langmuir-type pressure being much higher for methane than for carbon dioxide (discussed further in the next section). Whereas helium equilibrium took as little as one day, methane equilibrium took ten days or more.

Figure 5.2 shows raw methane depletion results for two methane samples. The two data sets from this part of the experiment were combined to establish a Langmuir-type model for volumetric strain using the equation:

$$\varepsilon = \frac{P*\varepsilon_\infty}{P+P_L} \qquad (5\text{-}2)$$

where P_L is the Langmuir-type pressure and ε_∞ is the maximum volumetric strain given infinite time (Levine, 1996). P_L and ε_∞ parameters were calculated from measured results and used to establish the model for the coal type tested. Similarities in these two coal samples are apparent when looking at raw shrinkage data, which gives values of negative strain due to starting at high pressure and measuring shrinkage with depletion. To simplify the modeling process, volumetric strain with depletion is made positive to follow the Langmuir isotherm trend. Maximum volumetric strain was found to be 0.0128 with a corresponding Langmuir-type pressure of 560psi. After grain compressibility was used to calculate the amount of mechanical compression due to pressure, true shrinkage parameters could be calculated. This was done by subtracting strain due to mechanical compression from measured matrix shrinkage strain, resulting in a higher overall total strain amount. Langmuir-type parameters were determined to be 0.0154 for ε_∞ and 664psi for P_L. Both modeled strain and true strain are shown in Figure 5.3.

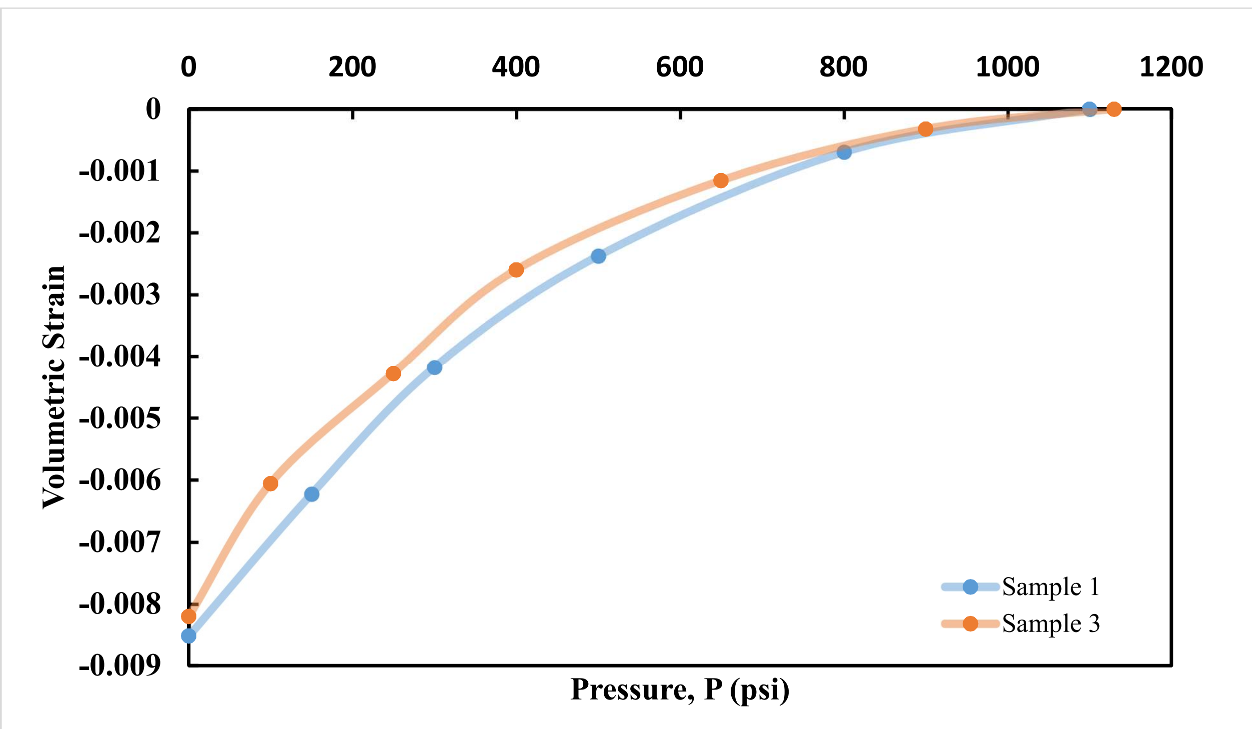

Figure 5.2 - Experimental data from methane shrinkage

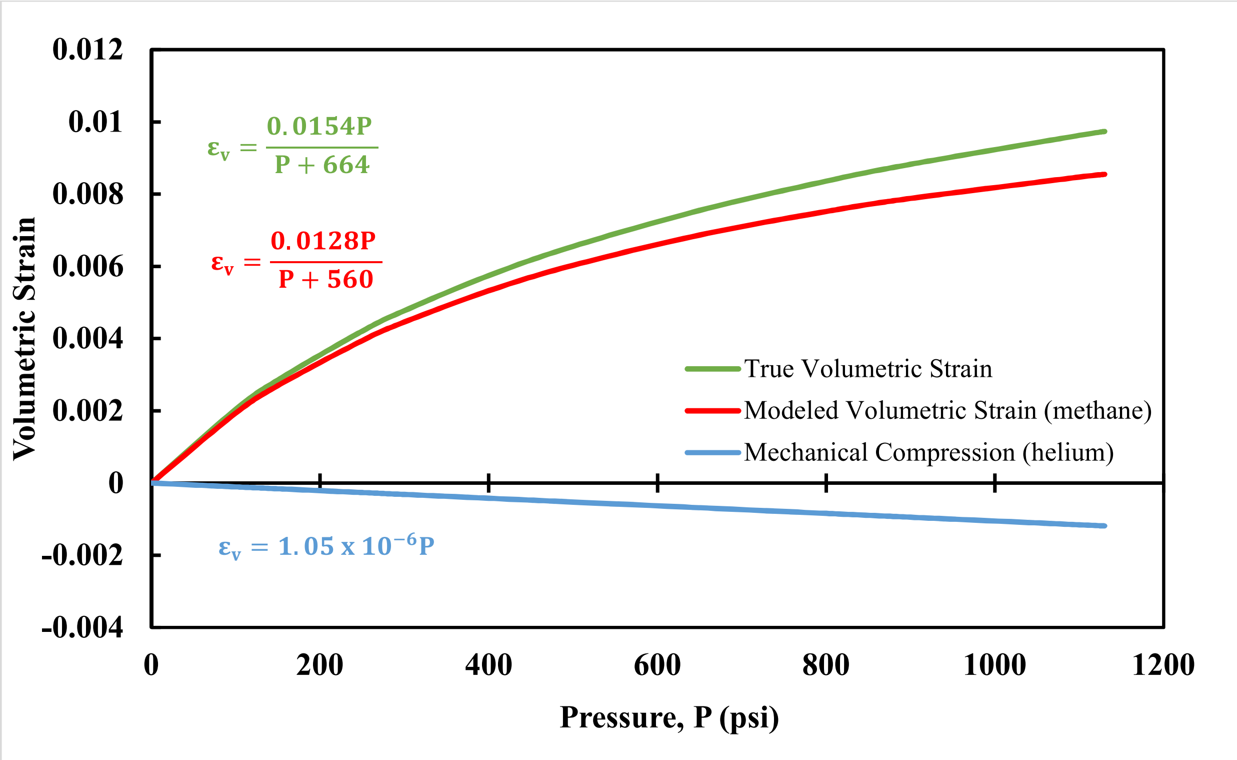

Figure 5.3 - Modeled and true volumetric strain with methane depletion

5.2.3 Carbon Dioxide Depletion Results

The experimental work using carbon dioxide was conducted using the same procedure as that used for methane. This sample, however, was only subjected to a maximum pressure of 800psi due to the fact that CO_2 transforms into a supercritical state at higher pressures. Furthermore, the partial pressure of CO_2 in situ is typically very low, thus justifying the use of lower pressure. In fact, for the area of the San Juan basin from whence the coal was retrieved, the concentration of CO_2 was ~1%. Hence, matrix shrinkage characteristics for CO_2 depletion were not really necessary or useful. Volumetric strains resulting from CO_2 depletion are shown in Figure 5.4. The corresponding transversely isotropic strain is not discussed given that this coal contains negligible CO_2; however, if the coal contained more CO_2, it would need to be included in any new or modified model.

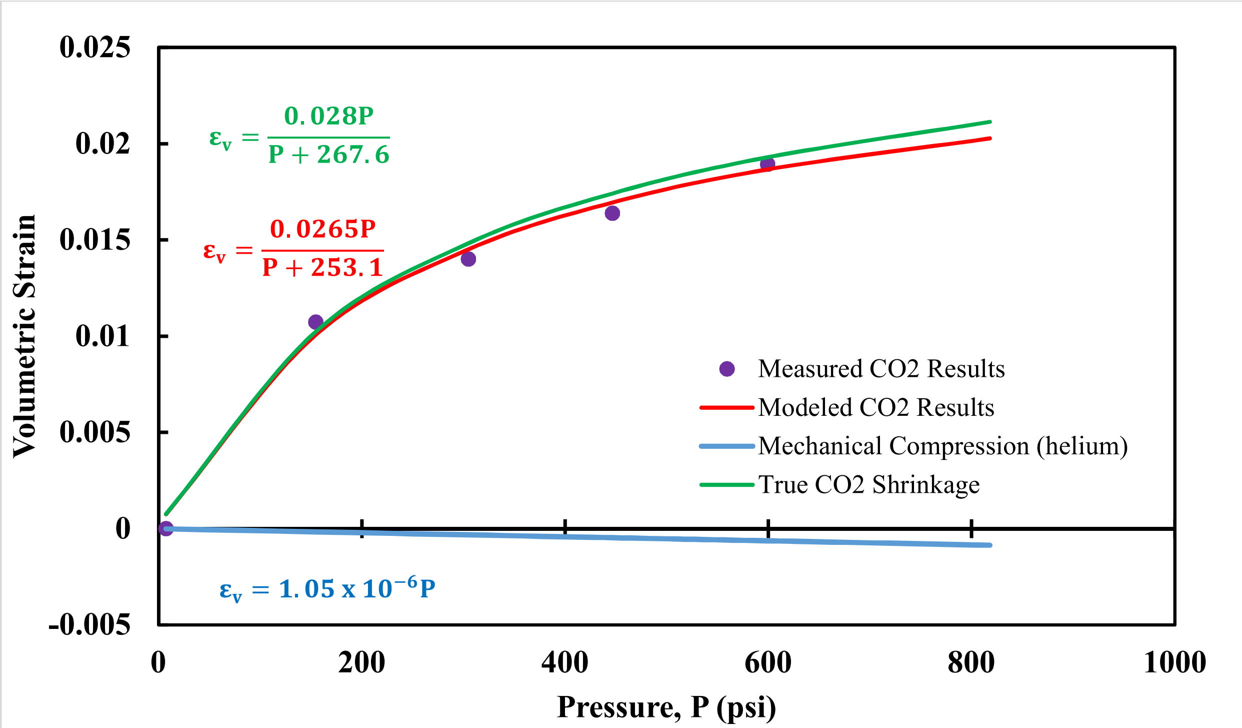

Figure 5.4 – Matrix shrinkage results with carbon dioxide

The true shrinkage ε_∞ value for CO_2 was calculated to be 0.028 with a P_L value of 268psi. The amount of strain from CO_2 shrinkage/swelling is roughly twice that of methane, while the Langmuir-type pressures are vastly different. The difference in P_L values means that methane takes significantly longer to fully adsorb or desorb from coal compared to CO_2.

5.3 COMPARISON OF VOLUMETRIC AND HORIZONTAL SHRINKAGE

The purpose of plotting results and establishing shrinkage constants, as presented in this section, is to show the difference in behavior between vertical strain and average horizontal strain, and to illustrate how this effect translates to volumetric strain compared to horizontal strain. By using the same modeling procedure detailed in Section 5.2.2, vertical strain was compared to average horizontal strain. After mechanical compression was accounted for, ε_∞values for vertical and horizontal average strains were calculated to be 0.0066 and 0.0044, respectively. This 50% increase from horizontal to vertical strain shows that vertical strain impacts volumetric strain results significantly more than horizontal strain in either horizontal direction. Figure 5.5 shows modeled values with their corresponding equations.

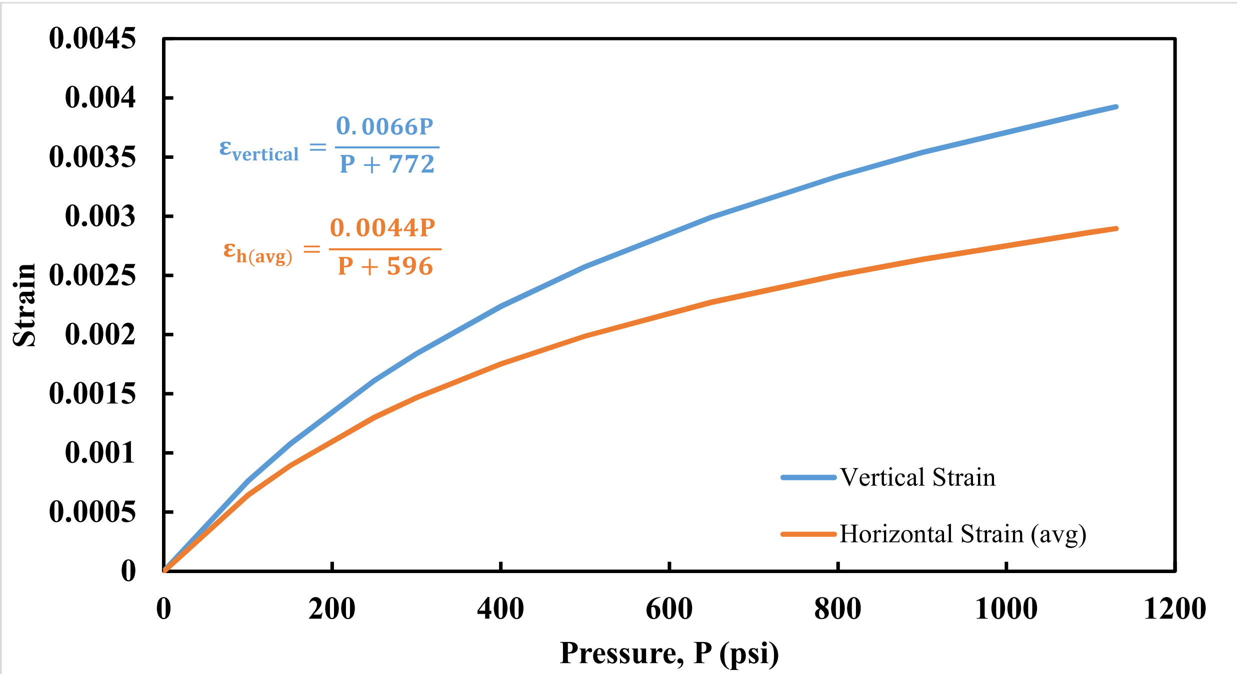

Figure 5.5 - Modeled values of true shrinkage for vertical and horizontal (avg.) strains

The discrepancy between horizontal and vertical strain translates directly into the volumetric versus horizontal strain, as seen in Figure 5.6. Using the Langmuir-type model for volumetric strain, values of ε_{∞} and P_L were calculated for volumetric strain as $\varepsilon_{\infty(v)} = 0.0154$ and $P_{L(v)}$ = 664psi. Although the model is for volumetric strain, it can also be applied for horizontal strain by removing the value for vertical strain. These values were calculated as $\varepsilon_{\infty(h)} = 0.0088$ and $P_{L(h)}$ = 596psi. Horizontal strain makes up two out of three orthogonal directions measured when calculating volumetric strain (ε_x and ε_y). For the coal type tested, however, it constitutes only 57% of modeled volumetric strain, meaning vertical strain contributes a disproportionate amount of the volumetric strain value. Comparing $\varepsilon_{\infty(v)}$

(volumetric strain) and $\varepsilon_{\infty(h)}$ (horizontal strain) values suggests that there should be a significant difference in the outcome of the permeability models using each respective parameter. Although the difference in $P_{L(v)}$ (Langmuir-type pressure for volumetric strain) and $P_{L(h)}$ (Langmuir-type pressure for horizontal strain) is less substantial than for ε_∞ values, it also impacts permeability modeling results. Thus, when all other factors were kept constant, permeability models gave significantly different results when using Langmuir-type pressure for volumetric strain versus when using Langmuir-type pressure for horizontal strain.

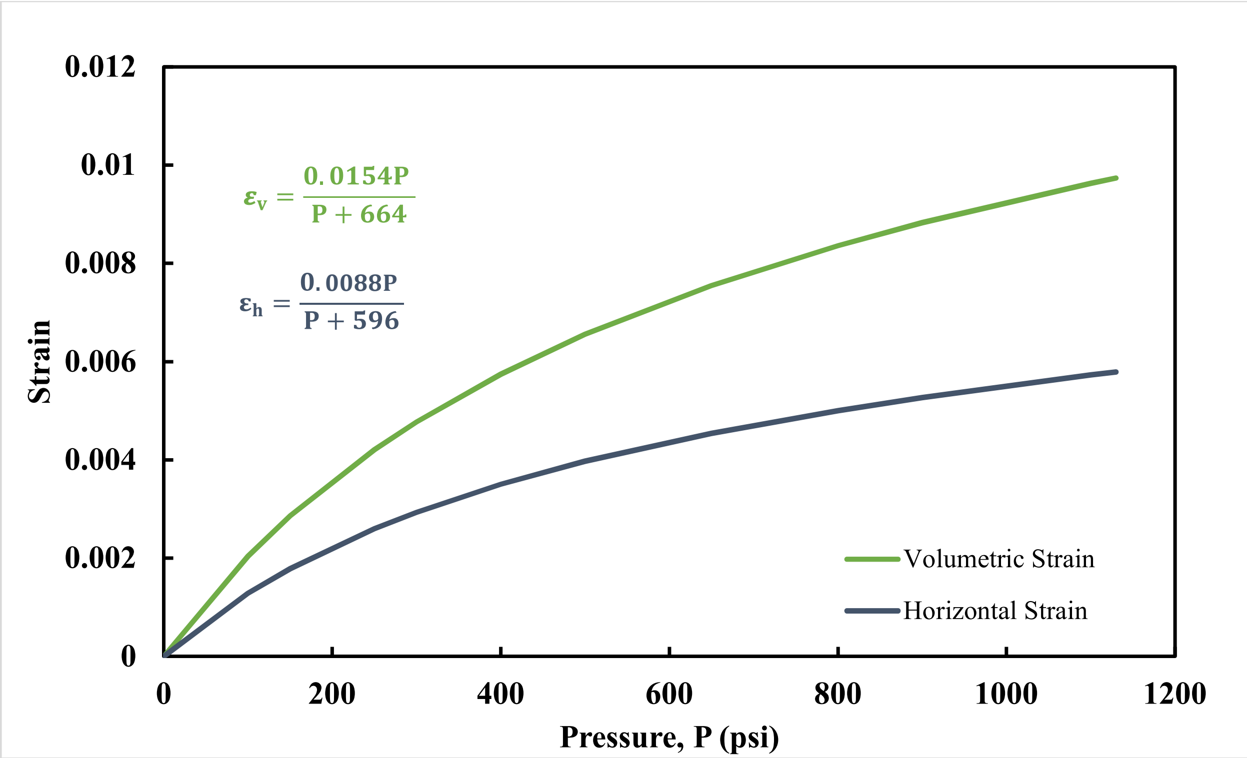

Figure 5.6 - Modeled values of true shrinkage for volumetric and horizontal strains

5.4 SUMMARY OF EXPERIMENTAL RESULTS

This chapter summarizes results from a shrinkage/swelling experiment on a type of San Juan basin coal that has not been tested prior to this experimental study. When horizontal and vertical strains were compared, it was found that vertical strain is significantly higher than horizontal strain. This experiment was performed for the purpose of gathering data to test the theory that using horizontal strain as a parameter would result in a different permeability trend than using volumetric strain as a parameter. Since horizontal strain substantially affects increases in coal permeability with methane and carbon dioxide depletion, it is important that it is not underrepresented in any permeability modeling exercise. The next chapter will cover modifying the permeability model used and subsequent results when using each of these parameters.

CHAPTER 6

PERMEABILITY MODELING RESULTS

6.1 INTRODUCTION

The overall goal of this thesis was to assess the difference in modeled permeability variation using volumetric strain as the input parameter versus using only horizontal strain as the input parameter. The previous chapter illustrated calculated differences in values of $\varepsilon_{\infty(v)}$ versus $\varepsilon_{\infty(h)}$ and $P_{L(v)}$ versus $P_{L(h)}$. This chapter shows results for modeled permeability variation using the P&M model, given as follows:

$$\frac{k}{k_0} = \left[1 + \frac{C_m}{\phi_0}(p - p_0) + \frac{\varepsilon_\infty}{\phi_0}\left(\frac{K}{M} - 1\right)\left(\frac{\beta p}{1+\beta p} - \frac{\beta p_0}{1+\beta p_0}\right)\right]^3 \quad (3\text{-}17)$$

(Nomenclature can be found with equation (3-17) in Chapter 3.) The purpose of permeability modeling in the industry is to match estimated permeability with modeled permeability and, after obtaining a good match, predict future permeability variation and, hence, long-term production. In the above model, there are three modeling variables that serve as "matching parameters." The first is initial porosity, ϕ_0. This is a difficult parameter to measure in the laboratory as well as in the field. The most reliable estimates are based on the amount of water produced during initial dewatering. The other two parameters are f and g terms, both of which are included in the term, C_m, as follows:

$$C_m = \frac{g}{M} - \left(\frac{K}{M} + f - 1\right)\gamma \quad (3\text{-}19)$$

These parameters can impact results of the model significantly. They need to be varied in order to find the best match between experimental and modeled data. Estimates and, for two of them, ranges are available for these parameters in recent literature. However, almost all of the work published in the past is for coal from the San Juan basin fairway, with practically nothing for coal from outside the fairway. The thrust of this thesis is not a permeability matching exercise; rather it is to assess the difference in permeability modeling results using volumetric strain parameters versus only horizontal strain parameters. This chapter assesses that difference and then takes horizontal strain modeling one step further by determining the amount of variance caused by changing each of the three unknown parameters, within a reasonable range, and coming up with a reasonable permeability variation range.

6.2 IMPACT OF HORIZONTAL VERSUS VOLUMETRIC STRAIN ON MODELED PERMEABILITY

Input parameters used in P&M permeability modeling are shown in Table 6.1. Values for β, ε_{∞}, P_L, and γ are obtained straight from experimental data presented in Chapter 5. Young's Modulus, E, and Poisson's Ratio, ν, are also the result of measured laboratory data for the coal type tested, although not as part of this experiment. Hence, the level of confidence in these parameters is excellent. The parameters shaded in yellow are the three variables that are not known. Initial porosity, ϕ_0, for San Juan basin fairway coals used by modelers in the past are in the 0.1% – 0.043% range (Clarkson et al., 2010). Based on the pressure-dependent-permeability work completed, the coal type tested in experiments for this thesis has lower permeability than that typically measured in the laboratory for fairway coals. Hence, an initial porosity value of 0.06% was chosen for the initial permeability assessment. However, later on, values of initial porosity were varied to show the effect it has on permeability variation with depletion. Values for f were also chosen in the middle of the typical range, which is usually 0.5-1. The unknown parameter, g, is used to compensate for the ratio of horizontal stiffness compared to vertical stiffness. The typical range for this parameter is 0.1-1, however other literature indicates it can be higher than 1 (Pan and Connell, 2011). Due to this coal having an unusually high Young's Modulus, g was chosen to be on the higher end, at 0.8.

Table 6.1- Modeling parameters for Palmer and Mansoori permeability model

Strain Type	ε_∞	$P_{(L)}$ (psi)	β (psi^{-1})	ϕ_0	p_0 (psi)	K (psi)
Volumetric	0.0154	664	0.00151	0.0006	1100	583333
Horizontal	0.0088	596	0.00168			

M (psi)	C(m) (psi^{-1})	f	γ (psi^{-1})	E (psi)	ν	g
942308	6.19E-07	0.6	1.1E-06	700000	0.3	0.8

Figure 6.1 shows modeled results obtained for permeability variation from 1100psi down to 50psi. The difference in modeling results obtained using volumetric strain versus horizontal strain is dramatic, to say the least. While permeability remains close during initial conditions, that is, at high pressures, volumetric strain takes off exponentially around 300psi while the horizontal strain increase is much less dramatic. Accuracy of a permeability prediction model strongly depends on values of the three unmeasured parameters ϕ_0, f, and g, but when they are kept constant and only Langmuir-type parameters are changed, the difference is significant. This confirms the hypothesis that there will be a difference in P&M modeling results when using volumetric versus horizontal strains.

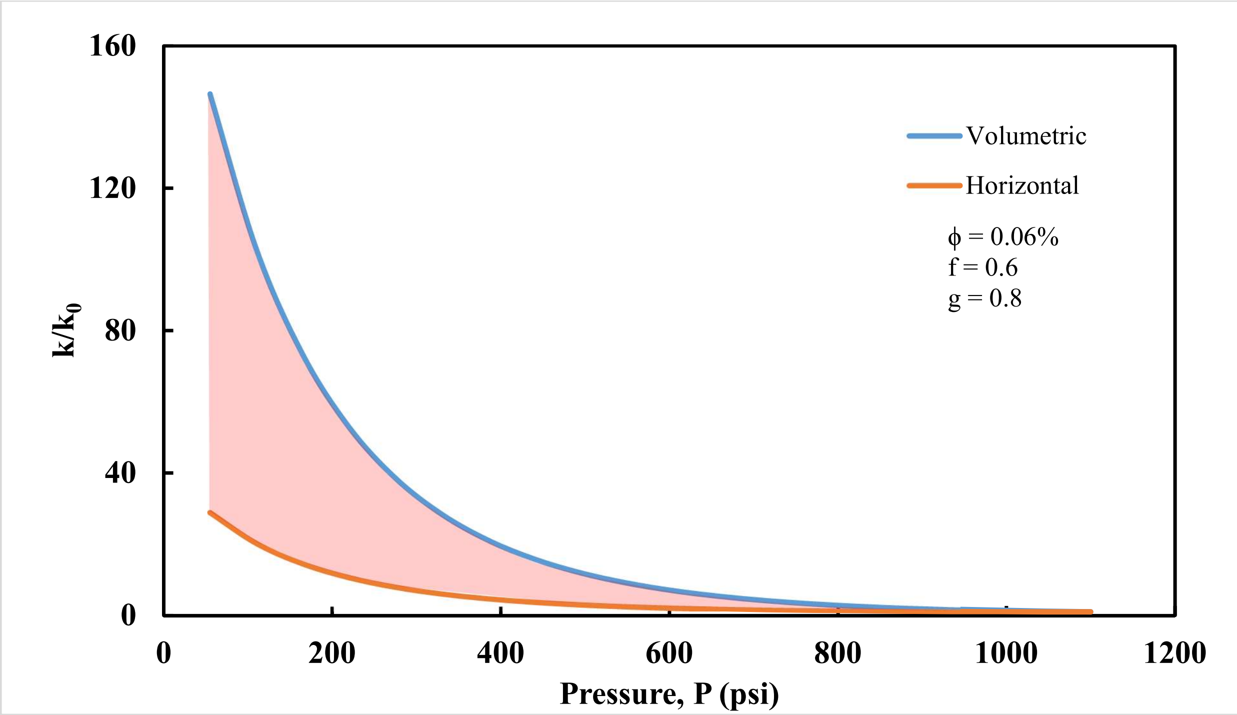

Figure 6.1 - Variation in permeability when using volumetric strain and horizontal strain

6.3 HORIZONTAL PERMEABILITY VARIATION

The confirmation of the difference when modeling using volumetric and horizontal strains in the P&M model now needs to be taken one step further. As previously stated, the three unknown parameters significantly affect model results. Permeability modeling is simply a history matching exercise to match laboratory-based results with modeling results, with the end goal being a good handle on values of parameters f and g. This section shows variations in the P&M permeability model for horizontal strain when assuming high and low values for these unmeasured parameters.

6.3.1 Variation in Porosity, f, and g Modeling Parameters

The most significant difference in permeability variation results comes from changing initial porosity, as shown in Figure 6.2. Previous research has shown that porosity of San Juan basin coal from the fairway can be as low as 0.043% and as high as 0.1%. Assumed high and low values for this exercise are based on that range and were set at 0.09% and 0.04%, respectively. Higher porosity at the start of pressure depletion leads to a lower k/k_0 ratio at lower pressures compared to a much higher k/k_0 ratio when initial porosity is lower at the start of pressure depletion. This behavior is well accepted for CBM permeability modeling of San Juan basin coals. This parameter has the most drastic effect on permeability modeling results with k/k_0 ratios ranging from as low as ~13 to as high as ~70 at 55psi.

While f and g also have an effect on the modeled k/k_0 ratio, the range of each is not as dramatic as it is for porosity. The effect of unmeasured parameter, f, can be seen in Figure 6.3, where the increase in permeability ranged from ~20 to ~50 at 55psi. Figure 6.4 shows the difference in using higher versus lower assumed g values. The k/k_0 ratio range from ~50 with a low g value to ~25 with a high g value. In Figures 6.2-6.5, the highlighted area shows the difference in modeled changes in permeability for different values of input parameters. It represents a range of all possible values that the k/k_0 ratio could be if the respective parameter were changed. The amount variation for each of the three unknown parameters was selected based on typical values used when modeling. The g parameter ranges anywhere from 0.1 to 1. With this being a strong coal, it is more appropriate to use the range between 0.5 and 0.9. The f parameter is the one that is the most in question. Recent publications suggest a range from 0.5 to 1 (Moore et al., 2015), but this exercise used 0.4 to 0.9.

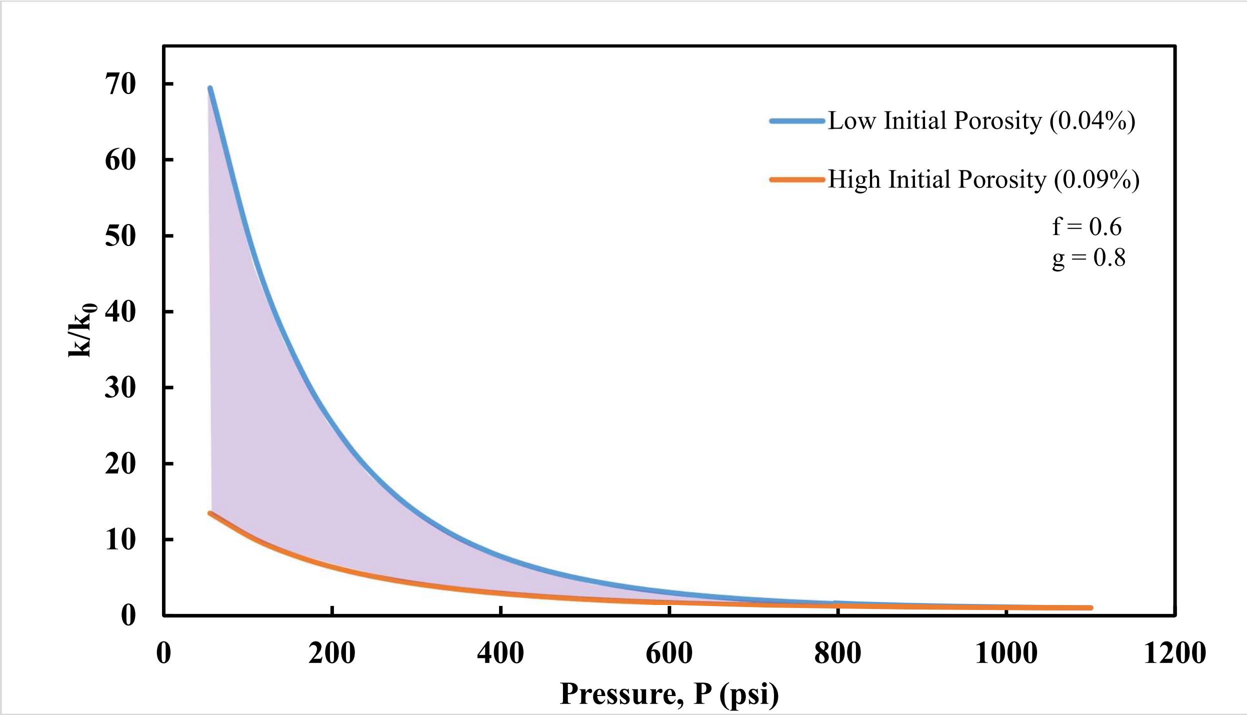

Figure 6.2 - Variation in permeability with high and low values of initial porosity

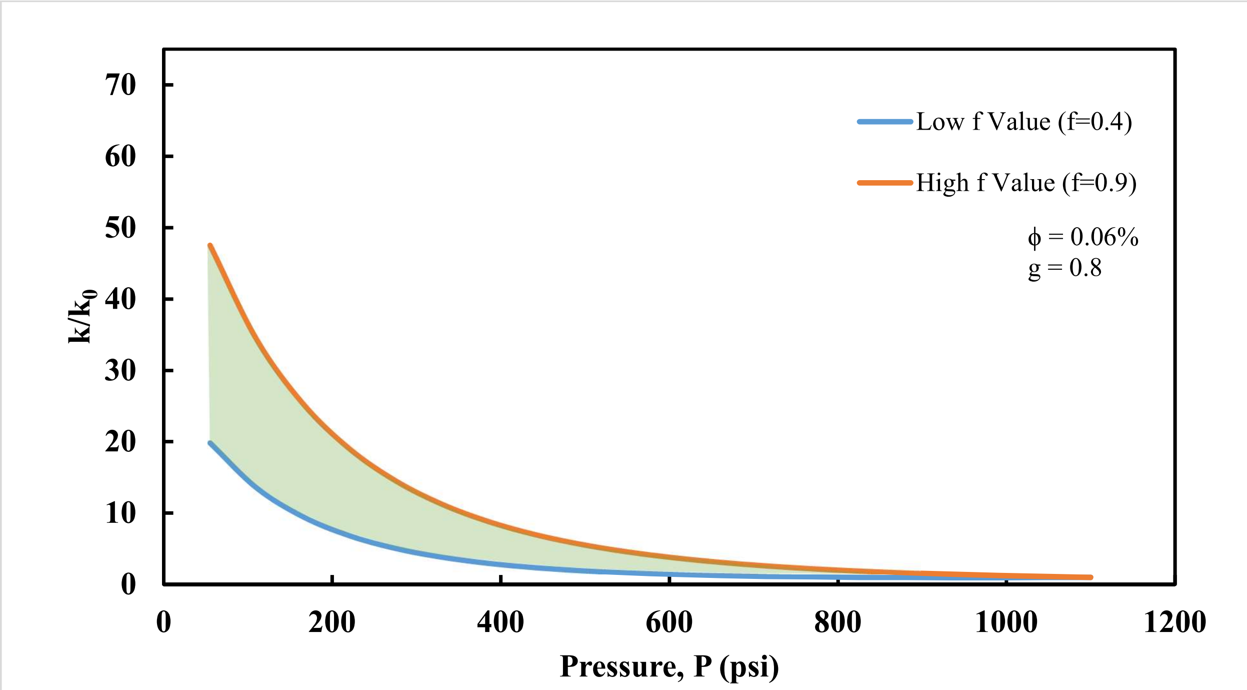

Figure 6.3 - Variation in permeability with high and low values of f

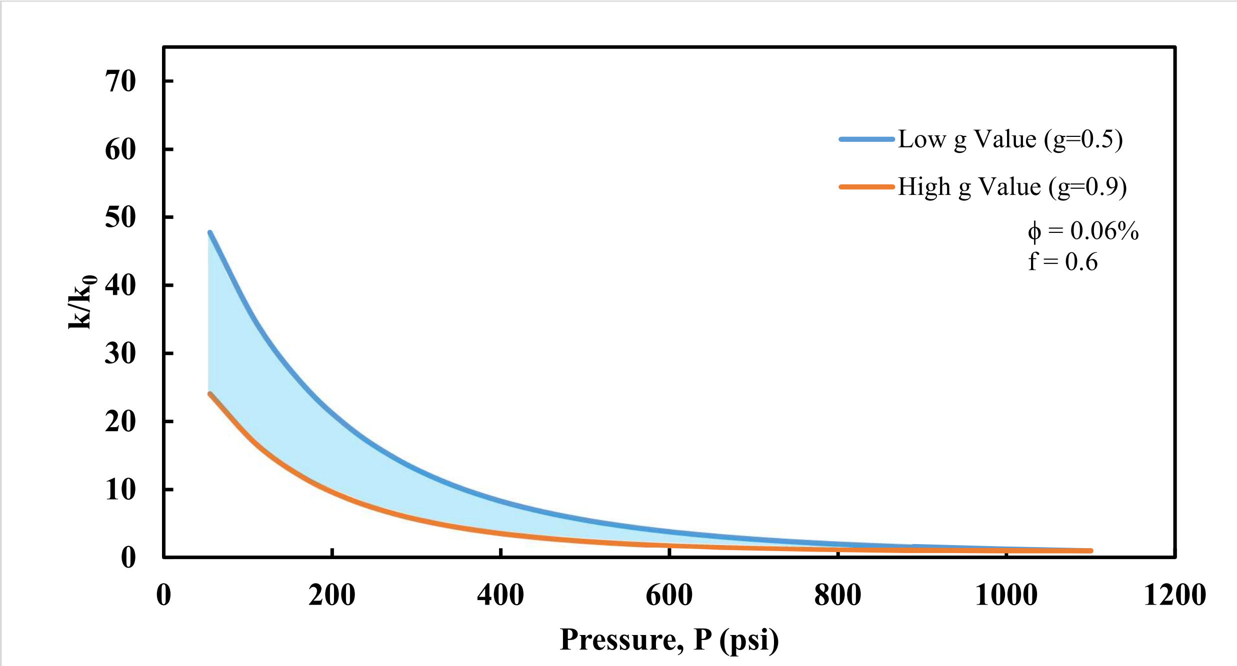

Figure 6.4 - Variation in permeability with high and low values of g

6.3.2 Combined Results

The six modeled variations in permeability shown in Figures 6.2-6.4 were obtained using different higher and lower assumed values for three unmeasured parameters in the P&M model. When combined, they represent an overall range for measured permeability change given available laboratory data. Figure 6.5 was made by taking the highest "low" plot and the lowest "high" plot from all six models to find the middle range for all three unknown parameters. Due to the initial porosity having such a large effect on the modeled k/k_0 ratio, Figure 6.6 was made to show the difference in modeling when porosity is changed from 0.06% to 0.04%. Results show that a lower initial porosity for this coal would result in much higher permeability increases at lower pressures.

The bottom line for these combined permeability modeling results is that all three unknown parameters have a major effect on k/k_0 ratio results. In order to provide accurate results, history matching needs to be performed. The most influential parameter is initial porosity. The other two parameters, f and g, have smaller effects on modeling results; however, they are still important for history matching. When compared with measured data, modeled data should be able to be matched accurately.

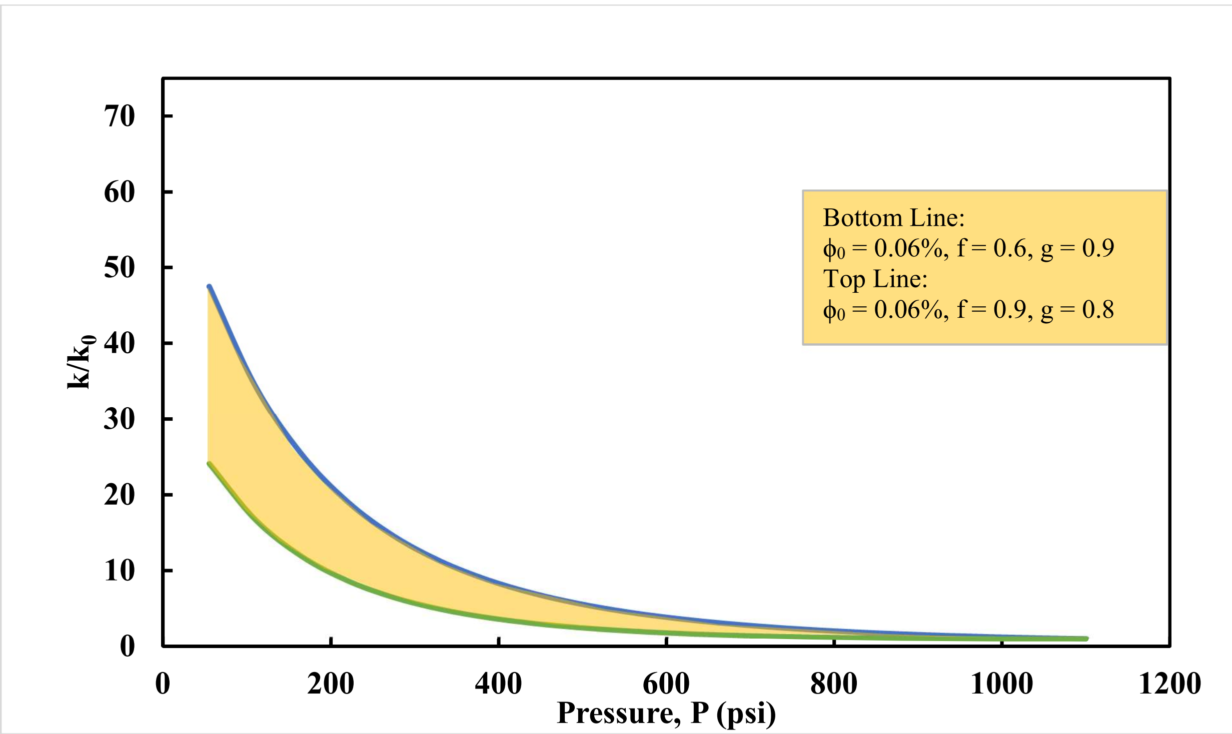

Figure 6.5 - Combined result for permeability variation using horizontal strain

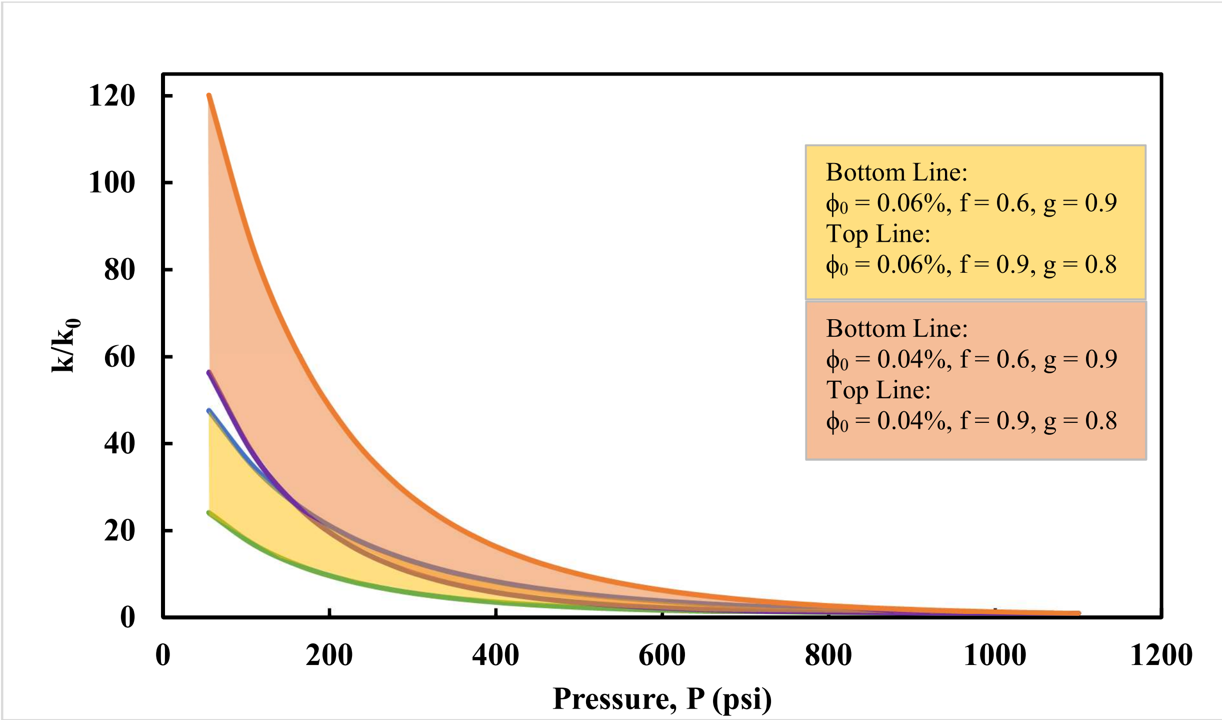

Figure 6.6 – Combined result for permeability when initial porosity is varied from 0.04% to 0.06%

6.4 SUMMARY OF PERMEABILITY MODELING

As seen in the graphs presented in this chapter, permeability variation when modeling is highly dependent on input parameters used in the P&M model. The result is a wide range of possible k/k_0 ratios. It is difficult to correctly guess the three unknown parameters in this model, which is why the permeability model needs measured data to compare with modeled results. While data may not be available to accurately model k/k_0 ratios for the coal type tested, it is apparent that horizontal strain does indeed present different modeling results when compared with volumetric strain, all other factors remaining constant. Horizontal strain results in much lower predictions of permeability change, confirming the most significant claim in this thesis.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

This thesis presents an experimental study aimed at assessing the difference in the results of the Palmer and Mansoori model for permeability variation when using two different variations of the matrix shrinkage parameter: volumetric versus horizontal strain. This process included a matrix strain experiment where strain was measured in three orthogonal directions by flooding coal samples with helium, followed by methane. Experimental data was used to determine Langmuir-type constants describing volumetric and horizontal strain. Based on results obtained from the experimental work and subsequent analysis, several conclusions are made as summarized below:

1. Under unconstrained conditions, volumetric strain for helium depletion varies linearly with depletion. However, methane and carbon dioxide depletion both follow Langmuir-type curves. This type of behavior is in agreement with several previously reported experimental studies. This part of the experiment was carried out in order to determine the grain compressibility of coal and to determine the amount of matrix shrinkage that occurs as a result of methane/carbon dioxide depletion. This was a necessary step, as knowing grain compressibility is critical for permeability modeling. Results supported the main argument in this thesis.
2. Under unconstrained conditions, the coal type tested behaved as a transversely isotropic medium during depletion. The two orthogonal horizontal directions illustrated isotropic

strain, but there was a significant difference when compared with strain in the vertical direction. This behavior is in agreement with multiple older and newer research studies. Each horizontal strain was on average two-thirds of the total vertical strain. Since vertical strain does not have as large an effect on permeability changes as horizontal strain, vertical strain may be disproportionately affecting results of current permeability models. This can have significant implications in the field due to the error introduced in permeability predictions.

3. Using the Palmer and Mansoori permeability model with volumetric strain predicts significantly higher changes in permeability during pressure depletion than using the same model with horizontal strain alone. Due to the large difference in permeability modeling results, when keeping all other parameters the same, volumetric strain could be overestimating the change in permeability with pressure depletion. Horizontal strain alone predicts smaller permeability changes at higher pressures than volumetric strain, which is in agreement with laboratory data. This shows a need for additional work in this area to determine which strain type is more accurate for permeability modeling. This can be done through history matching of measured data.

7.2 RECOMMENDATIONS FOR FUTURE WORK

Based on the knowledge acquired in this study, it is recommended that the following topics should be pursued further:

1. This study validates the hypothesis that the Palmer and Mansoori model using volumetric and horizontal strain parameters provide different results. In order to determine which type

of parameter provides more accurate results, the model using volumetric and horizontal strain should be rigorously tested and history matched with previously measured permeability data for San Juan basin fairway coals. This could provide a definitive understanding of how much vertical strain has been skewing permeability models using volumetric strain. This should be followed up with matching field permeability variations with modeled variations using horizontal strain alone.

2. In order to confirm the results of this study, a similar experimental study should be performed using a different permeability model, such as Shi and Durucan. This will help establish that the difference is significant, regardless of the model used, and provoke a discussion on the argument for changing both permeability models to be based only on horizontal strain instead of the current use of volumetric strain.

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Thesis Paper Title: MODIFICATION OF A CURRENT COALBED METHANE PERMEABILITY MODEL FOR HORIZONTAL STRAIN ONLY

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