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Comparing the Hydrodynamic Response of Fracture Shearing in Marcellus and Eau Claire Shales

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**Thesis submitted to the
Benjamin Statler College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements for the degree of
Master of Science in Energy Systems Engineering**

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Abstract

Comparing the Hydrodynamic Response of Fracture Shearing in Marcellus and Eau Claire Shale

Matthew Stadelman

Three samples of Marcellus and Eau Claire shales were sheared in a modified Hassler style core holder. Before testing and after each shear step, the hydraulic transmissivity was measured and a high-resolution 3-D image taken using a computer tomography (CT) scanner, resolution ranged from 26.7 to 27.6 microns. Each sample was sheared four to eight times during a test providing a total of 37 fracture geometries. The 3-D binary images of each fracture were processed based on a voxel connectivity graph, removing any clusters that were not connected to the main fracture. Two-dimensional aperture maps were then generated by flattening the 3-D image along the Y-axis creating a mesh to perform modified local cubic law simulations (MLCL) on. Experimental data were compared against MLCL simulations run on aperture maps produced before and after cluster processing to assess the effectiveness of this technique. Additionally, the discrepancy between experimental data and simulation results was investigated relative to several geometric parameters known to affect the accuracy of this MLCL formulation relative to a full Navier-Stokes simulation.

Cluster processing improved the agreement between experimental and simulated transmissivity and reduced the roughening effects of disconnected void space has when incorporated into the aperture map. The simulation error had no discernible relationship to the geometric parameters tested, indicating that the primary source of error is not the simplified physics of the MLCL model. This corroborates with results presented in a related study by Mofakham, et al. (2017). The cluster processed geometries were then used to compare the shearing responses of the Marcellus and Eau Claire shale families. Both sample sets are shown to have a very similar response to shearing when evaluated against multiple geometric and statistical quantities. Knowing that these distinctly different shales behave in a parallel fashion is an important step in understanding how sensitive shearing is to lithology composition and how applicable research performed in one region is to another.

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1. Introduction

Subsurface fluid flow is a dynamic and challenging field of research with far reaching implications for several industries, including hydrocarbon recovery, geothermal energy, carbon dioxide (CO₂) storage, and nuclear waste storage. In all cases, fractures represent the main conduit for flow in the rock strata and are even more critical in low permeability units. Understanding how fluid flows through rough natural fractures is of high importance and has been the subject of active study for the last 60 years dating back to the work of Lomize (1951), Romm (1966) and Louis (1969).

However, to understand what happens statically is not sufficient to fully characterize reservoir behavior. The conditions underground are dynamic. Fractures are constantly being shaped by naturally evolving stress fields and engineering activities such as hydraulic fracturing and fluid withdrawal from reservoirs (Yeo, 1998, Matsuki, et al., 2010, Crandall, et al., 2017). Stresses normal and parallel to the fracture surfaces can play a significant role in shaping the geometry of the fracture by changing the aperture distribution and crushing asperities on the fracture surface into material that can clog the fracture, commonly known as gouge.

Shear movement is common underground because preexisting fractures are zones of weakness in the strata and it often requires less force to reactivate a fracture than to fracture existing rock (Olsson, 2001, Crandall, et al., 2017). Several research studies have been conducted to examine the hydrodynamic response of fractures to normal and

shear stresses (Auradou, et al., 2006, Koyama, et al. 2008, Xiong, et al. 2011, Crandall, et al., 2017, Mofakham, et al. 2017).

One of the primary issues in subsurface research is the inability to collect direct measurements of rock and fracture properties. Rock characteristics can be extremely heterogeneous even within local regions of the same strata (Heller, 2014a); the same applies to the geometry of the fractures within (Xiong, et al., 2011). At the lab scale, very exact measurements of both mineralogy and geometry are possible, but still present several challenges. Early methods to characterize the internal geometry of fractures used techniques such as profilometry and resin casting (Brown, et al., 1985, Olsson, 1993, Hakami, et al., 1996, Brown, et al., 1998, Auradou, et al., 2006). Later techniques began to focus on non-destructive tests which used magnetic resonance imaging (MRI) and X-ray computed tomography (CT) scanners (Keller, 1998, Blunt, 2001, Karpyn, et al. 2008, Cnudde 2013, Crandall, et al., 2016). The key advantage of non-destructive measurements is that they are non-destructive, allowing for intermittent measurements throughout the experiment without interruption.

Accurate measurements of fracture geometry from any of the above methods open the door for numerical simulation of fluid flow. A single fracture is the primary building block of large discrete fracture networks used in reservoir simulation. Without a proper understanding of the hydraulic parameters acting within a single fracture it is impossible to accurately simulate large networks. As such, several studies have been performed to better understand the factors affecting fluid flow in both natural and numerically generated fractures (Tsang, et al. 1980, Brown, et al., 1995, Ge 1997, Brush, et al., 2003). To

provide context for the rest of the study a rough fracture is depicted in Figure 1, and the vertical aperture was used in aperture map creation.

Figure 1: Macroscopic fracture geometry with two aperture measurements (Crandall, et al. 2010)

The primary parameter is the aperture distribution within the fracture and as seen in Figure 1 is highly variable along the fracture length. Other key values studied in literature include aperture standard deviation, fractal dimension, aperture spatial frequency and contact area (Brown, et al., 1985, Brown 1987, Brush, et al., 2003). These can have significant effects on the flow, causing the fluid to channelize and follow a tortuous path, and must be properly accounted for either directly or implicitly by the numerical scheme.

The cubic law represents the highest level of simplification possible to model fracture flow. It simplifies the problem down to a single linear equation based on the one-dimensional solution of the Navier-Stokes equations for viscous flow between parallel plates (Brown, et al., 1995). All the parameters must be incorporated properly into the cubic law for it to accurately represent the hydraulic conductivity. To date there are many theories on how to account for different mechanical factors when calculating a cubic law based aperture. However, no universal relationship has been found thus far, nor it is

expected that one based on solely mechanical properties will be found (Brown, et al., 1995, Ge, 1997). The local cubic law offers a better approximation to real fluid flow in rough complex fractures by only assuming the cubic law holds over short distances or “locally” and allowing the overall aperture to vary smoothly (Brown, 1987, Zimmerman, et al. 1991, Ge 1997, Brush, et al., 2003). It is based on the two-dimensional Reynolds Lubrication equation which is a simplification of the full Navier-Stokes equations removing the inertial terms that make the problem nonlinear. While the local cubic law is well known to over predict flow (or transmissivity) by a large amount for complex geometries, it offers a middle ground between the cubic law and the full Navier-Stokes equations. Even with the powerful computing facilities available today, creating a viable mesh and running a full physics simulation of flow through a natural fracture is a nontrivial task (Crandall, et al., 2010). Therefore, the local cubic law remains a valuable tool for studying the flow through fractures.

In addition to understanding the general properties of flow through fractures there is also a need to understand what effects mineralogy has on fluid flow. Many different strata are targeted for different purposes. Crystalline rocks such as granite and marble are desirable to safely store hazardous wastes because of their small matrix permeability (Brown, et al., 1985, Hakami, et al., 1996). Shales are sought out both for their potential hydrocarbon resources and the ability to act as sealing layers above CO₂ storage reservoirs (Nuttall, et al., 2005, Karpyn, et al. 2005, Heller, et al., 2014a, Heller, et al., 2014b). However, even within a geologic family the actual composition of the rock can vary widely. Shales are far from an exception, opening the door for a wide range of possible responses to shearing forces and fluid flow. This study is focused on comparing

the shearing responses of two shale families with distinctly different mineralogical compositions: the Marcellus and Eau Claire. Marcellus shale has been heavily researched due to the rapid expansion of hydrocarbon production across this formation. It is also the largest play in the United States (Kargbo, et al., 2010). Eau Claire is studied for its potential as a sealing formation above the Mount Simon sandstone where large scale CO₂ sequestration projects are being performed (Decatur IL) and where an even larger CO₂ sequestration site was planned (FutureGen 2.0). Quantifying both the similarities and dissimilarities of the two families will provide a stronger sense of how well research can crosscut between specific areas of industry. Setting the stage for the future studies associated with other shales

2. Background

2.1 Fracture Shearing

Rocks in the subsurface are constantly subjected to forces that compress and shear surfaces together causing significant changes to the fractures and joints within (Yeo, et al., 1998, Gentier, et al., 2000). These types of deformation are common because they represent a zone of weakness in the stratum where rock can more easily move to a lower stress state (Olsson, et al., 2001, Crandall, et al., 2017). Several studies have been performed to better understand the dynamics of hydraulic response to shear and normal stresses. The common model used for simulation of fluid flow in fractures is either the cubic law or the local cubic law. However, both require assumptions about the

fracture geometry that in the best cases are not often true in rough natural fractures (Yeo, et al., 1998, Olsson, et al., 2001, Brush, et al., 2003).

The relationship between geometry and flow is further complicated when normal and especially shear stresses are accounted for. Movements due to stresses in different directions cause damage zones and material loss which can increase or decrease the aperture. The formation of these damage zones is based on the mechanical properties of the rock which are inherently heterogeneous and impossible to measure across the reservoir scale (Gentier, et al., 2000, Olsson, et al., 2001).

Early experiments focused on normal stress and fracture closure more than fracture shearing, with increasing normal stresses the conductivity of a fracture decreases (Tsang, et al., 1981, Olsson, et al., 2001). When undergoing cycles of normal stress, hysteresis is observed due to the crushing of asperities. Repeated compaction and relaxation has been shown to slightly increase the conductivity of fractures due to the breakdown of asperities (Tsang, et al., 1981, Olsson, et al., 2001, Crandall, et al., 2017). Initial work by Olsson and Brown (1993) used a natural fracture in Austin Chalk subjecting it to both normal and radial shear movements. Cycles of normal stress moderately increased fracture apertures in the sample and hysteresis was observed. After shear movement under a 4.3 MPa confining pressure the hydraulic conductance of the fracture changed by orders of magnitude. During the shear test, the peak stress was reached early on at only approximately 0.2 mm of shear out of the total 3.5 mm of displacement. Before reaching peak stress, the flow rates were not significantly changed but steadily increased after the peak. The recorded stress slowly dropped and then leveled off to remain constant after 2 mm of shear.

The rapid ascent to peak shear stress was also observed during the work of Yeo, et al. in 1998. Several fractures of varying lengths between 5 and 40 centimeters were tested. Total displacement at peak shear stress in all cases was approximately 1% of the overall fracture length. A fast rise to peak shear stress is not surprising in a well-mated fracture because the asperities would quickly bind together with only a small amount of movement, after which sufficient force is needed for either the asperities to fail or ride up onto each other overcoming the normal confining stress (Matsuki, et al., 2010). After peak shear stress the fracture continues to dilate with additional shearing, increasing the aperture (Yeo, et al., 1998, Gentier, et al., 2000, Auradou, et al., 2006). Experimental data from the radial flow tests showed that the fracture appeared to become more hydraulically anisotropic with shear. Additionally, the direction perpendicular to shear saw a larger increase in permeability than the parallel direction. The suspected cause of this is from the formation of “roughness ridges” perpendicular to shear which acted as channels to conduct fluid through.

The “roughness ridges” are an example of damage zones that form during shearing. Experimental work by Gentier, et al. in 2000 determined that the mechanical properties affecting shear were highly dependent on shear direction. Exact replicas of a natural granite fracture were created using non-shrinking cement to provide a repeatable initial geometry for the tests. Peak shear stress was reached very early on for all directions and the relationship of stress to displacement was very similar. Volumetric dilation is a key parameter affecting fluid flow and showed a very strong dependence on shear direction in their experiments. Three key concepts pulled from the experimental data are: very little damage occurs prior to surpassing peak shear stress, much of the

damage occurred once the shear stress drops to a relatively stable level with continued displacement, and finally, damage zones occurred in and around regions with the steepest slope (Olsson, et al., 2001).

Work performed by Xiong et al. (2011) found several interesting correlations between fluid flow and shearing. First, fluid tended to form a few major channels after shearing while being more evenly dispersed before. Flow channelization has significant impacts for geothermal applications and reactive flows such as brine-CO₂ mixtures that form in storage reservoirs (Auradou, et al., 2006). The suspected cause of the channelization was initially small, distributed contact points which coalesced into larger regions. Transmissivity changes with shear followed a trend like that predicted by Gentier, et al., (2000). The changes were very small relative to the overall fracture volume and even decreased slightly in some cases before peak shear stress was reached. The fracture rapidly dilated and transmissivity increased by 2 - 3 orders of magnitude shortly after peak shear stress was exceeded. Additional shearing motion continued to increase fracture transmissivity but at a slower rate. This last stage was indicated in the work of Gentier, et al., (2000) by the shear-stress-to-displacement curve remaining constant.

Research performed by Carey et al. in 2015 compared the fractures and permeability changes associated with fracturing intact samples of Utica Shale. Compression and direct shear fractures were created under various orientations relative to bedding and pore pressures. In all cases, direct shear experiments produced the largest increases in permeability. Significant sample deformation was required to generate new fractures, approximately 1%, which at the reservoir scale would be difficult to achieve using hydraulic fracturing. Reactivation of existing fractures is a more likely

outcome which validates the need to understand how pre-existing fractures react to shear forces.

2.2 Fracture Geometry Measurement

Accurately measuring the geometry of a natural fracture has always been challenging. Direct optical methods such as profilometry require the surfaces to be separated, preventing in situ measurement of the aperture. While surface profiling has inherent limitations, important early research was done using the technique. Surface profilers have considerably higher resolution than most computed tomography (CT) scanners, allowing smaller features to be measured. Brown and Scholtz (1985) confirmed natural fractures have a fractal nature although they are only self-similar over a limited spatial frequency. Using a range of fractal dimensions dictated by the spatial frequency allows for synthetic fractures to be generated with the expectation of reasonably similar characteristics (Brown, et al., 1985, Dougan, et al., 2000).

Experimental work by Keller, 1998, Bertels, et al., 2001, Karpyn, et al., 2008 and many more found that the stress state of the fracture plays a key role in the aperture distribution limiting the applicability of profilometry. Additionally, the process of separating and then realigning fracture surfaces adds a key area for experimental error. Resin, epoxy and Wood's metal casts can be performed without separating the fracture profiles and allow measurements under experimental conditions but destroy the fracture in the process (Keller, 1998, Bertels, et al., 2001). Methods that do not alter the sample or experimental conditions such as CT scanning or MRI are desirable because they solve both above problems (Cnuddle, 2013).

However, the heterogeneous nature of the rock as well as the use of core holders which are often metal present challenges. X-ray beams are streams of high-energy photons and as they pass through a sample are scattered, absorbed or transmitted cleanly through. The fraction of total X-rays emitted that are transmitted through the target into the sensor is a function of thickness, density and chemical composition (Keller, 1998, Cnuddle, et al., 2013). Beer's law, equation (1), is used to relate the transmitted intensity to the initial intensity for a single wavelength by combining the above parameters into a single attenuation coefficient.

$$I = I_0 e^{-\eta x} \quad (1)$$

Where η is the attenuation coefficient and x is the distance travelled through the sample. Data from the CT scanner is expressed in terms of CT Units or CT Number. This is the relative attenuation of a given pixel typically compared to the attenuation of pure water. The pixel value in a real sample is the volume averaged attenuation of each component contained, i.e. rock matrix and air for a pixel split by the fracture surface. Lower resolution medical scanning systems typically set the attenuation of air at -1000 and pure water as 0, however the attenuation settings vary for higher resolution equipment. Using the previous two values CT Number is calculated from equation (2).

$$CT\ Number = 1000 \left(\frac{\eta - \eta_w}{\eta_w} \right) \quad (2)$$

Typical X-ray sources are not monochromatic and as a result are affected by a phenomenon known as beam hardening. A larger percentage of higher energy beams are transmitted through the sample relative to lower energies. The resulting image has a noticeable pattern produced by beam hardening which needs to be corrected for during post-processing (Cnuddle, 2013). High density contrasts inside the sample can worsen

the effects of beam hardening. A large contrast can also be used to advantage, for example encasing the sample in a metal sleeve such as aluminum can relegate significant effects to the edges of the sample instead of in the center (Bertels, et al., 2001). Lastly, thin targets can be scanned from a single direction but larger targets need to be scanned on all sides. The ideal target being a cylinder placed at the center of the X-Ray source's rotation (Keller, 1997, Keller, 1998, Bertels, et al., 2001). Sharp corners produce artifacts that radiate from the corner into the center of the sample (Bertels, et al., 2001). The high-fidelity geometries produced by CT scans enable numerical simulation of natural fractures at various stress states allowing direct comparisons with experimental data (Crandall, et al., 2017).

One of the earliest examples of relatively high resolution CT scans was performed by Keller (1997). The native scan resolution of 0.27 mm was augmented by integrating over the CT number approximating features as small as 38 microns. The CT number is a proxy for density but is also affected by the chemical composition of the sample. It was noted that the variability in CT number was significant for a highly heterogeneous sample such as granite. Due to the variability in CT number a calibration curve needs to be reformulated for each sample. A lognormal or gamma distribution was fit to the aperture data and very small correlation lengths were observed. The maximum correlation length in all the scans was less than 10% of the bulk sample length indicating very little long range structure (Keller, 1997).

Bertels et al. (2001) also used the same technique to measure apertures from CT data but modified the CT number integration to help consider the effects of beam hardening. Due to this effect, the mean rock matrix CT number near the edges of the

sample can be noticeably higher than near the center. To correct this, the mean rock CT number was plotted as a function of core radius during calibration tests. The regression line fitted to the data was used to calculate the mean aperture used for the CT number integration at a given radius instead of applying an overall mean rock CT number for all points. Without the correction, aperture values near the edges of the core would be underestimated and increasingly overestimated moving towards the center. Additionally, flow experiments were run on the samples allowing an effective hydraulic aperture to be back calculated using the cubic law. The hydraulic aperture was less than half of the geometric mean aperture for all cases. Flow tortuosity and channeling in the fracture was suspected as the primary cause for the discrepancy between hydraulic and geometric mean apertures. The effects of flow channeling and tortuosity have been noted by several other authors and is easily observed through local cubic law simulations (Ge, 1997, Brown, et al., 1998, Brush, et al., 2003, Auradou, et al., 2006, Crandall, et al., 2017).

2.3 Fracture Flow Experiments

While the focus of this work is based on numerical simulations, early experimental work has provided many insights to the basic flow characteristics of rough fractures. Romm (1966) validated the cubic law using optically smooth glass plates for an aperture range of 0.25 to 100 microns. He also found that the critical Reynolds number for laminar flow under those conditions was 2400. Lomize (1951) and Louis (1969) reported similar findings. Rough fracture flows would become turbulent, or at least exhibit strong inertial forces at much smaller Reynolds numbers (Brush, et al., 2003, Koyama, et al., 2008, Lee, et al., 2014). The range of apertures tested are within the expected range encountered in

fractures and knowing the analytical solution fundamentally holds is key for construction of numerical models.

Witherspoon et al. (1980) performed flow experiments on granite, basalt and marble and noted that aperture changes were the dominate geometric factor that affected flow. A small change to the aperture distribution could easily overwhelm other changes due to normal or shear stresses. Tsang and Witherspoon, et al. (1981) showed that the cubic law can hold for rough fractures and flow was reduced as function of the asperity height. However, if the relative size of asperities was small compared to the macroscopic dimensions of the sample the magnitude of their effects is also small. More recent experimental work is discussed in the next section when it was coupled with numerical simulations. Coupled experimental and numerical studies allow direct quantization of error from both geometric measurements and complex flow characteristics.

2.4 Fracture Flow Modeling

Numerical simulation of flow through fractures was first done using the “Cubic Law” which is simply the steady-state solution of the Navier-Stokes equations for flow through parallel plates, equation (3), (Lomize 1951, Romm, 1966, Louis, 1969).

$$Q = -L_y \frac{d^3}{12\mu} \cdot \frac{dp}{dx} \quad (3)$$

The cubic law is a one-dimensional approximation of flow reliant on the aperture. When a proper averaged aperture is supplied, the hydraulic aperture, flow is accurately approximated. However, several authors have examined the cubic law using different geometric averages and no unified theory has emerged (Brown, 1987, Zimmerman, et al., 1991, Brown, et al., 1995, Hakami, et al., 1996, Ge, 1997). The full Navier-Stokes

equations can accurately measure flow through a geometry and thus accurately measure the hydraulic aperture. However, for a true rough fracture geometry, solving the full system of equations is both computationally challenging and numerically difficult (Ge, 1997, Lee, et al., 2014). Due to the difficulty in approximating the hydraulic aperture a priori and solving the full Navier-Stokes equations, a middle ground between the Cubic Law and full Navier-Stokes equations is sought. This comes in the form of the Reynolds equation or “Local Cubic Law” which offers a more numerically tractable two-dimensional system (Lee, et al., 2014).

Brown (1987) performed some of the first numerical simulations of fracture flow using the Reynolds (Lubrication) Equation on stochastically generated fractal surfaces. The Reynolds equation is a simplification of the full incompressible Navier-Stokes equation (4), assuming the convective acceleration term in square brackets approaches zero and limiting the domain to only two dimensions (White, et al., 2006).

$$\rho \left[\frac{\partial}{\partial t} + (V \cdot \nabla) \right] V = \rho g - \nabla p + \mu \nabla^2 V \quad (4)$$

Convective acceleration can be considered the “inertial force” term and is responsible for making the equation nonlinear. An additional simplification commonly made for small scale flows is to neglect the gravitational body force, as the hydrostatic pressures over small distances are negligible. The incompressible Stokes Equation is shown as equation (5) without gravitational body forces.

$$0 = -\nabla p + \mu \nabla^2 V \quad (5)$$

The Reynolds (lubrication) equation, also known as the Local Cubic Law, used by Brown (1987) is further derived from the Stokes Equation by limiting the geometry to two dimensions, equation (6). The intermediate steps of the derivation can be avoided by

revisiting the macroscopic cubic law, equation (3), assuming it will hold locally and that mass is conserved ($\nabla \cdot Q = 0$).

$$\nabla \cdot \left(\frac{d^3}{12\mu} \cdot \nabla p \right) = 0 \quad (6)$$

Where $d(x, y)$ is the local fluid thickness and $p(x, y)$ is the local fluid pressure. This equation is valid for flow between slightly non-planar and subparallel surfaces. While the assumptions in the derivation have limitations, this equation can account for the most basic effects of aperture variation (Brown, 1987).

Using the fractal nature of natural fractures, Brown (1987) numerically generated multiple surfaces. Simulations using the Reynolds Equation showed that in the presence of contact regions, fluid took a tortuous path through the fracture forming channels. If there was minimal contact area, the flow was still affected by surface roughness but to a lesser extent. A hydraulic aperture was back calculated using (3), and comparing the hydraulic aperture from simulation data to a geometric mean aperture allowed assessment of the cubic law's validity.

Sinusoidal fracture profiles offer an opportunity to simulate some of the effects of fracture roughness while providing a regular geometry for full Navier-Stokes simulations. This is possible because they can be simplified down to a single one-dimensional profile. Zimmerman et al. (1991) performed simulations on sinusoidal geometries using both the full Navier-Stokes and Reynolds Equations to study the effects of roughness on effective permeability. Two key conclusions were drawn from the work. First, the Reynolds equation maintains a high degree of accuracy when the surfaces are smooth over a distance greater than one standard deviation of the aperture. That relationship helps enforce the smoothly varying aperture restriction of the Reynolds Equation (Brown, et al.,

1995). Secondly, there is a correlation between the ratio of hydraulic aperture (b_h) to mean aperture (b_m), and aperture standard deviation (b_σ) to mean aperture. As the ratio of $\frac{b_\sigma}{b_m}$ increases the ratio of $\frac{b_h}{b_m}$ decreases. In other words, as the effective roughness ($\frac{b_\sigma}{b_m}$) increases the cubic law approximation becomes less accurate. The work by Zimmerman, et al. (1991) also confirmed the presence of channels due to aperture variation and the effective reduction of total flow capacity.

The Reynolds equation is known to over predict flow rates through rough fractures when compared to an exact solution. This numerical error was investigated by Brown et al. (1995) in sinusoidal fractures relative to Lattice Gas Automaton (LGA) simulations. The LGA method consists of discrete particles constrained to move across a fixed geometric grid. Particles undergo collisions that conserve momentum and particle numbers. The incompressible Navier-Stokes equation can be approximated by taking macroscopic averages over several particles and/or time steps. The three variables changed were the Reynolds number, roughness wavelength and phase offset between the two surfaces.

While the fractures were sinusoidal, important conclusions can be drawn from this and the previous study that have implications for accurate simulations on real fractures. First that the Reynolds number must be kept much lower than the critical value reported for parallel plate flow. A Reynolds number of 50 produced significant recirculation zones when phase offset was zero (mirror images) and the surfaces diverged. This limit was further refined by Brush and Thompson (2003) to suggest the Reynolds equation is only valid for Reynolds number less than unity. Increasing the slope of the roughness, i.e. increasing the frequency of the sinusoids, decreased the agreement between the Reynolds equation and LGA simulations. Lastly, the tortuosity of the fracture cannot be

ignored for accurate simulations. The conclusions made agree with previous results by Zimmerman, et al. (1991) and Brown, et al., (1995) as well results from additional publications (Brush, et al., 2003, Liu, et al. 2012, Wang, et al. 2015).

Ge (1997) analyzed the basic local cubic law used in the studies mentioned above and investigated a correction to better manage the effects of fracture tortuosity. Enforcing a local coordinate system for each volume allowed accurate approximations of both the true path length and aperture. The larger the deviation of the two surfaces from parallel, the more significant the correction is required. Errors in permeability measurements on simple sub-parallel fractures reached 10% with an inclination of 25 degrees between surfaces without correction.

Brush and Thompson (2003) built upon the numerical work of Ge and incorporated a correction for mildly tapered plates. Their study focused on three types of simulations, local cubic law, Stokes equations and lastly, the full Navier-Stokes equations on the same sets of fractures. Correcting for both tortuosity and a limited degree of converging/diverging aperture produced positive agreement with the three-dimensional Stokes equations. However, for rough fractures even at low Reynolds numbers an inertial core can develop causing significant deviations from the theoretical parabolic velocity profile. This was later observed by Koyama, et al., 2008 when aperture rapidly changed over relatively short distances.

Relative error between the three types of simulations performed by Brush and Thompson was quantified against combinations of three aperture statistics, mean (b_m), standard deviation (σ_b), and correlation length (λ_b). The combinations as well as the proposed limits are listed below as equations (7), (8) and (9).

$$\text{Relative Roughness} \quad \frac{\sigma_b}{b_m} < 1.0 \quad (7)$$

$$\text{Roughness Slope} \quad \frac{\sigma_b}{\lambda_b} < 0.2 \quad (8)$$

$$\text{Aperture Aspect Ratio} \quad \frac{b_m}{\lambda_b} < 0.5 \quad (9)$$

Relative error between the local cubic law and Stokes equations as well as between Stokes and Navier-Stokes increases rapidly as equations (7) and (8) exceed their proposed limits. The relationship with the aperture aspect ratio is not as clear.

Crandall et al., (2010) examined the relationship of Joint Roughness Coefficient (JRC) and fractal dimension (D_f) to the bulk fracture transmissivity. The bulk transmissivity (T) of a fracture can be calculated using an analogue of Darcy's Law for creeping flow through porous media, equation (10).

$$Q = -T \frac{\Delta P}{\mu} \quad (10)$$

The bulk transmissivity is a useful quantity for reservoir simulations because it accounts for all macroscopically observed flow resistances. A range of fractures were simulated using the full Navier-Stokes equations with a range of JRC (14.58 to 3.72), in which smaller values correspond to smoother fractures. The JRC was shown to have a direct effect on tortuosity of flow channels and therefore the transmissivity of the fracture. The fracture with the lowest JRC had nearly straight streamlines from inlet to outlet, while the highest JRC fractures exhibited tortuous flow paths. There appeared to be a linear relationship between the bulk transmissivity and JRC, indicating that it strongly encompassed the fundamental physics of the system.

Direct measurement of flow through a two-dimensional fracture profile was performed by Lee et. al. (2014) using particle imaging velocimetry (PIV). Real natural fractures were scanned and then reproduced as a two-dimensional thin profile in acrylic. Measurements allowed examination of how well the Stokes and local cubic law approximations hold at very low Reynolds number ($Re < 0.1$). Velocity measurements at the low Reynolds number verified that inertial forces were negligible, validating the use of the Stokes Equations. Qualitative flow characteristics were observed for $Re > 1.0$ and even in the roughest regions eddies (i.e. nonlinear flow effects) did not begin to form until $Re > 5.0$.

Velocity data for $Re < 0.86$ showed that even at a very low Reynolds number, abrupt aperture changes invalidate the assumption that the out of plane flow component is negligible. However, it was noted for smoother aperture variations the local cubic law assumptions are valid. Flow overestimation was quantified for the regions imaged and the fracture roughness, not inertial forces, was the primary source of error. Overestimation of flow was affected by Reynolds number as well with an average of 14% at $Re = 0.014$ and 33% at $Re = 0.086$. Results showed that while the Stokes equation could be applied to fractures at $Re < 1$ without concern for roughness the local cubic law can significantly over predict at $Re < 0.1$.

Additionally, when working with a 2-D simulation geometry the mesh can be exported to other CFD modeling packages, such as Fluent or OpenFOAM which have full Navier-Stokes implementations. Direct comparisons between the full Navier-Stokes equations and the local cubic law are desirable to help determine the cause of discrepancies between numerical and experimental data. Mofakham et al. (2017)

examined the differences between Navier-Stokes and modified local cubic law simulations for a set of test data used within this study, Induced Seismicity Test 6 (IS-6), and found in general good agreement between the two. Relative differences in the simulated pressure drop between the two models are shown below in Figure 2 for each shear step.

Figure 2: Simulation differential pressure for each shear step, adapted from Mofakham, et al. 2017

Larger discrepancies occurred when the flow rate was higher indicating the onset of some inertial forces for shear steps one and two. The corrections imposed by the modified local cubic law were too restrictive for the more open fracture geometries of shear step steps three and four, causing the MLCL to overestimate the pressure drop. The relatively small error between the two, less than 35%, indicated that the disparity between numerical and experimental results was not due to the simplified modeling

scheme for low Reynolds numbers. Instead a portion of the error can be attributed to the complex and difficult task of segmenting out the fracture geometry from the full CT scan data.

2.5 Shale Mineralogy

Shales are complex, heterogeneous rocks with varying composition and structure across all families and scales (Esteban, et al., 2012, Heller, et al., 2014a). The physical properties of shale play a central role in the response of the sample to shearing and normal forces. A key characteristic of shales is the highly-bedded lithology which forms due to thin deposits being compacted into layers during formation (Kargbo, et al., 2010). The orientation of bedding planes can significantly affect the hydraulic and physical properties of a shale sample (Carey, 2015).

Understanding how the composition and structure of shale affects its behavior is key to determining how “portable” data from different reservoirs are. A prime example is the brittleness of the shale. A brittle shale will more readily fracture and be less prone to self-healing, or closing, of fractures compared to a more ductile sample (Esteban, et al., 2012). However, depending on the desired use of the shale either characteristic may be sought out. A self-sealing shale makes for a much more secure cap rock on top of a CO₂ storage reservoir, while the same properties are detrimental to natural gas production. While this distinction is important to note, the time scales involved for this work are orders of magnitude too short to observe those types of effects. The immediate effects of shearing and compression are examined instead, i.e. how the aperture field breaks down and changes during this type of event.

2.5.1 Marcellus

Marcellus shale is a black, organic rich Devonian shale that is proposed to have been deposited approximately 359 to 416 million years ago and is typically found 1.6 km below the surface (Kargbo, et al., 2010). The composition of the Marcellus samples used in this study was largely quartz and calcite with a small fraction of illite and mica. Total carbon in the sample was 6.4% and 5.1% inorganic and organic carbon respectively. The small amount of clays and illite in the sample indicates that very little swelling from hydration during the tests was expected (Esteban, et al., 2012, Crandall, et al., 2017). An image of the Induced Seismicity Test 5 (IS-5) core is shown in Figure 3.

Figure 3: One-and-a-half-inch diameter fractured Marcellus shale core from test IS-5. Fracture is concordant with bedding, mostly planar (Crandall, et al., 2017).

2.5.2 Eau Claire

The Eau Claire formation is a shaly sandstone strata that overlies the Mount Simon sandstone formation and underlies the Galesville sandstone. The formation is divided into

three members, Elmhurst Sandstone, Lombard Dolomite and Proviso Siltstone. Each member has layers of interbedded green and/or black shale and sandstone (Willman, et al. 1975).

The samples used in this work are from the Elmhurst member at approximate depths of 3,898 (Core B) and 3,902 feet (Core D and E). Core log data taken during the drilling determined that the upper level of the Mount Simon sandstone begins at approximately 3,904 feet. Both samples were taken from the main core in regions with significant clay and siltstone bedding (Gilmore, et al., 2014). An excerpt from the core log data showing grain sizes for the sample depths used in this study is shown in Figure 4. The colors represent different lithologies but for this case can be generalized where yellow represents a very fine sandstone, brown a mudstone and green silty-shale. The longer the bar the larger the grain size at that location. Figure 5 is a larger image of the sections from the formation used in this study.

Figure 4: Core log data excerpt showing grain sizes for experimental samples, yellow is fine grained sandstone and green is smaller particles in the silty shale range. (Gilmore, et al., 2014)

Figure 5: Larger images of FutureGen Core-E sample region. (Gilmore, et al., 2014)

2.6 Literature Overview

The evolution of fracture geometry during shear displacement alone is a very complex process that is still being heavily studied. Several previous authors have investigated its effect alone to quantify the primary effects, including asperity degradation, formation of damage zones and in most cases an increase in permeability. Coupling the physical shearing response to the hydraulic conductivity changes adds an extra dimension to the problem. As damage zones form, which are nearly zero aperture, the flow field can dramatically evolve, changing from disperse field flowing around several asperities into larger channels avoiding the less permeable regions formed during shearing.

Numeric simulation utilizing the modified local cubic law offers a way to visualize flow field changes because of geometric deformation which is not possible from the high-resolution CT scans. Complementary simulation data can fill in both qualitative observations of the probable flow field as well as provide quantitative comparisons to experimental data, helping assess how well the combination of imaging data and numerical scheme match real world physics. When using the modified local cubic law as a lightweight substitute for the full Navier-Stokes equation it is important to ensure the geometric parameters are constrained to a reasonable degree to fit the assumption of “smoothly varying aperture” used to derive the equation. Brush and Thompson (2003) performed several simulations using numerically generated fractures to quantify the expected error between the a full Navier-Stokes simulation and a much quicker, modified local cubic law simulation.

Different samples of rock cannot inherently be expected to exhibit similar behavior. As such, direct comparisons between the two different families are an important step in quantifying the effects of physical properties and sample composition on shearing behavior. The degree of “portability” between results is of key concern because it opens the opportunity for past research to more accurately lay down the framework when working in a different region.

3. Experimental Method

3.1 Test Samples and Preparation

Two sets of shale cores were used for coupled flow and shear experiments, a sample of Marcellus shale and a sample of Eau Claire shale. The Marcellus shale sub-cores were taken from a larger core which was extracted from an outcrop in Bedford, Pennsylvania. The Eau Claire samples were sub-cored from the main core at depths of 3,898 feet and 3,902 feet. Both samples were fractured using the Brazilian technique which produced a single fracture lengthwise, approximately through the core’s center (Crandall, et al., 2017).

In both samples, there was some loss of material along the edges due to the mechanical preparation process. The losses were localized and poorly connected to the main fracture so no significant contribution to flow was expected. As an additional step to prevent fluid flow around the core, Lawson Products RTV silicone was used to seal the perimeter and reduce edge effects in the flow tests. Full details of the Marcellus shale test

sample preparation can be found in Crandall, et al. 2017. The Eau Claire samples were prepared following a very similar process.

3.2 Shearing Test Setup

A custom designed piston system that allowed axial force to be directly applied in measured increments was used for the shearing test. The core and pistons were wrapped in a watertight, heat-shrink Teflon sleeve and then aluminum shields were fixed to the outside of the sleeve. The entire system was inserted into a Buna-N nitrile rubber confining sleeve used to apply a normal stress to the core while being sheared to simulate the pressure of overburden. Aluminum shields were required to prevent the collapse of the confining sleeve into the space between the shale core and piston but to still allow application of overburden pressure. This was encapsulated in a Hassler style core holder as depicted in Figure 6.

Figure 6: Annotated cross sectional view of Hassler-style core holder with internal shear apparatus. (Crandall, et al. 2017)

The fracture surfaces were incrementally sheared by applying a known displacement per step rather than a known shear stress. The amount of shear displacement was controlled by a screw mechanism in the end cap that moved the piston system. The end cap was turned 45 degrees at a time for all shearing steps; however the actual core displacement was slightly non-uniform. Data from the CT scans were used to accurately measure the actual core displacement for each shearing step. Asperities binding and releasing during shear motion caused the minor differences in true displacement. The average amount of shear per step was 0.43 mm per turn. The Marcellus shale shearing tests were performed at a range of confining pressures: 200 psi, 500 psi and 1000 psi for tests 1, 2 and 3 respectively (Crandall, et al., 2017). All the Eau Claire shale shearing experiments were performed at a pressure of approximately 3100 psi and with a pore pressure of 100 psi to simulate in situ conditions. CT scans of the

fracture were taken before the first shear event and after each shearing step to measure geometric changes occurring in the fracture. Resolutions ranged from 26.7 μm (FutureGen-E) to 27.6 μm (IS-5).

3.3 Hydraulic Transmissivity Tests

Fluid flow transmissivity (T) tests were performed prior to shearing. After each shear step, single phase injection of deionized (DI) water was used to measure the transmissivity for the Marcellus samples. A solution of water and 5% NaCl was used for the flow experiments on the Eau Claire samples to reduce the possibility for swelling due to clay hydration. Fluid injection was performed using Teledyne Isco Syringe Pumps (500D). A Rosemount 3150CD differential pressure transducer (0-300 PSI range) was used to measure pressure drop across the core during flow. Fluid was injected through the core at a constant rate until the pressure drop stabilized and then an averaged value was used as the measurement. This was repeated for several flow rates to provide multiple data points when calculating the fracture transmissivity. The range of flow rates used was not always consistent across shear steps. If core transmissivity increased, or decreased, significantly after a shearing step then rates were adjusted as needed to provide accurate pressure measurements.

The transmissivity calculation at a specific differential pressure was done using a Cubic Law assumption for flow, equation (10) (Crandall, et al., 2017, Crandall, et al., 2010). Transmissivity was used instead of overall permeability because it can be assumed that flow is restricted to the fracture itself and not affected by the core cross

sectional area (Crandall, et al., 2010). Full details of the test procedure for the Marcellus samples is available in Crandall, et al. 2017.

3.4 Fracture Geometry Isolation

CT data from the scanner was received as 16bit tiff image stacks. ImageJ (Rasband 2016) and ilastik (Sommer, et al., 2011) were used to segment and threshold the image stacks into binary images. Thresholding images can be a difficult task when the sample is highly heterogeneous resulting in an unfavorable signal to noise ratio. Simple thresholding methods could not be used effectively for those scans, as a result the processing methods varied across tests to achieve the highest quality data. A full description of the image processing techniques used on the Marcellus samples can be found in Crandall et al. (2017). The Eau Claire samples were processed using the same techniques as the Marcellus samples however, resolving the fracture was more challenging due to the considerably higher confining pressures (~3100 psi). Presented in Figure 7 is a 3-D image of a fractured core prior to thresholding out the primary fracture geometry to exhibit the geometric complexity. A single voxel slice is shown running through the image perpendicular to length of the core.

Figure 7: Three-dimensional image of core prior to thresholding out the fracture geometry.

Once thresholding had been completed the radial binary image stacks were cropped into a rectangular prism. Cropping removed portions of the image that did not contain any fracture geometry as well as a small portion of the fracture near the circumference of the core.

Void space geometries in the fractured core are extremely complex with several features separate from the main fracture plane, as well as noise left over from thresholding. Additionally, during shear, it is not uncommon for additional features which are unconnected to form because of the changing stress field. When considering the hydraulic properties of the full 3-D geometry it is plainly understood that those void spaces do not affect fluid flow. However, simplifying the complex 3-D image data into a 2-D aperture map adds those disconnected voxels to the total aperture. Depending on the size and location of these “extra” voxels, fluid flow can be significantly affected because of the cubic relationship between aperture size and hydraulic conductivity.

To help reduce the effects of this void space, the binary image stacks were processed using Python code developed at NETL (Stadelman, 2017) to remove groups of one or more voxels that were disconnected from the primary fracture geometry. Two voxels were considered connected if a face, edge or corner was shared, also known as 26-point connectivity. This more forgiving scheme was utilized instead of face-to-face or 6-point connectivity because the nature of image thresholding can leave small artificial holes in the final geometry.

Overall connectivity was determined using an undirected graph which allowed for separate clusters of voxels to be identified and ordered by size. It was assumed the largest cluster of voxels corresponded to the main fracture geometry and in theory should be the structure that supports all the fluid flow. The fewest number of clusters required to span from inlet to outlet were retained, which in most cases was a single cluster. Figure 8 shows a highly discontinuous fracture, FutureGen Core-E shearing step 4, where large portions were unable to be resolved by the CT scanner. Each distinct color in the image represents one of the 16 largest clusters, while the remaining clusters are black.

Figure 8: Unprocessed fracture geometry colored by cluster number. All small voids are black.

A two-dimensional aperture map was then generated from the three-dimensional binary image stack. Maps were generated by collapsing the Y-axis of the three-dimensional image and summing all fracture voxels into a single value for a given X-Z coordinate. Reducing the geometry down to only two dimensions greatly reduces the complexity of the problem both numerically and for mesh generation. Some of the challenges of creating a suitable CFD mesh from CT scan geometries are discussed in Crandall et al. (2010). The primary limitation of this simplification is that the mid-surface is forced to be planar. Variations in the fracture mid-surface have been shown to have a significant effect on hydraulic properties (Ge 1997, Brush et al. 2003). Additionally, this geometry simplification allows one to perform both local cubic simulations and full Navier-Stokes simulations on the exact same mesh. The conversion of a full 3-D geometry into an aperture map is shown in Figure 9, the 3-D image is colored according to the corresponding cell value in the aperture map.

Figure 9: Collapsing a 3-D fracture geometry into a 2-D aperture map. Image colors correspond to each other.

Aperture maps were generated from the binary image stacks before and after cluster processing. This allowed an assessment of how the fracture transmissivity was affected by disconnected void space being incorporated into the aperture map. While the processing works very well to remove stray pockets of pixels there are many other

structures that connect to the main geometry but do not contribute to flow. Primary examples of these are fracture splays formed during shearing which extend into the core but do not reconnect with the main fracture, i.e. form a “dead end”. They are connected to the fracture and therefore are not removed by the simple algorithm but do not increase the transmissivity of the fracture. Features such as these would still need to be manually removed during image processing to mitigate discrepancies in the simulation data.

The processed fracture geometry for FutureGen Core-B after a single shear step is depicted in Figure 10, with an arrow denoting the macroscopic flow direction. The primary fracture geometry is shown in grayscale whereas vertical splays are partially colored in red. This highlights the issue encountered when working with complex samples using automated processes. A very large amount of manual image processing would be required to trace each vertical splay to its base and remove it. Fortunately, for this case all the features run perpendicular to the macroscopic flow direction, which reduces their effect on the flow characteristics of the aperture map.

Figure 10: Processed geometry for FutureGen Core-B after shear step one, in which the main geometry is in grayscale, fracture splays are colored in red. The arrow shows the macroscopic flow direction.

Contact zones or regions of zero aperture are easily identified using aperture maps and are of interest because of their effect on fluid flow. Evolution of these regions during shearing is a key indicator of major geometric changes due to asperity breakdown (Olsson, et al., 1993, Crandall, et al., 2017). However due to the limitations of CT scanning, features at or below the scan resolution can also appear as zero aperture regions because they cannot be adequately resolved, as shown in Figure 8.

4. Numerical Simulation Method

A modified local cubic law, utilizing a finite volume scheme was the chosen method to simulate flow through fracture geometries. Aperture maps were used to generate all 3-D mesh geometries. The values for each voxel are a “center point” measurement of the apertures and using the value in the map causes a stair step to form between neighboring voxels of different heights as shown in Figure 11.

Figure 11: Neighboring grid blocks without using corner point interpolation

Right angle corners pose a serious issue for full 3-D flow simulations, because they cause discontinuities in the mesh. Local cubic law simulations do not share the same issue because the Y axis block thickness, or aperture, is not discretized and instead a single conductance value can be used. However, using the same conductance value for both the X and Z axis flow out of a single cell is not realistic unless the aperture is constant. Instead, the local conductance between cells was calculated at each interface by interpolating corner points which smooths out the mesh like what is shown in Figure 12.

Figure 12: Neighboring grid blocks smoothed using corner point interpolation

Each voxel was subdivided four times to show the corner interpolation relative to the center cell value more clearly. The modification of the cell conductance was done matching the work of Brush and Thompson (2003) who utilized a correction based on an analytical solution to the Stokes equations for 2-D radial flow through tapered plates. The correction better assesses the true local transmissivity between grid block interfaces. However, their work also factored in a local tortuosity correction based on fracture mid-surface undulation which was not considered here. Experimental constraints of the shearing apparatus require fractures to be macroscopically planar over the entire domain (Crandall, et al., 2017). Thus, it is not anticipated that forcing a flat mid-surface (i.e. the aperture is symmetric over the X-Z plane) will cause significant numerical error.

The first step in calculating the corrected interface aperture was to average the aperture at the interface corners. The interface used for the following examples is shown in Figure 13 in yellow.

Figure 13: Interface (yellow) between two voxels (one in red and the other in blue). Corners are indexed 1 - bottom-left, 2 - bottom-right, 3 -top-right and 4 - top left

The effective aperture at this interface is calculated by equation (11) using a simple average and denoted as b_f .

$$b_f = \frac{b_1 + b_4}{2} \quad (11)$$

The interface aperture is then compared to the center cell values to calculate the corrected transmissivity between the two cells. Figure 14 shows an annotated cross section through the center, following the middle grid line, of the voxel pair in Figure 13. Interface locations are labeled with a triangle and the centers of the voxels are denoted with a circle. The aperture at interface point f is equal to the value calculated by equation (11). The apertures at center cell locations P and F are equal to the values that would have been read from an aperture map.

Figure 14: Interface control volume, cell centers denoted by a circle and interface points a triangle. The interface being considered by the equations is f , highlighted by a yellow line.

When the mid-surface is planar the distance from the cell center to the interface, δ_{LfP} and δ_{LfF} , is equal to exactly half the edge length of a voxel. Equation (12) is used to calculate the tapered plate corrected aperture for one half of the interface, in this case voxel P. The slope between the fracture surfaces is θ_{fP} , which can be calculated from

equation (13). These two equations are then used to calculate the corrected aperture for voxel F.

$$b_{fp} = \frac{2 \cdot b_f^2 \cdot b_P^2}{b_f + b_P} \cdot \frac{3(\tan\theta_{fP} - \theta_{fP})}{\tan^3\theta_{fP}} \quad (12)$$

$$\tan\theta_{fP} = \frac{|b_f - b_P|}{\delta_{LfP}} \quad (13)$$

The final aperture value used in the local interface transmissivity calculation is computed using a weighted harmonic mean, equation (14).

$$\frac{\overline{b_f}^3}{\delta_{Lf}} = \left[\frac{\delta_{LfP}}{b_{fP}^3} + \frac{\delta_{LfF}}{b_{fF}^3} \right]^{-1} \quad (14)$$

The corrected aperture from equation (14) better reflects the true hydraulic aperture between both converging and diverging plates. Equation (15) is used to calculate the local X direction transmissivity $T_{x,i,j}$ through interface f . $\Delta z_{i,j}$ is the width of the cell perpendicular to the flow direction. The local transmissivity in the Z direction uses the equivalent form of equation (15) substituting $\Delta z_{i,j}$ for $\Delta x_{i,j}$ as the perpendicular width of a cell and is shown for completeness as equation (16).

$$T_{x,i,j} = \frac{\overline{b_f}^3}{\delta_{Lf}} \cdot \frac{\Delta z_{i,j}}{12 \cdot \mu} \quad (15)$$

$$T_{z,i,j} = \frac{\overline{b_f}^3}{\delta_{Lf}} \cdot \frac{\Delta x_{i,j}}{12 \cdot \mu} \quad (16)$$

The local interface transmissivities are isotropic and to save computational expense only the top and right faces of each cell are calculated, the value is then reused when considering flow in the opposite direction. The local transmissivities were used as the coefficients in the finite volume formulation which solves for the pressure distribution throughout the fracture. Experimental conditions were set up for fluid to be injected from

the bottom and collected at the top. While the model allows for any side to be defined as the inlet, the grid indices are ordered with experimental conditions in mind. Figure 15 shows how cells are indexed relative to each other and to the global coordinate orientation. The origin of the system is the bottom left corner, with positive X considered to the right and positive Z moving upward.

Figure 15: Grid block indexing scheme relative to global coordinate system alignment. Arrows denote positive flow directions through each face.

The system of equations is generated using a central finite difference scheme with each integration point defined at the interface between two voxels. The mesh is only discretized along the X and Z axes and assumes parabolic flow between the surfaces, which is the fundamental assumption of the local cubic law or Reynolds equation. Equation (17) is the general finite volume formulation used to generate the linear system of equations.

$$0 = T_{x,i,j-1}(p_{i,j} - p_{i,j-1}) - T_{x,i,j}(p_{i,j+1} - p_{i,j}) + T_{z,i-1,j}(p_{i,j} - p_{i-1,j}) - T_{z,i,j}(p_{i+1,j} - p_{i,j}) \quad (17)$$

Static pressure (dirichlet) boundary conditions were applied at the exterior faces of the mesh, not defined at the first and last rows of the aperture map. This was numerically accomplished by adding extra rows to the solution matrix in the proper locations. Alternatively, one boundary, inlet or outlet, could be set to a fixed flow rate and the other a static pressure condition. A bulk flow rate boundary condition was applied by creating a single artificial cell, or “manifold”, that connected to every cell along the chosen boundary side. Transmissivity between the manifold and grid cell was dictated by the grid cell’s transmissivity. A numerically defined manifold cell is desirable because it prevents forcing an artificial velocity across all cells at the boundary. Instead, allowing for a solution at the boundary that conforms to the complete hydraulic characteristics of the aperture map.

Figure 16 shows the full grid including numerically added rows for a pressure controlled simulation. Figure 17 shows the same mesh with a flow rate condition and a pressure condition, as before both boundary condition rows only exist numerically.

Figure 16: Full numerical grid including rows added to apply fixed pressure conditions at both the inlet and outlet.

Figure 17: Full numerical grid including rows added to apply a bulk injection rate at the inlet and a fixed pressure condition at the outlet.

5. Results and Discussion

5.1 Effects of Cluster Processing Image Data

Cluster processing based on connectivity has the desirable effect of removing void space from the fracture that does not contribute to fluid flow. While it cannot remove every undesirable feature, it offers a method to remove many voxels that would otherwise need to be manually removed. The amount of void space discarded is highly variable based on overall connectivity. Although there is a one to one relationship between total void space removed and a reduction in the mean aperture, there is not a similar relationship to transmissivity reduction. This is depicted in Figures 18 and 19.

Figure 18: Linear relation between total volume removed and mean aperture reduction.

Figure 19: Lack of a relationship between total volume removed and transmissivity reduced.

A direct relationship was not expected between the void space removed and transmissivity reduced because of flow channelization. The behavior is akin to the

inconsistent relationship between the mean aperture and hydraulic aperture. The average transmissivity increased slightly in some cases because the Stokes tapered plate correction applied penalizes a sharp variation in aperture more heavily than gradual changes. This is reinforced by the increase in correlation length after cluster processing presented in Figure 20.

Figure 20: Increase in correlation length because of cluster processing.

An increase in correlation length is not unexpected because any void space that is not part of the main fracture cluster would inherently add unrelated features into the aperture map. Correlation length and by association the rate at which roughness varies is a key parameter affecting the accuracy of local cubic law simulations. Extending the correlation length, in addition to the corresponding reduction in mean aperture shown in Figure 18, help improve the accuracy of simulations relative to the original geometry.

The final geometric parameter examined before and after cluster processing was the aperture standard deviation which is considered a proxy for fracture roughness. The

standard deviation for most cases was not heavily affected by cluster processing, with one exception FutureGen Core-D. The lack of change in standard deviation indicates that cluster removal does not change the inherent roughness characteristics of the fracture; however, the changes in FutureGen Core-D accompanied a very large decrease in volume as depicted in Figure 21. Indicating that the nature of the surrounding void space in the image was significantly different from the main fracture.

Figure 21: Changes in aperture standard deviation as a function of volume removed.

5.2 Comparing Simulation Data to Experimental Measurements

The cluster processed simulation results were compared to experimental data, although simulation data were not expected to closely agree with experimental values due to challenges in image capture and processing. Error between the simulated fracture transmissivity and experimental measurement varied over five orders of magnitude with the extremely complex FutureGen fractures having the largest error. Shear step three and four of sample IS-6 are omitted from this comparison because the fracture transmissivity

was too high to produce a measureable differential pressure. Shear step one of sample IS-8, and shear steps one and four of FutureGen Core-E are omitted because the aperture could not adequately be resolved at the given scan resolution to produce a viable simulation mesh.

Figure 22 shows the evolution of the log scaled error for each sample as shearing progresses. Points approaching zero indicate the simulation more accurately approximated experimental transmissivity. There is no correlation between the amount of shear and simulation error.

Figure 22: Log scaled error between simulated fracture transmissivity and the experimentally measured transmissivity.

To help quantify the source of the large discrepancy between simulation results and experimental data the log scaled error was plotted against six geometric parameters. The first three are the simple statistical quantities of mean aperture, standard deviation of aperture and aperture correlation length. The comparison between the error and the

parameters are presented in Figures 23, 24 and 25, and as before values closer to zero are more accurate.

Figure 23: Log scaled error between simulated fracture transmissivity and the experimentally measured transmissivity as a function of mean aperture.

Figure 24: Log scaled error between simulated fracture transmissivity and the experimentally measured transmissivity as a function of aperture standard deviation.

Figure 25: Log scaled error between simulated fracture transmissivity and the experimentally measured transmissivity as a function of aperture correlation length.

It can be seen from the plots that there is no correlation between the simple geometric parameters and the relative error between experimental and simulation results. The next three plots consider the error as function of the dimensionless ratios defined in Brush and Thompson (2003). The parameters are relative roughness equation (7), Figure 26, roughness slope equation (8), Figure 27 and the aperture aspect ratio equation (9), Figure 28. The limits proposed in reference Brush and Thompson, (2003) are denoted by a black vertical line, in an ideal case all points would be to the left of the line.

Figure 26: Log scaled error between simulated fracture transmissivity and the experimentally measured transmissivity as a function of relative roughness. Ideal limit is less than 1.0.

Figure 27: Log scaled error between simulated fracture transmissivity and the experimentally measured transmissivity as a function of roughness slope. Ideal limit is less than 0.2.

Figure 28: Log scaled error between simulated fracture transmissivity and the experimentally measured transmissivity as a function of aperture aspect. Ideal limit is less than 0.5.

Except for relative roughness, all simulations fall close to or within the proposed limits for good agreement with the Navier-Stokes equations. This was confirmed in Mofakham, et al. (2017) where the local cubic law model used in this study was directly compared against results from ANSYS Fluent software for all four shear steps sample IS-6. It is evident that there is no strong relationship between the relative error and any of the six geometric parameters investigated. The lack of dependence on geometric factors suggests that the primary contributor of error is outside of the simulation method used. Without full Navier-Stokes simulations for every geometry to compare against this cannot be confirmed.

While there is a large degree of error between the simulated fracture transmissivity and the experimental measurement quantitative comparisons between the two were not anticipated to match. Qualitatively, the simulation results match the transmissivity evolution of each sample during shearing which indicates the geometries are still

representative of the real flow characteristics. Without a qualitative match it would not be possible to compare data between the different shale families. Figure 29 exhibits the transmissivity progression as a function of shearing with each test in its own subplot.

Figure 29: Comparison of simulated and experimental transmissivity for each shearing test.

Additionally, several important flow characteristics can still be discerned from the aperture maps. The main visual characteristic of interest is the flow field evolution because of shearing and how much the flow channelizes. The degree of channelization can have important effects when considering activities such as geochemical reactions, geothermal heat transfer and CO₂ sequestration. An initial investigation of channelization with shearing was performed in Crandall, et al. 2016 and is attached in Appendix C. It was found that shearing reduces the number of flow channels, with an expected increase in channel width. More accurately quantifying this effect will be a component of future work. Visually it is very easy to see the how flow coalesces because of shearing for sample IS-5. Figure 30 depicts the flow through the fracture for shearing step two (left) and eight (right).

Figure 30: Flow field coalescing into fewer channels because of shearing, comparing sample IS-5 step 2 (right) and IS-5 step 8 (left).

5.3 Shale Comparison

Understanding how different families of shale respond to shearing relative to each other is critical in assessing the portability of research and techniques across different industries. Within this study three samples of Marcellus shale (IS) and three samples of Eau Claire (FutureGen) shale were compared using statistical geometric parameters as well as numerical simulation results.

The geometric parameters investigated were the same as in the previous comparison of the cluster processed and raw binary data. All aperture maps used in this comparison were cluster processed and the values plotted against shear steps to track changes due to deformation. Comparison of the basic aperture statistical parameters show that both the Eau Claire and Marcellus shales have similar behavior during shearing. FutureGen Core-B is an outlier in all cases, however from shear step three onward the values are still significantly higher and they follow the same trend as the other samples. Figures 31, 32 and 33 illustrate the evolution of the mean aperture, aperture standard deviation and aperture correlation length as a function of shearing.

Figure 31: Mean aperture change because of shear displacement.

Figure 32: Aperture standard deviation change because of shear displacement.

Figure 33: Aperture correlation length change due to shear displacement.

When plotting the evolution of the three dimensionless ratios against the shear step a much stronger correlation is seen for relative roughness, equation (7), and roughness slope, equation (8). Rather than the values following the same trend, as shearing progresses the ratios converge to similar values across all samples. The same pattern does not occur for aperture aspect ratio, equation (9), where the values deviated widely from sample to sample. Plots showing the change in these ratios as a function of shear displacement are presented in Figures 34, 35 and 36 respectively.

Figure 34: Aperture relative roughness change as a function shear deformation.

Figure 35: Aperture roughness slope change due to shear displacement, all samples have similar values but no clear correlation.

Figure 36: Aperture aspect ratio change due to shear displacement, where no clear correlation between any samples was observed.

The significant decrease in relative roughness confirms that the “roughest” regions are impacted the most by shearing. However, it appears at a certain threshold, approximately unity, shearing no longer has a significant effect on relative roughness. While no shear stress measurements were taken during the experiment, the results correspond well with the results reported by several previous shearing studies. A peak shear stress is reached early on as asperities lock together and afterwards the two faces enter a stable sliding regime where the stress state remains more constant.

Both shale families share similar trends in the geometric quantities because of shearing. During which the mean aperture, aperture standard deviation and aperture correlation length all moderately increase except for FutureGen Core-B. The relative roughness appears to converge towards unity with increasing shear displacement. While a general convergence to a single value within each family may be expected due to

aperture deformation occurring in a similar fashion it is notable all six samples approach the same value. Relative roughness does not show a clear trend as a function of shearing, however the values across all samples are relatively close to each other. Lastly, while the aperture aspect ratio is uncorrelated to the amount of shear, there is also no correlation between samples within the same family.

6. Conclusion

Cluster processing proves to be a useful method to pull out the primary flow conduit from a complex image if the undesirable void space does not connect to the main voxel cluster. Working from a pure computational fluid dynamics perspective it can remove disconnected void space in the image regardless of size or location, both of which are constraints often applied to other image processing methods. However, a large amount of volume removed does not always produce a matching drop in overall transmissivity (see Figure 19). This was not expected on the same basis that a change in mean aperture does not have a consistent effect on fracture conductivity. A few small groups in key locations can drastically affect conductivity when the 3-D geometry is flattened if they bridge regions isolated by contact zones.

An increase in correlation length was observed for all 37 geometries considered after cluster processing, as evident in Figure 20. Removal of disconnected void space smooths out the resulting aperture map preventing those extra features which do not contribute to flow from adversely affecting simulation results. Additionally, a longer correlation length has been shown to reduce the simulation error between local cubic law

and full Navier-Stokes simulations, in this work the correlation length was increased by an average of 10%.

Having many fracture geometries with experimental flow data permitted evaluation of the local cubic law's agreement with experimental results as a function of basic geometric parameters defined in Brush and Thompson (2003). A direct match between experimental and simulation data was not expected, yet any observable trend in the numerical error would indicate the presence of higher order flow characteristics. All the simulations were within or close to the limits of aperture aspect ratio and roughness slope proposed in Brush and Thompson (2003). Relative roughness often exceeded the limit but for most cases by less than 50%. There was no clear relationship linking simulation error to the parameters, indicating that the primary source of error was not directly tied to the numerical scheme used.

Finally, a comparison between two distinctly different families of shale was performed to assess how they respond to shearing relative to each other. Quantifying how similar, or dissimilar different shale families react is an important stage in determining the portability of the available shearing research. The same parameters used to quantify the error between simulation and experimental data were described as functions of shear displacement. FutureGen Core-B was an outlier to varying degrees for all cases, although after shear step 3 the trend of its values matched the other samples. Aperture aspect ratio was the only parameter that appeared completely uncorrelated. It shared no relationship to the amount of shear displacement nor the behavior of other samples used in the study.

All the simple aperture statistical measures (mean, standard deviation and correlation length) used show a general agreement in the trends observed because of

shearing. While the initial values for the Eau Claire samples were higher, after two to three shearing steps the parameter progression mirrored that of the Marcellus. While the aperture aspect ratio did not follow an appreciable trend the relative roughness appeared to either remain at, or converge toward unity in all cases. Experimental transmissivity increased with shearing for all samples, except FutureGen Core-B, by approximately an order of magnitude. Provided the similar evolution of geometric parameters and hydraulic conductivity between both families of shale it can be seen both the Marcellus and Eau Claire shales have a very similar response to shear displacement.

Appendix

A. Acronyms and Abbreviations

2-D	= Two Dimensional
3-D	= Three Dimensional
CFD	= Computational Fluid Dynamics
CO ₂	= Carbon Dioxide
CT	= Computed Tomography
DI	= Deionized Water
expT	= Experimental Transmissivity
FGen	= FutureGen
IS	= Induced Seismicity
JRC	= Joint Roughness Coefficient
LCL	= Local Cubic Law
LGA	= Lattice Gas Automaton
MLCL	= Modified Local Cubic Law
ml/min	= Milliliter per minute
mm	= Millimeter
MPa	= Megapascal
MRI	= Magnetic Resonance Imaging
NaCl	= Sodium Chloride
NETL	= National Energy Technology Laboratory
PIV	= Particle Imaging Velocimetry
psi	= Pounds per Square Inch
Re	= Reynolds Number
simT	= Simulated Transmissivity
T	= Transmissivity
μm	= Micrometer

B. Variable Definitions

b	= Aperture
b_m	= Mean mechanical aperture
b_h	= Hydraulic aperture
b_f	= Average Aperture at grid block interface
b_1, b_2, b_3, b_4	= Average aperture at each corner point
$\bar{b}_f^3$	= Corrected interface aperture
$d(x, y)$	= Local fluid thickness
g	= Gravitational body force
I	= Transmitted beam intensity
I_0	= Initial beam intensity
L	= Length
η	= Material attenuation
η_w	= Attenuation of pure water
$p(x, y)$	= Local fluid pressure
$p_{i,j}$	= Local fluid pressure
ΔP	= Macroscopic pressure drop across the fracture
Q	= Volumetric flow rate
$T_{x,i,j}$	= Local transmissivity in the X direction
$T_{z,i,j}$	= Local transmissivity in the Z direction
V	= Fluid velocity vector
W	= Width
$\Delta x_{i,j}$	= Local grid block length in the X direction
$\Delta z_{i,j}$	= Local grid block length in the Z direction
δ_{fF}, δ_{fP}	= Distance from cell center to grid block interface
$\overline{\delta_{Lf}}$	= Interface length from cell center to center
θ_{fF}, θ_{fP}	= Slope from cell center to grid block interface
λ_b	= Aperture correlation length
μ	= Fluid viscosity
ρ	= Fluid density
σ_b	= Aperture standard deviation

C. Associated Research Attached

Crandall, D., Moore, J., Gill, M., Stadelman, M.: Hydrodynamic response of sheared fractures. Submitted to the International Journal of Rock Mechanics and Mining Sciences (2017)

Mofakham, A., Stadelman, M., Ahmadi, G., Shanley, K., Crandall, D. "Fluid Flow in Rock Fractures under Various Shearing Conditions." 2017 (in preparation).

D. References

Ahrens, J., Geveci, B., & Law, C. (2005). ParaView: An end-user tool for large data visualization.

In The Visualization Handbook (pp. 717–731). Oxford: Elsevier. ISBN-13: 978-0123875822

Auradou, H., Drazer, G., Boschan, A., Hulin, J. P., & Koplik, J. "Flow channeling in a single fracture induced by shear displacement." *Geothermics* 35.5 (2006): 576-588.

Bertels, Stephanie P., David A. DiCarlo, and Martin J. Blunt. "Measurement of aperture distribution, capillary pressure, relative permeability, and in situ saturation in a rock fracture using computed tomography scanning." *Water Resources Research* 37.3 (2001): 649-662.

Brown, Stephen R., and Christopher H. Scholz. "Broad bandwidth study of the topography of natural rock surfaces." *J. geophys. Res* 90.B14 (1985): 12575-12582.

Brown, Stephen R. "Fluid flow through rock joints: the effect of surface roughness." *Journal of Geophysical Research: Solid Earth* 92.B2 (1987): 1337-1347.

Brown, Stephen R., Harlan W. Stockman, and Sally J. Reeves. "Applicability of the Reynolds equation for modeling fluid flow between rough surfaces." *Geophysical Research Letters* 22.18 (1995): 2537-2540.

Brown, Stephen, Arvind Caprihan, and Robert Hardy. "Experimental observation of fluid flow channels in a single fracture." *Journal of Geophysical Research: Solid Earth* 103.B3 (1998): 5125-5132.

Brush, David J., and Neil R. Thomson. "Fluid flow in synthetic rough- walled fractures: Navier- Stokes, Stokes, and local cubic law simulations." *Water Resources Research* 39.4 (2003).

Carey, J. W., Lei, Z., Rougier, E., Mori, H., & Viswanathan, H. "Fracture-permeability behavior of shale." *Journal of Unconventional Oil and Gas Resources* 11 (2015): 27-43.

Cnudde, Veerle, and Matthieu Nicolaas Boone. "High-resolution X-ray computed tomography in geosciences: A review of the current technology and applications." *Earth-Science Reviews* 123 (2013): 1-17.

Crandall, Dustin, Grant Bromhal, and Zuleima T. Karpyn. "Numerical simulations examining the relationship between wall-roughness and fluid flow in rock fractures." *International Journal of Rock Mechanics and Mining Sciences* 47.5 (2010): 784-796.

Dougan, L. T., P. S. Addison, and W. M. C. McKenzie. "Fractal analysis of fracture: A comparison of dimension estimates." *Mechanics research communications* 27.4 (2000): 383-392.

Ge, Shemin. "A governing equation for fluid flow in rough fractures." *Water Resources Research* 33.1 (1997): 53-61.

Gentier, S., Riss, J., Archambault, G., Flamand, R., & Hopkins, D. "Influence of fracture geometry on shear behavior." *International Journal of Rock Mechanics and Mining Sciences* 37.1 (2000): 161-174.

Gilmore, T J, A Bonneville, V Vermeul, F Spane, M E Kelley, C Sullivan, J Hoffmann, *Overview of the CO2 Geological Storage Site for the FutureGen Project in Morgan County Illinois, USA*, Energy Procedia, Vol 63, pp 6361-6367, (2014)

Hakami, Eva, and Erik Larsson. "Aperture measurements and flow experiments on a single natural fracture." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. Vol. 33. No. 4. Pergamon, 1996.

Heller, Robert, and Mark Zoback. "Adsorption of methane and carbon dioxide on gas shale and pure mineral samples." *Journal of Unconventional Oil and Gas Resources* 8 (2014): 14-24. (denoted 2014a)

Heller, Rob, John Vermylen, and Mark Zoback. "Experimental investigation of matrix permeability of gas shales." *AAPG bulletin* 98.5 (2014): 975-995. (denoted 2014b)

Josh, M., Esteban, L., Delle Piane, C., Sarout, J., Dewhurst, D. N., & Clennell, M. B. "Laboratory characterisation of shale properties." *Journal of Petroleum Science and Engineering* 88 (2012): 107-124.

Jones E, Oliphant E, Peterson P, et al. SciPy: Open Source Scientific Tools for Python, 2001-, <http://www.scipy.org/> (Accessed 2017-03-08)

Kargbo, David M., Ron G. Wilhelm, and David J. Campbell. "Natural gas plays in the Marcellus Shale: Challenges and potential opportunities." (2010): 5679-5684.

Karpyn, Zuleima Tharays. *Capillary-driven flow in fractured sandstone*. Diss. The Pennsylvania State University, 2005.

Karpyn, Z. T., Alajmi, A., Radaelli, F., Halleck, P. M., & Grader, A. S. "X-ray CT and hydraulic evidence for a relationship between fracture conductivity and adjacent matrix porosity." *Engineering Geology* 103.3 (2008): 139-145.

Keller, A. A. "High resolution CAT imaging of fractures in consolidated materials." *International Journal of Rock Mechanics and Mining Sciences* 34.3-4 (1997): 155-e1.

Keller, A. "High resolution, non-destructive measurement and characterization of fracture apertures." *International Journal of Rock Mechanics and Mining Sciences* 35.8 (1998): 1037-1050.

Koyama, T., Ivars Neretnieks, and Lanru Jing. "A numerical study on differences in using Navier–Stokes and Reynolds equations for modeling the fluid flow and particle transport in single rock fractures with shear." *International Journal of Rock Mechanics and Mining Sciences* 45.7 (2008): 1082-1101.

Lee, Seung Hyun, Kang- Kun Lee, and In Wook Yeo. "Assessment of the validity of Stokes and Reynolds equations for fluid flow through a rough-walled fracture with flow imaging." *Geophysical Research Letters* 41.13 (2014): 4578-4585.

Liu, Qing-quan, and Hong-guang FAN. "The characteristics and estimation of flow through a single rough-walled fracture." *Journal of Hydrodynamics, Ser. B* 24.3 (2012): 315-322.

Lomize, G. M., Flow in Fractured Rocks (in Russian), 127 pp., Gosenergoizdat, Moscow, 1951

Louis, Claude. *A study of groundwater flow in jointed rock and its influence on the stability of rock masses*. Imperial College of Science and Technology, 1969.

Matsuki, K., Kimura, Y., Sakaguchi, K., Kizaki, A., & Giwelli, A. A. "Effect of shear displacement on the hydraulic conductivity of a fracture." *International Journal of Rock Mechanics and Mining Sciences* 47.3 (2010): 436-449.

Nuttall, B. C., Eble, C. F., Drahovzal, J. A., & Bustin, R. M. "Analysis of Devonian black shales in Kentucky for potential carbon dioxide sequestration and enhanced natural gas production." *Kentucky Geological Survey Report DE-FC26-02NT41442* (2005).

Olsson, W. A., and S. R. Brown. "Hydromechanical response of a fracture undergoing compression and shear." *International journal of rock mechanics and mining sciences & geomechanics abstracts*. Vol. 30. No. 7. Pergamon, 1993.

Olsson, R., and N. Barton. "An improved model for hydromechanical coupling during shearing of rock joints." *International Journal of Rock Mechanics and Mining Sciences* 38.3 (2001): 317-329.

Python Software Foundation. Python Language Reference, version 3.6. Available at <http://www.python.org>

Rasband, W.S. (2016) ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, <http://imagej.nih.gov/ij/>, (Accessed 3/07/2017).

Romm, E. S. "Flow characteristics of fractured rocks." *Nedra, Moscow* 283 (1966).

Sommer, Christoph, Strähle C., Köthe U., Hamprecht., F. A. "Ilastik: Interactive learning and segmentation toolkit." *Biomedical Imaging: From Nano to Macro, 2011 IEEE International Symposium on*. IEEE, 2011.

Stadelman, M. stadelmanma/netl-AP_MAP_FLOW: Initial Release.
<https://doi.org/10.5281/zenodo.495652>. 8 Apr. 2017.

Stadelman, M., Bromhal, G. S., Moore, J., Gill, M., & Crandall, D. "Direct Measurement of Changes to a Sheared Shale Fracture." *AGU Fall Meeting Abstracts*. 2015.

Tsang, Y. and P. A. Witherspoon. "Hydromechanical behavior of a deformable rock fracture subject to normal stress." *Journal of Geophysical Research: Solid Earth* 86.B10 (1981): 9287-9298.

Wang, L., Cardenas, M. B., Slottke, D. T., Ketcham, R. A., & Sharp, J. M. "Modification of the Local Cubic Law of fracture flow for weak inertia, tortuosity, and roughness." *Water Resources Research* 51.4 (2015): 2064-2080.

White, Frank M., and Isla Corfield. *Viscous fluid flow*. Vol. 3. New York: McGraw-Hill, 2006.

Willman, H. B., Elwood Atherton, T. C. Buschbach, Charles Collinson, John C. Frye, M. E. Hopkins, Jerry A. Lineback, and Jack A. Simon, 1975, Handbook of Illinois Stratigraphy: Illinois State Geological Survey Bulletin 95, 261 p.

Witherspoon, P. A., Wang, J. S., Iwai, K., & Gale, J. E. "Validity of cubic law for fluid flow in a deformable rock fracture." *Water resources research* 16.6 (1980): 1016-1024.

Xiong, X., Li, B., Jiang, Y., Koyama, T., & Zhang, C. "Experimental and numerical study of the geometrical and hydraulic characteristics of a single rock fracture during shear." *International Journal of Rock Mechanics and Mining Sciences* 48.8 (2011): 1292-1302.

Yeo, I. W., M. H. De Freitas, and R. W. Zimmerman. "Effect of shear displacement on the aperture and permeability of a rock fracture." *International Journal of Rock Mechanics and Mining Sciences* 35.8 (1998): 1051-1070.

Zimmerman, R. W., Sunil Kumar, and G. S. Bodvarsson. "Lubrication theory analysis of the permeability of rough-walled fractures." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. Vol. 28. No. 4. Pergamon, 1991.

Hydrodynamic Response of Sheared Shale Fractures

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Abstract:

Shale formations, and black shales in particular, are of great interest for their energy production potential and ability to serve as seals for sequestered anthropogenic carbon dioxide (CO₂). Because of the low permeability of shale, fractures are typically as the primary flow conduits in these formations. It is therefore imperative to understand the fundamental processes that influence fracture properties in shale to accurately predict unconventional resource production as well as ensure that sequestered CO₂ doesn't migrate out of a storage reservoir. In this study, a novel shearing apparatus was used in conjunction with a Hassler-style core holder to incrementally shear shale cores while maintaining various confining pressures, simulating a fracture in a sealing formation subjected to shearing forces. Intermittent computed tomography scans performed after each shearing event were used to obtain information on evolving fracture morphology. Transmissivity of the fracture was measured after each shearing event to better understand the hydrodynamic response. Characteristics of fracture geometries were derived from the computed tomography scans and the digital volumes were used in laminar single phase flow simulations to qualitatively examine the small scale variation in flow paths within the altered fractures. Fractures were found to increase in aperture after several shear slip events, with corresponding increases in transmissivity. Flow paths within the fractures was largely shown to be controlled by the location and evolution of zero aperture locations. A reduction in the primary flow pathways through the fracture was observed during all shearing tests.

Highlights:

- Developed and implemented an experimental shearing device to examine fracture evolution in rocks
- Measured permeability and geometric changes of sheared fractures
- Simulated laminar flow through real sheared fracture geometries
- Change in shearing behavior observed at different confining pressures

Graphical Abstract Image: Figure 6

Keywords:

Computed tomography, local cubic law, fractured seals, fracture transmissivity

1. Introduction:

The presence or absence of fractures, as well as an accurate description of their flow properties, are critical to describe a wide range of subsurface energy activities. The resistance

to fluid flow within a fracture can be many orders of magnitude less than that of unfractured rock matrix, with fractures often forming “super highways” for fluid flow in the subsurface. Flow in rough natural fractures is complex and vital for many subsurface activities (e.g recovery of oil/gas from shales, operation of enhanced geothermal systems, exploitation of water resources, etc). Conversely, the presence of fractures in sealing formations at geologic carbon sequestration sites can enable upward flow of carbon dioxide (CO₂) and brine from deep reservoirs, and compromise long term storage potential. Several review articles discuss the wide range of subsurface applications that rely on accurate descriptions of flow in fractures and difficulties in developing accurate models (Berkowitz, 2002; Zimmerman and Bodvarsson, 1996).

Numerous detailed laboratory and computational studies of fluid flow through rough-walled rock fractures illustrate the importance of fracture wall roughness, aperture, zero aperture zone distribution, and introduction of fines/clogging when describing the relationship between fracture geometries and fluid flow properties (Bertels, 2001; Brush, 2003; Carey, 2015; Crandall et al 2010; Montemagno, 1999; Oron, 1998; Watanabe, 2011; Witherspoon et al. 1979). To date, no universally accepted simple relationship between easily-measured fracture geometric properties and fluid flow properties is available. Often, the complex relationship of varying aperture and flow is described at the reservoir scale using a simplification of the Navier-Stokes equations known as the 'cubic law' and a hydraulic aperture. This simplification is appropriate when little is known about the detailed fracture properties, but masks the true complexity of flow observed in real rock fractures.

Fractures in rock correspond to zones of weakness which deform more readily than surrounding rock in response to elevated stresses in the subsurface. The zones act as a localized release of stress through mechanical movement of the rock. Shearing along fractures, where displacement occurs between complementary, rough walls of a fracture plane, can also occur as a result of the induced seismicity associated with many human activities in the energy and carbon capture sectors (Jackson et al., 2014; Majer et al., 2012; Myer and Daley, 2011; Zoback, 2012; Zoback and Gorelick, 2012). Hydraulic fracturing operations, in particular, produce many micro-seismic events that may be used to monitor the extent of the stimulated reservoir (Angus and Verdon, 2013). There is a complex relationship between in-situ stresses, changes introduced by shearing along fractures, and fracture flow properties. The effects of shearing on the transmissivity of fractures at in-situ overburden pressures are not well understood.

In this study, laboratory experiments that examined changes in fracture geometry and transmissivity as a function of shearing were conducted to evaluate the mechanisms and characteristic properties of shales under shear stress. Shearing events at various overburden pressures using modified traditional Hassler style core holders and computed tomography (CT) scanning were performed on shales. CT scanning enables high resolution images of major morphologic changes to be captured (Cnudde and Boone, 2013), including the development of additional fractures and clogging mechanisms. Simultaneous measurement of changes in pressure and flow rates across the core enable capture of concurrent changes in bulk transmissivity. High-fidelity fracture geometry can be obtained from CT scans for modeling efforts.

The bulk transmissivity of fractures as a function of shearing movement is important for coupled geomechanical-flow modeling of reservoir performance. However, it may be helpful to understand how the underlying fine resolution variations in the fracture morphologies influence flow properties when upscaling to reservoir-scale simulations or modeling geochemical effects. CT-derived geometries of fractures subjected to shear were examined using a local cubic law model to simulate flow patterns (Brush and Thomson, 2003; Stadelman et al 2015). Coupling small changes in geometry to changes in flow properties can illustrate which properties have the largest impact on fracture transmissivity and thus inform upscaled models.

This work was performed with the goal of assessing the relationship between mechanical evolution and hydrologic properties in fractured shale reservoirs. The use of CT and traditional core flooding in conjunction with a novel shearing apparatus has enabled characterization of both parameters simultaneously, allowing an analysis of the links between the aforementioned physical measurements. Modeling efforts corroborated the development of discrete channels that evolved as a function of material displacement and subsequently controlled the hydrodynamics in the fracture.

2. Methods

2.1 Experimental Procedure

Three Marcellus Shale cores were created from the lower basal unit of the formation, equivalent to the Union Springs Member (Soeder 2014). A large sample with a single natural fracture was identified and targeted as the source for all samples. A single 6" long by 1.5" diameter core was extracted using a diamond carbide drill bit, and cut such that the planar beds were parallel to the long dimension of the core and so that the fracture bisected the core at approximately the center. The 6" core was subsequently cut into three 1.5" long sections. The fracture was a single, mostly planar opening that extended the length of the core all three samples (Figure 1). Small losses of core material were observed on the periphery of the fracture due to the mechanical preparation process; these losses were not significant in contribution to flow mechanics as they were localized and not interconnected. Additionally, Lawson Products RTV silicone was used to fill the outer periphery of the fracture to minimize flow around the core and to reduce channelization at the edges of the fracture plane where the material had been lost.

The sample was also analyzed for mineralogical composition using a PANalytical X'Pert Pro X-Ray diffractometer and the carbon constituency using a Perkin Elmer 2400 Series II CHNS/O elemental analyzer. The sample was primarily composed of quartz and calcite with some minor illite/mica. The total carbon was 11.5% by weight percent and comprised of 6.4% and 5.1% of organic and inorganic carbon respectively which is typical for the Marcellus shale. The illite in the sample and lack of other clays indicates that very little swelling or hydration occurred during the exposure to water.

Fractured cores were loaded into a custom designed piston system that allows axial force to be applied directly in measured increments inside of a Hassler style core holder (Figure 2). The entire core system was then wrapped in a heat-shrink Teflon sleeve to provide a water-tight barrier around the core perimeter and pistons. Aluminum shields were placed outside of the Teflon sleeve and then the entire apparatus inserted into a Buna-N nitrile rubber confining

sleeve. The shields were designed to prevent the collapse of the confining sleeve, while still allowing confining pressure to be applied to the core.

Rather than applying a known stress to the piston system shearing displacement was controlled by turning the end cap in 45° increments; the physical displacement of the screw mechanism pushing the pistons induced the shearing. The amount of each displacement was also measured from the CT scans because the applied displacement to the end caps did not result in a 1 to 1 displacement within the core. Asperities restricted core displacement at times and the total measured displacement for each shearing event was slightly non-uniform, with an average core displacement of 0.69 mm per turn and a standard deviation of 0.3 mm for all the tests performed.

Overburden pressure was applied with a Teledyne Isco Syringe Pumps (500 D). The shearing system design was the same in every test, with the applied confining pressure varied between the three tests, from 200 to 1000 psi (1.4 to 6.9 MPa, Table 1). In addition, the third shearing test was conducted after the core had gone through 3 pressurization cycles, prior to shearing.

To capture the geometric changes to fracture morphology and aperture, CT scans were taken after each shearing step in all three tests. Scans were taken with a North-Star Imaging Inc. M-5000 Industrial Computed Tomography System (Industrial CT). Samples were scanned with a source voltage of 174 kV and a current of 300 μ A. Each scan was comprised of 1,440 projections with each projection being the average of five radiographs taken with a 0.5 s exposure time. North-Star Imaging eFX[®] software was used to reconstruct data into 3 dimensional volumes. Resolutions ranged from 27.6 μ m per pixel in Test 1 to 26.8 μ m in Tests 2 and 3.

2.2 Hydraulic Analysis

At each step, both in the shearing progression and cyclic pressurization (Test 3), transmissivity (T) tests were conducted with a single phase water injection. Teledyne Isco Syringe Pumps (500 D) were used as the injection pumps and a Rosemount 3150CD differential pressure transducer (0-300 PSI range) was used to measure pressure drop across the core. The transmissivity was calculated using the Cubic Law with a Darcian flow assumption using the following:

$$k = v \mu L / \Delta p$$

where k is the permeability of the sample (m^2), v is the averaged flow velocity (m/s), μ is the dynamic viscosity ($\text{Pa} \cdot \text{s}$), L is the length of the sample (m), and ΔP is the pressure gradient across the sample (Pa). Considering $Q = v \cdot A$, where Q is the volumetric flow rate in the sample (m^3/s) and A is the total area of the sample perpendicular to the direction of flow (m^2), one can define transmissivity, T (m^4), as:

$$T = kA = Q \mu L / \Delta p$$

T was used in this study in preference to k for two reasons, being 1) the use of T eliminates the need to know the exact area of the fracture aperture, which is highly variable and 2) flow was likely only in the fracture plane; not a function of the core cross-sectional area.

For each determination of T, the ΔP was measured at a minimum of 3 flow rates between 0.1 and 8 ml/min. Flow rates were used to obtain a ΔP that was measureable using the Rosemount 3051CD differential pressure transducer. Shearing and transmissivity testing were stopped once

hydraulic measurements were no longer possible with the 0-300 psi transducer, which happened when Q was greater than 8 ml/min.

2.3 CT Data and Aperture Isolation

CT data was exported as 2D 16-bit tiff cross section images that were perpendicular to the primary fracture plane. ImageJ (Rasband, 2016) was used to process the data in the form of tiff image stacks, which serve as a proxy for 3D volumes, with each slice representing a thickness of one voxel.

Fracture apertures were isolated from the bulk matrix via thresholding, which can be cumbersome and difficult if the media in question has a high degree of heterogeneity or if scan quality is poor (Kutchko et al. 2013). Due to sample heterogeneity and the presence of high attenuation materials, some of the tests had a prohibitively high signal to noise ratio, which did not allow for simple thresholding methods to be effective.

In Test 1, segmentation was performed using simple thresholding techniques, using the median value between the mean matrix and air grayscales. For more detail on this technique see Kutchko et al. (2013). In Tests 2 and 3, a K-Means clustering algorithm (ImageJ Plugins Toolkit, 2015) was used. In k-means clustering, the image is partitioned into a user-defined number of clusters (k) based on all observations (n) within the image; in this case n would be the total voxels. The algorithm then seeds points within the 3D volume and assigns those points as cluster centroids. Each n is then sequentially assigned to a given cluster (k). The new assignments are used to calculate new mean values, and these new mean values are then assigned as centroids for the observations. The process continues iteratively until assignments no longer change, demonstrating convergence. In this study, 4 clusters were used to differentiate the experimental components within the scans which included the fracture aperture, bulk rock matrix, shearing pistons/core holder, and confining fluid (water).

After thresholding, fracture apertures were determined using the ImageJ plugin LocalThickness (Dougherty and Kunzelmann, 2007), which uses a rolling ball algorithm where the aperture is assumed to be equal to the diameter of the largest sphere that fits within the fracture at a given coordinate. This type of measurement is uniquely suited to 3D data analysis, as it takes into account the true 3D distribution of fracture apertures, and was used as the basis for the generation of the final aperture maps.

The identification of zero aperture zones, or areas of no flow where opposing fracture walls meet, is of particular interest because they play a large role in the determination of preferential flow pathways. These zones are also the biggest areas of change as smearing and mechanical breakdown occur through shearing; they therefore act as the primary indicators of major geomechanical and geometric changes. It should be noted that areas where the fracture aperture is at or below the scan resolution of 26.8-27.6 μm also appear as zero aperture zones, as it is not possible to adequately isolate them from the bulk matrix within the CT images.

2.4 Modeling Procedure

Flow through fractures was modeled using a 2-D Darcian flow assumption with the aperture map derived from the CT scans as the local variation in the transmissivity along the fracture, i.e. a Local Cubic Law (LCL) simulation (Witherspoon et al. 1980; Zimmerman et al. 1991; Brush

and Thompson, 2003). This finite volume problem was solved using the backwards time centered space method. Every point in the aperture map data was converted to a grid block with no additional averaging. The model outputs include the pressure distribution, flow rate distribution, and a VTK legacy file to post-process the data in Paraview (Ahrens et al. 2005). Pressure conditions, flow rate, and physical size of the scanned voxels were matched to the experimental conditions for the transmissivity tests previously discussed.

The flow in the fracture was assumed to obey Darcy's law for slow laminar flow through porous media, an approximation that is derived from the assumption of flow through narrowly spaced parallel plates from the Navier-Stokes equations of continuity of fluids as described by the following:

$$Q = T_{\text{local}} \cdot \Delta P / L$$

where T_{local} is the transmissivity of the gridblock and ΔP is a 2-D pressure difference across length L . T_{local} combines the physical characteristics of the boundary between two grid-blocks due to the change in aperture size, permeability, and viscosity of the fluid. K was calculated using the LCL on an adjusted aperture value using the Stokes Tapered Plate Solution (Brush and Thompson, 2003). The Stokes Tapered Plate Solution corrected the T_{local} values based on the amount of variation between grid-blocks, reducing the aperture used in the LCL to a value representing the influence of the smaller aperture.

The generation and solution process make a few key simplifications to create a tractable problem. Flow is assumed to be two-dimensional and the fracture mid-plane is flat throughout. The flow is assumed to be "creeping", or slow, laminar, viscous flow, driven only by a pressure gradient and no other body forces. These simplifications likely contribute to the differences between experimental data and simulation data. Another minor assumption is one of constant viscosity. The test conditions are isothermal, and for an incompressible fluid such as water, the change in viscosity due to pressure is negligible across the pressure gradients present.

Because of these simplifications and a limitation on the resolution which can be derived from the CT scan (i.e. small roughness cannot be resolved) we did not expect, nor did we obtain, a direct match between simulation and experimental results. Instead we utilized the simulation to increase our understanding of the observed experimental changes in fracture T during shearing. The model outputs, in conjunction with the post-processing power of tools such as Paraview, allow for a qualitative analysis of the data. Although the CT scanner is not able to directly visualize fluid flow, it is well understood that fluid follows preferential channels through fractures. The results generated through simulation work allowed the visualization of the probable fluid paths and supplemented experimental results.

3. Results

3.1 Hydraulic Data

The results from the T measurements at each shearing step are shown in Figure 3. Permeability (k) is shown on the right axis of Figure 3 for comparison and were calculated using the cross-sectional area of the entire core (11.4 cm^2). Tests 1, 2, and 3 were performed with similar cores from the same parent material and the same apparatus and techniques previously described. The primary variable between tests was the confining pressure, P_{conf} , which was 200, 500, and 1000 psi (1.38, 3.45, and 6.89 MPa) for Tests 1, 2, and 3, respectively.

In Test 1, T varied by two orders of magnitude through the 7 shearing steps, from 9.2×10^{-16} to $3.9 \times 10^{-15} \text{ m}^4$. T was low and generally unaltered for the first 4 shearing steps (Figure 3). At shear step 4, an abrupt increase in T was observed. Post shear step 4, T remained nearly the same with little deviation between shearing steps, indicating good flow connectivity within the fracture aperture. The variation in ΔP used to calculate the T may be due to nonlinear flow regimes at higher fluid flow rates causing deviations not accounted for in Eq. 1, in addition to variation in experimental measurements from the equipment.

Resistance to flow varied more in Test 2, ranging from a low T of $5.65 \times 10^{-19} \text{ m}^4$ in the base unsheared condition, to greater than $1.0 \times 10^{-15} \text{ m}^4$ at the end of the experiment (Figure 3). The first shearing event resulted in a 2 order of magnitude increase in T . Subsequent increases were observed in shear steps 2-4. However, T in shear steps 3 and 4 was not measurable due to no appreciable ΔP across the core and thus assumed to be at least $1.0 \times 10^{-15} \text{ m}^4$.

In Test 3, with $P_{\text{conf}} = 1000 \text{ psi}$, shearing of the sample resulted in T values ranging from 1.65×10^{-18} to $1.80 \times 10^{-16} \text{ m}^4$. Initially T decreased after shear step one and then increased during shear steps two through four (Figure 3). This initial reduction in T at the highest P_{conf} was unique among the three tests, but as seen in the other sheared fractures, an overall increase in T was observed after the sample was sheared more than 1 mm.

3.2 CT Image Analysis

The apertures of the fracture from the first two scans of Test 1 (the unsheared base and the first shearing event) were near the resolution of the CT imaging voxel size. Hence no CT analysis was performed on these initial scans. However, shear steps two through eight did generate appreciable changes in aperture (Figure 4 and Table 2). Particularly large apertures formed at the inlet of the core resulting from large splaying events that mobilized rock material (Figure 5). The contact area (Table 2) of the fracture surfaces increased until shear step four, then decreased for several steps before increasing during the final shear steps. Modelling efforts discussed in the following section illustrated the importance of the aperture development at the inlet and the contact area zones for controlling the flow distribution.

The base fracture in Test 2 was also at or near the one voxel resolution and therefore wasn't processed. There were areas in the base unsheared scan that showed a pre-existing aperture greater than 'zero', but these were the result of material loss during the sample preparation and could not adequately be described by the aforementioned processes. In shear step 1, the average aperture was approximately 1.23 mm. The subsequent shearing events increased aperture in some areas while causing decreases in others. Average apertures increased with each shear event culminating in an average of 2.35 mm by the fourth and final shearing event. The contact area between surfaces fluctuated between 9 and 16% during the shearing events, with no direct linkage to the observed changes in T . Highest apertures appeared in areas that were originally at or near zero, indicating that the pre-existing apertures from material loss had little effect or further degradation during the shearing events; this is further evidenced in Figure 6, where the opening apertures concentrate flow. The four shearing events in Test 2 resulted in a total measured displacement of approximately 2.45 mm (Table 2).

The base fracture of Test 3 was easier to isolate than in the two previous tests, indicating poorer mating of fracture or the presence of more roughness and material loss (Figure 4). This was further supported by the presence of distinct channels ($>70 \text{ }\mu\text{m}$) in the aperture plane that run

parallel to flow direction (Figure 7). The first shear event resulted in significant reduction in parallel channels and their transition to troughs that were perpendicularly oriented to the direction of flow. In addition, an improved mating of the fracture surfaces was observed after shear step one that resulted in a slightly smaller mean fracture aperture (Table 2). Even though there was a minor change in the bulk fracture aperture there was a large decrease in the fracture T after this first shearing step. The flow-perpendicular features persisted and became more pronounced as shearing progressed. A reduction in the percent of contact areas was observed after each shear step for Test 3 (Table 2). The measured shear displacement totaled approximately 1.9 mm over a period of 4 shear steps.

3.3 Flow Simulations

Local cubic law (LCL) simulations utilizing the Stokes Tapered Solution (Brush and Thompson, 2003) previously discussed were executed for all 16 shearing steps with high quality CT derived aperture maps. The distribution of pressure and flow magnitude from LCL simulations with a set injection rate of 10 ml/min along the fractures obtained from these tests are shown in Figures 5, 6, and 7 with the flow direction from the bottom to the top of each image. Additional runs of the model were performed for each of the differential pressures measured at each shear step as well. The flow rate does not affect the flow distribution because the model assumes creeping flow conditions. For all simulations the highest flow channels were observed to meander around zones of zero (or very low) aperture, within preferential channels becoming more dominant with each shear step. Narrow bands of zero aperture that span the width of the fracture have a dramatic effect on the pressure distribution causing most of the ΔP to occur over a small length. Pressure across the entire fracture decreased with shearing, similar to the increase in the T observed for each of these experiments. The simulated T was between half to two orders of magnitude greater than the values observed in the experiments; this discrepancy will be discussed further in the conclusions section.

For Test 1 ($P_{\text{conf}} = 200$ psi) the evolution in fracture geometry shown on the left of Figure 5 illustrates the large zones of high aperture (> 0.2 mm) that formed during the shearing throughout the fracture. A zone of restriction roughly 1/10 of the fracture length from the inlet created a large local pressure differential (middle images, Figure 5). The ΔP along the entire fracture decreased substantially after shear step 5.

For Test 2 ($P_{\text{conf}} = 500$ psi) zones of large apertures (> 0.5 mm) formed throughout the fracture in a more dispersed manner than in Test 1. A region of material loss in the center of the effluent side of the fracture localized flow at the exit to a primary discharge channel (Figure 6). The ΔP across the core decreased quickly from 0.5 psi to a ΔP of less than 0.1 psi as the fracture sheared and opened. A zone of lower apertures roughly $\frac{1}{4}$ of the fracture length from the exit side persisted through the shearing, though this did not appear to restrict flow dramatically when examining the pressure contours. Fewer and more disperse channels of high magnitude flow were observed in this region though.

The simulated response of flow to the shearing of the fracture in Test 3 ($P_{\text{conf}} = 1000$ psi) is unique in several ways. The reorientation of the larger aperture zones (> 0.5 mm) from along the flow direction to perpendicular to it from the base case during shear step one was visualized and resulted in a dramatic increase in ΔP along the length of the fracture, from ~ 8 to 20 psi (Figure 7). Subsequent shearing steps propagated broader zones of large apertures and the ΔP along the core dropped to less than 1 psi. This behavior mirrors the shift in T observed experimentally (Figure 3). In addition, high flow zones along the edge of the fracture formed

after the 1st shear step, and appeared to provide the majority of fluid conductivity during all subsequent shearing events.

To quantify the channelization of flow in the flow magnitude maps shown in Figures 5, 6, and 7 locations with local Q greater than the total flux/1000 were isolated. Along the width of the fracture, the higher flow channels were counted and their width measured at each transect along the fracture length (Figure 8). Several characteristics of these fracture channels qualitatively observable in the flow plots are illustrated in the relationships in Figure 8. The high Q channel widths are similar for all sheared fractures, and for all tests they increase from ~ 0.5 to 1.5 mm during the shearing. In addition, the higher P_{conf} tests have a fewer number of channels formed within the fractures. For all tests the number of channels is roughly halved during the shearing of the fractures. The analysis of these flow channels with the LCL simulations, while semi-qualitative illustrate the complex coupled relationship between the rough fracture geometry, the effective pressure confining the fracture, and how fracture evolution during shearing impacts the flow of fluid.

4. Discussion and Conclusions

Experimental results suggest that, while important, initial fracture geometry is not a dependable indicator of either hydrodynamic or geomechanical response to shear. Three sets of experiments were conducted on subcores from the same parent material cut along a common fracture, with the primary variable among the three experiments being the overburden pressure applied to the core. Test 1 showed a non-linear sample evolution, with a sudden T increase tied to mechanical failure and corresponding morphological change; T before and after the mechanical shift was relatively stable. Test 2 demonstrated a more linear response, with both T and fracture aperture increasing incrementally during the course of the experiment. Test three was unique, in that it exhibited an initial drop in T , followed by a roughly linear increase (Fig 3). This result was surprising, considering that fracture dilation was the expected outcome of shearing, due to naturally occurring asperities. Fracture dilation was supported by a volumetric increase in the aperture (Table 2 and Figure 7). CT data suggests that the initial decrease in T is due to the reorientation of linear zero aperture zones from an initial position parallel to the flow direction in the base scan, to an orientation perpendicular to the flow direction, effectively blocking some preferential flow pathways. Comparison of simulation results with experimental data further strengthens the conclusion that one of the primary controls on flow is the location and size of zero aperture zones. Despite the anomalous initial behavior in Test three however, in general fractures subjected to shear stress responded with unaltered or increased T as a function of increasing shear.

Increases in fracture T correlated to increases in average fracture apertures in all three tests; the only exception to this was shear step 1 in Test three. CT derived fracture morphology suggests that rough walled fractures can increase in aperture after shear events due to the presence of asperities, which prop the fracture in a more open position. Mechanical failure and losses of matrix material can also lead to increased fracture apertures. While the experimental design focused on flow through a single main fracture, it should be noted that development of secondary splay fractures was especially notable in Test 2, and their potential contribution to T increases could influence flow in a natural setting. Within results presented here no secondary

fractures along the length of the core formed and the impact to the T measurements is assumed to be minimal.

While the introduction of fine gouge material created during fracture slip may play a role in reducing fracture apertures and T, this did not appear to be a controlling factor in these experiments. Flow magnitudes used in these experiments are orders of magnitude higher than the rock would likely experience in the subsurface and may have swept away any fine residual material.

As discussed earlier, the degree of overburden pressure, e.g. deviation between principal stresses within the system, was the experimentally altered independent variable changed between tests. It is likely the primary controlling factor on fracture morphology and ultimately on variation in hydrodynamic response. Increasing confining pressure, and therefore also increasing disparity between shear stress and overburden stress, resulted in a system transition from one of sudden mechanical failure to one of slower, gradual, more linear change. This type of evolution could reflect the “holding” power of the confining stresses on weakly bedded lithologies, preventing slip along bedding except in the primary fracture where the rock is imperfectly mated, and frictional stresses are lower. This indicates that the degree of separation between the principal stresses during shearing may play into the magnitude and type of mechanical changes that occur, which consequently determines the hydrodynamic response.

Coupling the LCL simulations to the CT derived fracture geometries enabled the flow paths created by the complex geometry within the fracture to be visualized. As previously mentioned, the T magnitude determined by LCL simulations differed from experimentally measured values by one to two orders of magnitude. While deviation from experimental measurements is well documented in the literature (Konzuk and Kueper, 2004; Brush and Thomson, 2003), research is continuing to understand how this discrepancy between results can be reduced. The relatively high flow rates necessary to measure experimental transmissivities created regions of localized flow that were likely much higher than the LCL model assumptions of laminar creeping flow. In addition, despite the high resolution of the CT scans, the roughness of the shale walls is below the voxel resolution and may contribute to discrepancies between results. Regardless of the difference in macroscopic flow properties determined from the LCL model and experiments, the microscopic behavior is qualitatively well illustrated by the models.

The flow magnitude maps shown in Figures 5, 6, and 7 show a reduction in the number of channels as fractures shear. This is confirmed by the channel analysis for these tests (Fig 8) which show that the average flow channel width triples for all tests and the number of channels within the fractures decreases threefold. This localization of flow as an individual shale fracture shears could be critical for the migration of proppants, the extraction of natural gas, and any geochemical alterations due to CO₂ migration through sealing layers. Future studies examining how to quantify this variation as a function of not only P_{conf} , but also as a function of the shale constituents are warranted.

Future work will study fracture surface roughness and the mechanical properties of each sample (e.g. brittle versus ductile) as these affect fracture response to shearing. Additionally, the mineralogical content of the samples will need to be evaluated to detect the presence of swelling clays or other reactive phases that may contribute to permeability variations. Future

tests should also include samples sourced in the subsurface, in order to eliminate the potential effects of outcrop weathering on sample behavior. These further avenues of research will enable us to develop relationships that can be upscaled and applied to regional systems.

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References:

- Ahrens, J., Geveci, B., & Law, C. (2005). ParaView: An end-user tool for large data visualization. In *The Visualization Handbook* (pp. 717–731). Oxford: Elsevier. ISBN-13: 978-0123875822
- Angus, D. a., & Verdon, J. P. (2013). Using Microseismicity to Estimate Formation Permeability for Geological Storage of CO₂. *ISRN Geophysics*, 2013, 1–7.
<http://doi.org/10.1155/2013/160758>
- Bertels, S. P., DiCarlo, D. a., & Blunt, M. J. (2001). Measurement of aperture distribution, capillary pressure, relative permeability, and in situ saturation in a rock fracture using computed tomography scanning. *Water Resources Research*, 37(3), 649–662.
<http://doi.org/10.1029/2000WR900316>
- Berkowitz, B. (2002). Characterizing flow and transport in fractured geologic media: A review. *Advances in Water Resources*, 25, 861-884.
- Brush, D. J., & Thomson, N. R. (2003). Fluid flow in synthetic rough-walled fractures: Navier-Stokes, Stokes, and local cubic law simulations. *Water Resources Research*, 39(4).
<http://doi.org/10.1029/2002WR001346>
- Carey, J. W., Lei, Z., Rougier, E., Mori, H., & Viswanathan, H. (2015). Fracture-permeability behavior of shale. *Journal of Unconventional Oil and Gas Resources*, 11(5), 27–43.
<http://doi.org/10.1016/j.juogr.2015.04.003>
- Cnudde, V., & Boone, M.N. (2013) High-resolution X-ray computed tomography in geosciences: A review of the current technology. *Earth-Science Reviews*, 123, 1-17.
- Crandall, D., Bromhal, G., & Karpyn, Z.T. (2010) Numerical simulations examining the relationship between wall-roughness and fluid flow in rock fractures, *Int. J. Rock Mech. Mining Sci*, 47, 784-96, doi: 10.1016/i.ijrmms.2010.03.015

- Dougan, L.T., Addison, P.S., & McKenzie, W.M.C. (2000) Fractal analysis of fracture: a comparison of dimension estimates. *Mech Res Commun*, 27(4), 5125-32
- Dougherty, R. P., & Kunzelmann, K.-H. (2007) Computing Local Thickness of 3D Structures with ImageJ. In *Microscopy & Microanalysis 2007 Meeting*. Ft. Lauderdale.
- ImageJ Plugins Toolkit (2015). K-Means Clustering. Retrieved from: <http://ij-plugins.sourceforge.net/plugins/segmentation/k-means.html>
- Konzuk, J.S., & Kueper, B.H.; (2004) Evaluation of cubic law based models describing single-phase flow through a rough walled fracture, *Water Resources Research*, 40, W02402
- Kutchko, B.; Crandall, D.; Gill, M.; McIntyre, D.; et al. (2013). Computed Tomography and Statistical Analysis of Bubble Size Distributions in Atmospheric-Generated Foamed Cement; NETL-TRS-2-2013; EPACT Technical Report Series; U.S. Dept. of Energy, NETL: Morgantown, WV; p 28.
- Kohli, A. H., & Zoback, M. D. (2013). Frictional properties of shale reservoir rocks. *Journal of Geophysical Research: Solid Earth*, 118(9), 5109–5125. <http://doi.org/10.1002/jgrb.50346>
- Lei, Z., Rougier, E., Knight, E. E., Munjiza, A., Carey, J. W., & Viswanathan, H. (2015). FDEM Simulation on a Triaxial Core-Flood Experiment of Shale. In *49th US Rock Mechanics/Geomechanics Symposium*. San Francisco. <http://doi.org/10.13140/RG.2.1.4390.0001>
- Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., & Wong, I. (2012). Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems. U.S. Department of Energy Geothermal Technologies Program (Vol. DOE/EE-066).
- Montemagno, C. D., & Pyrak-Nolte, L. J. (1999). Fracture network versus single fractures: Measurement of fracture geometry with X-ray tomography. *Physics and Chemistry of the Earth*, 24(7), 575–579.
- Myer, L. R., & Daley, T. M. (2011). Elements of a best practices approach to induced seismicity in geologic storage. *Energy Procedia*, 4, 3707–3713. <http://doi.org/10.1016/j.egypro.2011.02.303>
- Oron, A. P., & Berkowitz, B. (1998). Flow in rock fractures: The local cubic law assumption reexamined. *Water Resources Research*, 34(11), 2811–2825. <http://doi.org/10.1029/98WR02285>
- Olsson, R., & Barton, N. (2001). An improved model for hydromechanical coupling during shearing of rock joints. *International Journal of Rock Mechanics and Mining Sciences*, 38, 317–329. [http://doi.org/10.1016/S1365-1609\(00\)00079-4](http://doi.org/10.1016/S1365-1609(00)00079-4)
- Rasband, W.S. (2016) ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, <http://imagej.nih.gov/ij/>, (Accessed 2/23/2016).
- Soeder, D., Enomoto, C., and Chermak, J. (2014) The Devonian Marcellus Shale and Millboro Shale. *GSA Field Guides*, 35, 129-160. [http://doi.org/10.1130/2014.0035\(05\)](http://doi.org/10.1130/2014.0035(05))

Stadelman, M. Bromhal, G.S., Moore, J., Gill, M., and Crandall, D. (2015) Direct Measurement of Changes to a Sheared Shale Fracture, presented at the 2015 Fall American Geophysical Union Meeting, December 2015.

Watanabe, N., Ishibashi, T., Ohsaki, Y., Tsuchiya, Y., Tamagawa, T., Hirano, N., ... Tsuchiya, N. (2011). X-ray CT based numerical analysis of fracture flow for core samples under various confining pressures. *Engineering Geology*, 123(4), 338–346.
<http://doi.org/10.1016/j.enggeo.2011.09.010>

Witherspoon, P.A., Amick, C.H., Gale, J.E., & Iwai, K. (1979) Observations of a Potential Size Effect in Experimental Determination of the Hydraulic Properties of Fractures. *Water Resources Research*, 15(3), 1142-1146.

Witherspoon, P.A., Wang, J.S.Y., Iwai, K., and Gale, J.E. (1980) Validity of Cubic Law for Fluid-Flow in a Deformable Rock Fracture, *Water Resources Research*, 16(6), 1016-1024.

Zimmerman, R.W. & Bodvarsson, G.S. (1996). Hydraulic Conductivity of Rock Fractures. *Transport in Porous Media*, 23, 1-30.

Zimmerman, R.W., Kummar, S., and Bodvarsson, G.S.(1991) Lubrication Theory Analysis of the Permeability of Rough-Walled Fractures, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 28(4). 325-331.

Zoback, M. D. (2012). Managing the Seismic Risk Posed by Wastewater Disposal. *Earth*, 57(4), 38.

Zoback, M. D., & Gorelick, S. M. (2012). Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proceedings of the National Academy of Sciences*, 109(26), 10164-10168.

Test	Shear Steps	Sheared Length Total (mm)	Confining Pressure (MPa)
1	8	6.35	1.38 (200 PSI)
2	4	3.18	3.45 (500 PSI)
3	4	3.18	6.89 (1000 PSI)

Table 1: Shearing Test Parameters

Test	Shear Step	Measured Displacement (mm)	Fracture Aperture (μm)		Fracture Volume (mm^3)	Contact Area (%)
			Mean	Standard Deviation		
Test 1	2	0.98	227.30	120.78	332.6	6.04
	3	1.44	256.11	160.52	369.6	6.56
	4	2.48	283.15	267.47	400.8	9.97
	5	3.11	298.51	259.15	420.4	9.54
	6	4.53	326.62	273.73	441.6	7.34
	7	5.66	338.50	263.29	466.7	9.40
	8	6.14	338.21	299.83	455.1	11.29
Test 2	1	0.47	122.83	71.50	123.5	12.11
	2	1.20	171.85	117.01	173.2	15.64
	3	1.82	235.47	159.38	226.9	9.18
	4	2.45	235.29	185.13	224.7	10.05
Test 3	0	0.00	63.65	61.52	72.7	31.25
	1	0.29	63.31	51.78	72.0	29.25
	2	0.87	101.86	76.19	113.6	21.69
	3	1.35	146.77	103.20	161.0	16.40
	4	1.86	163.55	125.44	173.7	17.37

*Missing shear steps are because the apertures were similar in size to the resolution of the scans

Figure 1: One and a half inch diameter fractured Marcellus shale core from Test 1. Fracture is concordant with bedding, mostly planar.

Figure 2: Cross sectional views of Hassler-style core holder housing the shearing apparatus. 1) Stainless steel spacer and fluid distribution, 2) half moon aluminum piston with fluid distribution channel, 3) shrink wrap Teflon sleeve, 4) sheared sample, 5) aluminum confining shield, 6) buna-N confining sleeve, 7) confining fluid, and 8) threaded core holder cap for inducing shear.

Figure 3: Measured flow resistance of fractures. Permeability (k) values calculated using the entire core area, 11.4 cm² (1.76 in²). Need to indicate shear steps 3 & 4 in Test 2 results outside of range of DP measurements.

Figure 4: Mean aperture variations - these are all without the error bars.

Figure 5: Results from Test 1 image processing and LCL simulations

Left: Aperture Map, 0-0.414 mm. Middle: Calculated Pressure, 998.5-1000 psi.

Right: Calculated flow magnitude, 0-150 uL/min.

Labels on left indicate shear step 2, 3, 4, 5, 6, 7 & 8

Figure 6. Results from Test 2 image processing and LCL simulations

Left: Aperture Map, 0-0.934 mm. Middle: Calculated Pressure, 999.5-1000 psi, Right: Calculated Flow Magnitude, 0-150 uL/min. Labels on left indicate shear step 1, 2, 3 & 4.

Figure 7: Results from Test 3 image processing and LCL simulations. Left: Aperture Map, 0-0.67 mm. Middle: Calculated Pressure, 0-20 psi (note shortened scale in 2nd column). Right: Calculated Flow Magnitude, 0-1 mL/min. Labels on left indicate shear step 0 (base), 1, 2, 3 & 4.

Figure 8: Left, Average channel widths of primary flow paths. Right. Average number of channels containing primary flow paths.

Fluid Flow in Rock Fractures under Various Shearing Conditions

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Abstract In this investigation flow through a mechanically sheared Marcellus shale fracture was studied experimentally and computationally. Fluid flow resistance was measured experimentally and computed tomography (CT) scanning for the sheared fracture geometry was obtained with $26.8 \mu\text{m}^3$ resolution. The CT images were used to generate aperture maps of the complex fracture geometries. Computational models of water flow using the aperture maps through the fractures were performed using a modified “local cubic law” approach and a full Navier-Stokes solver (ANSYS-Fluent software). Averaged aperture maps, with less fine structural detail, were generated to examine the effect of scan resolution on the accuracy of numerical results and computational time. The simulation results of pressure drop along the fracture lengths were compared with each other, with experimental data, and with a simple cubic law approximation assuming the average aperture controlled fluid resistance. The local cubic law and full Navier-Stokes results of the full map fractures are comparable with each other, and with one of experimental results. The experimental pressure of the first sheared fracture poorly matches the numerical results, quite likely because the fracture structure is inadequately captured by the scanning resolution. The numerical results for the averaged map, for which the nonlinear losses are insignificant, were found to be in good agreement with each other. However, the averaged fracture map simulations predict lower pressure drops than the full map, particularly for high flow rates. These discrepancies imply that not capturing the fine scale geometric complexity of a fracture affects the prediction of fluid flow in the fracture. The simple cubic law estimates using an average mechanical aperture value consistently underestimate the pressure drop of the full resolution simulations and experiments, and a correction to this approximation is proposed to address this concern. These methods provide robust estimations of fluid flow and will aid in convergence of experimental and computational results.

Keywords Computed tomography, local cubic law, simple cubic law, Navier-Stokes

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1 Introduction

Fractures in subsurface rocks are conduits for fluid migration in a multitude of energy applications. Subsurface hydraulic fracture stimulation has enabled oil and gas recovery from unconventional low permeability reservoirs. Similarly, fracture stimulations in hot, dry reservoirs have enhanced energy production in engineered geothermal systems. Understanding flow characteristics in fractures is critical for assessing risk in both the sealing formations above geologic carbon sequestration reservoirs and to the long-term migration in proposed subsurface nuclear waste repositories. The National Academy of Sciences (National Research Council 1996) and the U.S. Department of Energy's Subsurface Technology and Engineering Research, Development and Demonstration (SubTER AGU Townhall TH25I 2015) initiative have recognized the importance of fracture flow characterization and control as an area of needed research.

When simulating fluid migration at the reservoir (kilometer) scale, flows in fractures and fractured zones must be approximated with the use of empirical equations, such as 'Cubic Law' relationships in discrete fracture models (Makedonska et al. 2015; Myshakin et al. 2015; McKoy and Sams 1997) or 'dual permeability' approximations in continuum models (Pruess et al. 1999; Unsal et al. 2010). However, laboratory experiments and core scale (centimeter) simulations enable detailed characterizations of the complex fracture geometries that control fluid flow within these ubiquitous natural structures. Early works examining flows in natural rough walled fractures used various methods to describe their complex structures. For example, Gangi (1978) used the 'bed-of-nails' description of geomechanical response of compressed fractures to pressure, and Tsang (1984) introduced the varied resistor model to describe fluid flow through tortuous fractures. Prior to the advent of non-destructive imaging technologies such as computed tomography (CT) scanning (Montemagno and Pyrak-Nolte 1995; Cnudde and Boone 2013), fracture traces along the surface of rocks were used to describe fracture roughness (Brown et al. 1986; Tse and Cruden 1979). Alternatively, destructive testing was used to obtain fracture geometries inside of rock units by casting the fracture and then mechanically destroying the sample to extract the cast (Pyrak-Nolte et al. 1987). Past researchers have used separated fractured cores and measured the rough fracture surfaces with profilometry (Hans and Boulon 2003). The ability to digitally image the internal structure of fractured rocks with CT scanning (Bertels et al. 2001; Cnudde and Boone 2013) however, has provided a powerful tool for obtaining the complex geometries of fractured rock that fluids preferentially flow through without separating the fractured core.

The cubic law idealizes steady laminar flow through fractures by assuming fractures are smooth, wide, parallel plates with a small consistent aperture. The form of the cubic law,

$$Q = \frac{h^3 W}{12\mu} \nabla P \quad (1)$$

is similar to Darcy's law for flow through porous media,

$$Q = k \left(\frac{A}{\mu} \nabla P \right) \quad (2)$$

where Q is the volumetric flow rate, W is the fracture width, A is the cross-sectional area of the porous media perpendicular to the flow direction, μ is the fluid viscosity, ∇P is the pressure gradient along the length of the core, h is the fracture aperture and k is the porous media permeability. The similarity of these mathematical descriptions is convenient for describing flow through both porous media and fractured media in subsurface models, but neglects the variation in fluid transport observed within individual rough walled fractures. The local cubic law (LCL) model is a method to introduce the

variability in flow by approximating individual fractures by a collection of interconnected small parallel plates with a range of apertures and solving for the flow field in this more complex domain. Several researchers have shown that LCL models provide a functional tool for describing channelization of fluid pathways and the influence of tortuous structures on fluid transport in fractures (Brush and Thomson 2003; Konzuk and Kueper 2004; Oron and Berkowitz 1998; Pyrak-Nolte et al. 1988; Witherspoon et al. 1980).

CT scanning coupled with traditional core flow measurements can provide visualization of rock fracture geometries and how small scale features in these structures that influence bulk transport parameters relationships for porous media and fractures. The geometry of fractures can be isolated with image processing software from CT scans. As with any imaging process, the resolution and fidelity of the images captured will dictate the features that can be resolved. CT scanning relies on capturing a large number of 2D x-ray radiographs around a physical sample at various increments and then utilizing algorithms to interpolate a 3D digital representation of the object. Coupling traditional core flow measurements with CT scanning enables the fracture $k = h^2/12$ values to be obtained. In addition, simulations of the fluid transport in the isolated fractures can be performed to understand the influence of sub-millimeter geometric features.

Modeling with the LCL method is relatively fast, but requires assumptions on the fluid flow regime and behavior. Several researchers have used numerical solutions to the full Navier-Stokes equations for fluid flow through rough walled fractures to avoid relying on these assumptions. Crandall et al. (2010a) showed that the algorithms used to tessellate a mesh within these individual fractures can smooth small scale features out of the flow domain and reduce the resistance to flow within these digital fracture volumes. Petchsingto and Karpyn (2010) as well as Zimmerman and Yeo (2000) showed that localization of flow along preferential pathways and vortices of fluid adjacent to flow constrictions within individual fractures can be isolated from the full Navier-Stokes solutions to single phase flow through fractures. Multiphase immiscible flow simulations within fractures can be performed as well with full Navier-Stokes models, though these often have a high computational cost (Crandall 2007), and simpler pore-throat type models can sometimes better resolve the multiphase flow problem (Piri and Karpyn 2007; Karpyn and Piri 2007; Ferer et al. 2011). This study examines single-phase flows through fractures.

The current study used a unique fracture flow apparatus in a high resolution CT scanner to observe the evolution of fracture hydraulic properties under shearing. Bulk measurements of the core behavior were obtained in conjunction with CT scans of the fracture geometry. The digital fracture volume was converted to LCL and ANSYS-FLUENT computational models to examine the fine scale flow structures and behavior within the evolving flow conduits. Numerical results were compared with the experimental data and the impact of fine scale features of the rough fracture walls on the bulk transport of fluid in rock fractures was studied.

2 Experimental Procedure

A fractured core of Marcellus shale obtained from an outcrop in Bedford PA was used for the experiments and fracture flow simulations. The 1.5 in diameter and 1.5 in length core was fractured using a Brazilian technique (Karpyn et al. 2007) parallel to bedding. The fractured core was placed in a custom shearing mechanism within a Hassler style core holder, shown in Figure 1a, that enabled incremental displacements of the fracture surfaces along each other. A heat shrink Teflon sleeve was wrapped around the fractured core and the encapsulated fractured core was placed inside of the National Energy Technology Laboratory's (NETL) CT flow system in Morgantown West Virginia. Figure 1b shows a schematic of the experimental setup. For further description of the core holder, flow system, and shearing

apparatus please see (Crandall et al. 2016; Moore et al. 2015). The shearing of rock fractures was performed to examine the change in the geometry and fluid flow resistance of a rock fracture when the rough surfaces of the fracture slip past each other. This shearing is a common occurrence in a number of subsurface energy activities, including hydraulic fracturing of tight shale formations for gas and oil recovery, where the shearing of fractures are associated with micro-seismic events (Hammack et al. 2014).

Figure 1. (a) Hassler style core holder. (b) Schematic of the experimental setup.

A confining pressure of 500 psi (3.45 MPa) was applied to the core and shearing steps of 0.61 mm were applied sequentially to the core ends to induce the slippage along the rough fracture surfaces. Pressure differences across the core were measured using a 0-300 psi (0-2 MPa) Rosemount 3150CD pressure transducer with water injection flow rates ranging from 1 to 10 mL/min after each shearing event. The pressure difference along the length of the core was small, less than ~3 psi (0.2 MPa) for all but one set of the measurements. As will be discussed, this led to uncertainty in some of the experimental measurements, which will be further examined in a future work.

Computed tomography scans using a NorthStar Imaging M-5000 Industrial CT Scanner were obtained with a resolution of 26.8 μm after each shearing step. The scans were performed with a source voltage of 174 kV, and a current of 300 μA . The fracture geometry was isolated from the rock matrix using standard tools within the image processing software ImageJ (Rasband 1997-2016). For further details on this thresholding process see (Kutchko et al. 2013). The base fracture, with no shearing, was very well mated and the majority of the fracture aperture was below the resolution of the CT scan and thus no fracture geometry was extracted. In all other shear steps the fracture aperture was large enough to be isolated and extracted.

3 Numerical Methods

3.1 Mesh generation

2D aperture maps of the digital 3D geometries were used to construct the numerical models. Aperture maps are generated by collapsing the y-axis of the 3D CT data into a 2D map of aperture values. A simplified 2D grid maintains much of the geometric complexity while automatically preventing isolated cells, which complicate traditional mesh generation. However, by using this method no macroscopic undulations of the fracture plane are retained, forcing the fracture mid-surface to be flat. This is not a significant limitation for this dataset because the experimental shearing setup required the fracture to be macroscopically planar.

In addition, a reduced resolution map of the apertures was created by averaging the measured apertures in 10x10 grids over the full resolution aperture map using the ImageJ scale tool (Rasband 1997-2016).

Averaged maps ran an order of magnitude faster; by comparing the results of both the full and average geometries, we can better understand the cost – to – benefit ratio of sacrificing small-scale features to reduce computational time. As has been previously discussed in (Crandall et al. 2010b), this averaging of the small scale features of a rough walled rock fracture can reduce the resistance to flow through fractures. Both the average and full resolution aperture maps were analyzed numerically to determine the influence of this smoothing on the hydraulic parameters of the fracture.

The meshes for both the Local Cubic Law (LCL) and ANSYS-Fluent Navier Stokes simulations were generated directly from the aperture maps. Each point in the map was transformed into a rectangular prism, or cell, with a square base and a local height dictated by the aperture map. Voxels were converted to physical units using the known CT scan resolution. Each block in a full resolution mesh had a base of $26.8 \mu\text{m}^2$ and the average maps had a base of $268 \mu\text{m}^2$. The initial mesh is a single layer where interior cells have a neighbor cell on all four sides with no cells touching the top or bottom faces. The mesh was used “as is” for the LCL simulations with no internal refinement. To perform the ANSYS-Fluent simulations on the aperture map a Python script was used first to generate an input file for the open source grid generator BlockMesh, part of the OpenFOAM package. The blockMesh was then converted using a built-in utility, foamMeshToFluent, to generate an ASCII format file readable by ANSYS-Fluent for simulations. Using BlockMesh allowed the grid to be internally refined along all axes, improving numerical results and convergence. Results of the sensitivity study done to determine the optimal internal refinement are shown in section 3.3.1.

3.2 Local Cubic Law Simulations

Modeling of a single discrete fracture as set of parallel plates obeying the Cubic Law is a common simplification made to create an easily tractable problem. However, it is well understood that fractures have a very rough and complex geometry, which is not well suited for application of the Cubic Law unless a hydraulic aperture has already been determined (Brush and Thomson 2003; Brown 1987). The Local Cubic Law (LCL) relaxes the Cubic Law’s assumptions, instead approximating the fracture as a series of connected parallel plates. The flow through this regime obeys the laminar creeping flow driven by a pressure gradient. That is,

$$0 = -\nabla P + \mu \nabla u^2 \quad (3)$$

where u is the fluid velocity. The finite volume method is a natural choice to discretize the domain when using the aperture maps. Each “volume” or cell obeys the Cubic Law and the flow is evaluated in both the x - and z - directions.

$$q_x = \frac{h^3 \Delta z}{12 \mu} \cdot \frac{\Delta P}{\Delta x} \quad (4)$$

$$q_x = \frac{h^3 \Delta x}{12 \mu} \cdot \frac{\Delta P}{\Delta z} \quad (5)$$

Here h is the separation between each set of “local parallel plates” or aperture, and Δz is the width of a cell, for flow in the x -direction. Alternatively, Δx is used as the cell width for flow in the z -direction. The aperture at the interface of two cells was adjusted using the Stokes Tapered Plate solution (Brush and Thomson 2003). The correction adjusts the aperture to better represent the influence of aperture variation across neighboring cells, weighting the smaller aperture value more heavily. Boundary conditions allowed free movement between the four faces of a grid-block into adjacent cells but the top and bottom faces were defined as no-slip boundaries. The right and left edges of the fracture were set to zero flux. The inlet

and the outlet of the fracture were assigned to match the physical inlet and outlet edges in the experiments. The flow equations were then solved using a two-dimensional central difference scheme.

$$T_x = \frac{h^3 \Delta z}{12 \Delta x} \quad (6)$$

$$T_z = \frac{h^3 \Delta x}{12 \Delta z} \quad (7)$$

$$0 = -T_{x_{i,j}}(P_{i+1,j} - P_{i,j}) + T_{x_{i-1,j}}(P_{i,j} - P_{i-1,j}) - T_{z_{i,j}}(P_{i,j+1} - P_{i,j}) + T_{z_{i,j-1}}(P_{i,j} - P_{i,j-1}) \quad (8)$$

Where T_x and T_z are local transmissivities, respectively, for the x- and z-directions. Simulation conditions were tuned to match the experimental parameters for both constant injection rate and constant pressure drop. Constant injection rate simulations were performed with a manifold that allowed the injected fluid to distribute itself along the varied inlet aperture values. Without the use of a manifold, the flow rates would have to be uniformly defined across the inlet creating an unrealistic initial pressure distribution. The model outputs several data files for post-processing; primary files include a legacy formatted VTK file and a run statistics file in both a CSV and YAML format. The legacy VTK file is read by ParaView to allow for easy visualizations of the simulation results. The statistics file stores several calculated values such as the estimated effective hydraulic aperture, flow rate, inlet and outlet pressure for direct comparison with experimental data or other simulation results.

3.2.1 Simple Cubic Law

As noted before, the use cubic law for predicting the pressure drop of the entire fractures was suggested in the past (Bear and Braester 1972; Konzuk and Kueper 2004). Accordingly, Equation (1) may be restated as,

$$\Delta p = \frac{12 \mu L}{W h_{eq}^3} Q \quad (9)$$

where h_{eq} is the effective aperture height. Since the areas with smaller aperture significantly affect the pressure drop and the effects of surface roughness and tortuosity also need to be accounted for, using an average aperture height $\bar{h}$ in Equation (9) lead to underestimation of the fracture pressure drops. There have been a number of efforts to improve the prediction of cubic law by modifying the effective aperture height. Among them, Nazridous et al. (2006) suggested using the average aperture minus the standard deviation as the effective aperture height for two-dimensional fractures. Here the following expression for the equivalent aperture is proposed,

$$h_{eq} = \bar{h} - \alpha \sigma \quad (10)$$

where α is constant and its value needs to be optimized for these three-dimensional fractures.

3.3 Navier-Stokes Simulations

The commercial CFD software ANSYS-Fluent released 16.1 (ANSYS® FLUENT) was used to simulate fluid flow in rock fractures for different levels of shearing. The equations of conservation of mass and momentum are given as,

$$\nabla \cdot u = 0 \quad (11)$$

$$\rho u \cdot \nabla u = -\nabla P + \mu \nabla^2 u + \rho g \quad (12)$$

where g is gravitational acceleration and ρ is the density. Steady laminar isothermal flow with constant properties was assumed and since the size of the apertures is so small, the gravitational effects were neglected. A no-slip boundary condition on the solid walls was applied, and pressure boundary

conditions were imposed on the fracture inlet and outlet. Use of a pressure inlet boundary condition was preferred to the mass flow inlet condition. This is because imposing a uniform mass flow at the inlet leads to unrealistically high and localized pressure at constricted areas at or near the inlet. The outlet pressure was set at atmospheric conditions. An iterative procedure was used to determine an inlet pressure, which resulted in a flow rate that matched the experimental values.

SIMPLE scheme was used for pressure-velocity coupling of the governing equations, while least square cell based, second order, and second order upwind discretization methods were used respectively to interpolate gradient, pressure, and convective terms of the governing equations.

3.3.1 Grid Sensitivity Study

Table 1 shows the results of the grid sensitivity study performed for step 1 shearing of the average map for a flow rate of 1 mL/min. Here five grids with 13 thousand to 8.7 million elements were studied. The pressure drop differences between the grids decreases with an increase in number of elements. Based on the results shown in Table 1, the Case 4 grid was chosen for these simulations because the percentage of pressure drop difference was small, and the required CPU time was reasonable. For other shearing steps of the average map, the same resolution was considered. The same procedure was performed for the full map and the appropriate grid size with 11,213,050 elements was selected for those simulations. A computer with two Xeon E5-2640 v3 CPU processors was used to run all ANSYS-Fluent Navier Stokes simulations.

Table 1 Grid sensitivity study data.

Case ($N_x N_y N_z$)	Number of elements	CPU time (min)	Obtained pressure drop (Pa)	Pressure drop difference %
(1 1 1)	13,690	0.23	134.45	-
(1 5 1)	68,450	0.50	372.10	176.76
(1 10 1)	136,900	1.08	394.85	6.11
(2 20 2)	1,095,200	12.45	399.40	1.63
(4 40 4)	8,761,600	240	402.90	0.88

The first column of Table 1 represents the number of grids for each pixel of CT data in different directions. For example, (1 10 1) indicates each pixel has one grid in x- and z-direction and 10 grids in y-direction.

4 Results and discussion

A fractured core of Marcellus shale from Bedford PA was used to study the behavior of fluid flow through a rock fracture during different stages of shearing. Simulations were performed with the LCL and Navier Stokes models. The computational results are presented in this section and are compared with the experimental data that were obtained at the CT Scanner Lab at NETL in Morgantown WV.

4.1 Average map

The fractured core was sheared in four steps. Each step, typically referenced as 1–4, are labeled on each figure as a–d, respectively. At each step, high resolution and low resolution maps were generated following the procedure described in Section 2. The simulation results for the fracture geometries produced from the low resolution maps (average map) are presented in this section.

Figure 2 shows the contours of the aperture height for the different shearing steps. The white areas identify the regions that the fracture apertures are zero. The aperture heights appear to vary due to the structural heterogeneity within the shale, with ‘ridges’ of the large and small aperture zones perpendicular to the flow direction. In general, there appears to be an increase of aperture along the flow direction (z-direction). In addition, adjacent to the inlet there are some regions of very high aperture due to the breakage of the core margins during shearing. For clarity, these zones are shown in grey in Figure 2. Near the outlet, there is also a noticeable drop in the aperture height. Comparing subfigures a–d, there is a noticeable increase in aperture height as shearing increases.

Figure 2. Aperture height contours of the average map at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4 (the white and grey areas respectively represent zero aperture and contours above 3.2 mm).

Figure 3. Aperture frequencies of the average map and the Gaussian distribution fitted them at different shearing steps.

Figure 3 shows the frequency distribution of fracture aperture heights for various bin sizes for different shearing steps. Here a Gaussian distribution is also fitted to the frequency distribution at each step. This confirms that the aperture heights of the fracture increased due to shearing from step 1 to 3. The frequency distributions for shear steps 3 and 4 are similar and further shearing beyond step 3 does not affect the aperture height distribution significantly. The frequency distribution of each step roughly follows the Gaussian distribution, as seen in earlier literature (Tsang 1984; Brown 1995; Crandall et al. 2010a).

The overall average aperture heights and standard deviation of aperture distribution of different shearing steps are listed in Table 2. The mean aperture height increases more than 60% and 35%, respectively, from shearing step 1 to 2 and 2 to 3. However, it increases only approximately 8% between shearing step 3 to 4. The standard deviation increases with each shear step, which is consistent with the trend shown in Figure 3.

Table 2. Overall average and standard deviation of apertures and estimations of pressure drop using different methods of the average map fracture at different shear steps with a flow rate of 1 mL/min.

Shear Step	1	2	3	4
Overall average aperture, $\bar{h}$ (mm)	0.101	0.163	0.223	0.242
Standard deviation of aperture, σ (mm)	0.060	0.143	0.180	0.226
Equivalent aperture, $\bar{h} - 0.45 \sigma$ (mm)	0.074	0.099	0.142	0.140
Pressure drop ANSYS-Fluent (Pa)	395	164	54	58
Pressure drop LCL (Pa)	420	184	57	61
Pressure drop Simple cubic law ($\bar{h}$) (Pa)	161	38	14	11
Pressure drop Simple cubic law ($\bar{h} - 0.45 \sigma$) (Pa)	405	172	56	57

Figure 4. Normalized pressure contours of the average map with a flow rate of 1 mL/min at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4.

The normalized static pressure contours at the fracture mid-section at a flow rate of 1 mL/min are shown in Figure 4. The inlet pressure for each case was used to normalize the contours for better comparison. Figure 4 shows that the pressure decreases from the inlet toward the fracture outlet, with most of the pressure reduction occurring within the first 40% of the fracture length. While the general features of the normalized pressure drop contours are similar, there are marked differences for different shearing steps. For example, in step 1 shearing, 80% of the pressure drop occurs from the inlet to 1.5 cm along the length of the fracture. As shearing continues, the width of the band in which the pressure drop occurs become narrower. For shearing step 4, the pressure stays almost constant across the beginning 0.5 cm of the fracture and then it decreases sharply across the distance of 0.5 to 1 cm.

Figure 5. Average static pressure along z-direction of the average map for different flow rates at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4.

Variations of the average static pressure along the z-axis for different shearing steps for flow rates of 1, 2, 4, 6, and 10 mL/min are shown in Figure 5. Here the averaging was done on the mid-section along the x-axis perpendicular to the main flow direction. This figure shows that the average pressure decreases monotonically from the inlet toward the outlet, however, the pressure gradient is much sharper in the region within 0.5 cm to 1.5 cm from the fracture inlet. As mentioned before, the average aperture increases for steps 1 to 3 of shearing which is a reason for the sharp reduction in pressure drop with shearing for step 1 to 3.

Figure 6. Velocity magnitude contours of the average map fracture at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4 (values below 0.1 cm/s not shown for clarity).

For different shearing steps, Figure 6 shows the velocity contours at the fracture mid-plane, with the contours below 0.1 cm/s are removed for clarity. The channeling flow patterns are clearly seen in this figure, particularly, in the first half of the fracture. Figure 6 indicates that for shear step 1 the flow is more scattered in a large number of small channels through most of the fracture. As shearing increases, smaller, but wider, primary flow channels appear in the fracture, particularly near the inlet. The velocity magnitude decreases with the shearing step as the aperture height increases and as some wider primary flow channels appear in the fracture, which is likely another reason for the reduction of the pressure drop by shearing.

Figure 7. Variations of average velocity magnitude along z-direction of the average map fracture for different shear steps. Flow rate = 1 mL/min.

Figure 7 shows the variation of average velocity magnitude along the z-direction for different shearing steps. The average aperture heights and the width of the primary flow channels increase by shearing, at least for steps 1 to 3, and as expected the velocity magnitude decreases. The velocity magnitude has a peak at the distance of approximately 0.5 to 1 cm from the inlet where the main channeling of the flow occurs, and then reaches a roughly flat region with some increase near the outlet.

The pressure drops predicted by the Navier-Stokes simulations are listed in Table 2; the pressure drop decreases with shearing steps since the average aperture increases for shearing steps 1 to 3. The pressure drop is reduced by about 50% between shearing steps 1 and 2, while it is reduced by a factor of 3 between shearing steps 2 and 3. However, for steps 3 and 4 the inlet pressure (pressure drop) remains roughly the same; this is because the average fracture aperture height does not increase beyond step 3.

The prediction of the simple cubic law for the pressure drops as given by Equation (9) using the overall average aperture, $\hat{h}$, as the equivalent aperture is shown in Table 2. Comparing these estimates with those predicted by the numerical simulations shows that the overall average aperture does not represent an appropriate effective aperture height for use in the cubic law. Here, with some trial and error, Equation (10) for the effective fracture aperture with $\alpha=0.45$ is used. The corresponding pressure drops for different shearing steps are evaluated using Equation (9) and the results are listed in Table 2. It is seen that the prediction of cubic law with $h_{eq}=\hat{h}-0.45\sigma$ are in good agreement with those of numerical simulations for these fractures.

Figure 8. Comparison of ratio of average static pressure to $\Delta p_{eq} = \left(\frac{12 \mu L}{W h_{eq}^3} Q \right)$ for different flow rate at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4.

Figure 8 shows the normalized average static pressure profiles of what was shown in Figure 5. The static pressure was normalized by the equivalent cubic law pressure drop $\Delta p_{eq} = \left(\frac{12 \mu L}{W h_{eq}^3} Q \right)$ in which h_{eq} was substituted by the equivalent aperture values listed in Table 2. The normalized values were obtained to study the accuracy of the equivalent apertures in predicting the pressure drops for the range of flow rates at different shearing steps and to explore the potential effects of nonlinear inertial losses by increasing the flow rate. Figure 8 shows that the maximum value of the normalized pressure for the flow rate of 1 mL/min is almost equal to 1 for all shearing steps. This confirms that Equation Error: Reference source not found) with $\alpha = 0.45$ is an appropriate estimation of the equivalent apertures for the flow rates in the range of 1 to 10 mL/min of all shearing steps. That is, the normalized average pressures for flow rates in this range coincide. This coincidence implies that the nonlinear losses do not play a significant role on the total pressure drop for the average map fractures for which the surface roughness was smoothed out by averaging.

The pressure drops predicted by the LCL simulation models for the average map are also listed in Table 2. The pressure drops evaluated by the LCL are comparable with those predicted by the Navier Stokes simulations and the simple cubic law model using h_{eq} . Again, with the creeping flow assumptions of the LCL model the good agreement of these results implies that there are negligible nonlinear forces acting on the flow than when the coarser averaged aperture distributions are considered.

4.2 Full map

The simulation results on the geometries produced from the high resolution maps (full maps) are presented herein.

Figure 9 shows the aperture height contours for different shearing steps for the full map. As noted before, the white areas correspond to the regions of zero fracture apertures. There are high aperture areas near the inlet (contour values are grey in this figure for clarity); during the shearing process pieces of rock were broken off at the inlet region to create these zones. Beyond these high aperture areas near the inlet, there is a sharp decrease and then a slight increase in the aperture height along the flow direction that drops off near the outlet. Similar to the average map, Figure 9 shows that there is a noticeable increase of fracture aperture height with shearing; due to shearing the areas of zero aperture height merge and some primary flow channels in the fracture are formed in the first half of the fracture.

Figure 9. Aperture height contours of the full map at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4 (the white and grey areas respectively represent zero aperture and contours above 3.6 mm).

Figure 10. Aperture frequencies of the full map and the Gaussian distribution fitted them at different shearing steps.

Figure 10 shows the frequency distribution of fracture aperture heights for the entire map for different shearing steps. As in Figure 3, a Gaussian distribution is fitted to the frequency distribution of each shearing step and it is observed that the fracture aperture height increases by shearing. This is certainly the case for shear steps 1 to 3. Like the average map fracture, the frequency distributions for shear steps 3 and 4 are quite similar, further shearing beyond step 3 does not significantly affect the aperture height distribution.

The corresponding average aperture height and standard deviations of the full map are shown in Table 3. As expected, the average apertures of different shearing steps are similar to those of the average map and are increased by shearing for steps 1 to 3. However, the aperture standard deviations for different shearing are somewhat higher than those for the average map, since the full map captures more details of the roughness of the fracture surfaces.

Table 3. Overall average and standard deviation of apertures and the estimations of pressure drop using different methods of the full map fracture at different shear steps for a flow rate of 1 mL/min.

Shear Step	1	2	3	4
Overall average aperture, $\bar{h}$ (mm)	0.101	0.164	0.225	0.243
Standard deviation of aperture, σ (mm)	0.073	0.158	0.187	0.237
Equivalent aperture, $\bar{h} - 0.45 \sigma$ (mm)	0.068	0.157	0.141	0.136
Pressure drop ANSYS-Fluent (Pa)	622	309	66	79
Pressure drop LCL (Pa)	597	381	83	107
Pressure drop Simple cubic law ($\bar{h}$) (Pa)	162	38	14	11
Pressure drop Simple cubic law ($\bar{h} - 0.45 \sigma$) (Pa)	529	208	58	64

Figure 11. Normalized pressure contours of the full map fracture for a flow rate of 1 mL/min at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4.

For a flow rate of 1 mL/min, Figure 11 shows the normalized static pressure contours at the fracture mid-section for different shearing steps. Similar to the average fracture map, the inlet pressure for each case is used to normalize the contours for comparison. The inlet pressures (pressure drops) for different shearing steps of the full map fracture for the flow rate of 1 mL/min are tabulated in Table 3. The general patterns of the normalized pressure contours for different shearing steps are quite similar, and the major pressure drops occur within the first 1 cm of the fracture near the inlet. Like the trend observed for the average map fracture, the general features of the normalized pressure drop contours are similar, but there are certain differences for different shearing steps. In particular, the localization of the pressure drop increases with the shearing step. Table 3 shows that the maximum pressure decreases with shearing steps as the average aperture increases for shearing steps 1 to 3. The pressure drop reduces by about 40% between shear step 1 and 2, while it is reduced by a factor of 6 between shear steps 2 and 3. For steps 3 and 4, the inlet pressure actually increases slightly because the average fracture aperture height does not increase significantly by shearing beyond step 3. These trends are similar to those observed for the average map fracture shown in Table 2, however, the maximum pressure drops for the full map fracture larger than that for the average map fracture. This is because the average map fracture has smoothed out fine geometric details by averaging over a small area. The aperture height contours in Figure 9 show that the zero aperture zones of the full map fracture are noticeably rougher compared to those of the average map fracture shown in Figure 2. Therefore, the pressure drops of the full map fracture are greater compared to those of the average map fracture.

Figure 12. Average static pressure along z-direction of the average map for different flow rates at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4.

Figure 12 shows the variation of the average static pressure along the z-axis of the full map fracture for flow rates of 1, 2, 4, 6, and 10 mL/min. There is a sharp pressure gradient in the distance of 0.6 to 1.3 cm from the fracture inlet. The pressure drop for different flow rates becomes steeper as the shearing step increases such that the pressure does not vary from the inlet to the distance of 0.5 cm for shear step 4 and then it drops sharply across a narrow band.

Figure 13. Velocity magnitude contours of the full map fracture at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4 (values below 0.1 cm/s not shown for clarity).

Figure 13 shows the velocity contours at the mid-plane of the full map fracture for different shearing steps (contours below 0.1 cm/s are removed for clarity). The strong channeling of flow patterns can be clearly seen in the first half of the fracture. Like the average map fracture, the velocity magnitude decreases with the shearing step as the aperture height increases. During shearing the primary flow channels join and form fewer but wider flow channels, particularly, in the first half of the fracture near the inlet and near the outlet. The formation of these wider flow channels reduces the fracture pressure drop.

Figure 14. Variations of average velocity magnitude along z-direction of the full map fracture for different shear steps. Flow rate = 1 mL/min.

Figure 14. shows the variation of average velocity magnitude along the z-direction of the full map fracture for different shearing steps. The average aperture height increases by shearing for steps 1 to 3, and the velocity magnitude decreases. Figure 14 shows that the velocity magnitudes in the full map fracture are comparable with those in the average map fracture for the same flow rate.

The pressure drop estimations of ANSYS-Fluent software are listed in Table 3. The pressure drops of the full map for different shearing steps are greater than those of the average map and the pressure drop decreases due to shearing as the average aperture increases for shearing steps 1 to 3. The pressure drop is reduced by about 50% between shearing step 1 to 2, and by a factor of more than 4 for shearing steps 2 to 3. However, since the average aperture does not increase significantly for shearing steps 3 to 4, the pressure drop does not decrease for these shearing steps and in fact increases slightly.

The overall average aperture values of the full maps as shown in Table 3 were used as the effective aperture height in the cubic law as given by Equation Error: Reference source not found, and the corresponding pressure drops are listed in Table 3. These pressure drop estimates underestimate the predictions of the numerical simulations. This suggests that the overall average aperture height does not represent proper effective aperture to be used in the cubic law for estimating the pressure drops, that is, the equivalent aperture height is much smaller than the overall average aperture. Therefore, as in the average map case, Equation Error: Reference source not found) with $\alpha=0.45$ was used for evaluating the equivalent aperture height. These values are listed in Table 3 for different shearing steps. These values are used as the equivalent aperture height in Equation Error: Reference source not found) and the corresponding pressure drops are listed in the sixth row of Table 3. These pressure drop values estimated with the cubic law are comparable to those obtained from the numerical simulations, however, the accuracy of these estimates are not as precise as those for the average map.

Figure 15. Comparison of ratio of average static pressure to (flow rate* h_{eq}^3) for different flow rates at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, and (d) Shear step 4.

Like Figure 8 for the average map, Figure 15 shows the average static pressure profiles of the full map normalized by $\Delta p_{eq} = \left(\frac{12\mu L}{W h_{eq}^3} Q \right)$ in which h_{eq} was substituted by the equivalent aperture values shown in the fourth row of Table 3. For the full map, the maximum value of the normalized pressure for the flow rate of 1 mL/min is higher than 1 for all shearing steps which implies that Equation Error: Reference source not found) with $\alpha = 0.45$ does not represent the equivalent aperture for the full map as accurately as it did for the average map. In addition, Figure 15 shows that the normalized average pressures increase slightly with flow rate, which differs from the average map fracture that the graphs for different flow rates coincide. The increase of the normalized average pressure is attributed to nonlinear inertia losses, which are significant for the full map fracture due to the rougher surfaces and higher corresponding localized Q , while they were negligible for the smoothed out average map fracture. Shear step 2 has the maximum increase of the normalized average pressure, which suggests that the nonlinear

losses have more impact in this geometry with more zero aperture locations distributed throughout the domain.

The pressure drops predicted by the LCL simulation models for the full map are also listed Table 3. The pressure drops evaluated by the LCL model are comparable with those predicted by the Navier Stokes simulations. The LCL model predictions are mostly greater than those of estimated by the Navier Stokes simulations, though the reason for this discrepancy is unclear.

Figure 16. Comparison of the pressure drops predicted by ANSYS-Fluent, LCL, simple cubic law for average and full map fractures with the experimental results at (a) Shear step 1, (b) Shear step 2, (c) Shear step 3, (d) Shear step 4.

For a range of flow rates between 1 to 10 mL/min and for different shearing steps, Figure 16 compares the computational model predictions for the pressure drops in full and average map fractures to each other and with the experimental data. The experimental data was available only for shear steps 1 and 2. For all shearing steps, the pressure drops for the full map fracture are larger than those for the average map fractures, especially at higher flow rates; this is due to the smoothing of the fracture surfaces for the average map case (Crandall et al. 2010a). For shearing step 1, the pressure drops in the average map fracture predicted by the ANSYS-Fluent code, LCL model, and simple cubic law are also in good

agreement, but underestimate the experimental data. This difference between the experimental data and the simulation results is believed to be due to the fracture aperture being at or below the resolution of the CT scans (26.8 μm , e.g. Figure 9). The isolated fracture geometry from the CT images may be missing some of the fine scale features of the fracture that create additional constrictions in the flow path. These small and distributed constrictions would have increased the observed pressure drop in the experiments. For shearing step 2, the model predictions for the full map fracture are in good agreement with each other and with the experimental data. In this case, the predictions of ANSYS-Fluent code are somewhat higher than those of the LCL model, especially, for higher flow rates. The inertia effects in the loss prediction appear to have a greater effect for the higher resolution full map fracture. Figure 16 shows that the LCL and the simple cubic law results for the average map match well with those of the Navier Stokes simulation predictions, but those of the full map show some discrepancies.

5 Conclusions

Flows and pressure drops in a sheared Marcellus shale fracture for different flow rates were studied experimentally and computationally. The fracture was CT scanned at a high-resolution of 26.8 μm^2 (full map). Low-resolution representations of the CT scans were created at 268 μm^2 (average map) for different shearing steps to enhance computational time. The fracture flows were studied numerically using the LCL method and full Navier Stokes simulations. In addition, the equivalent apertures for the full and average map fractures for different shearing steps were estimated and were used to predict the fracture pressure drop for different flow rates at different shearing steps by the simple cubic law. By exploring the predictions of the LCL method, the ANSYS-Fluent software, and simple cubic law model for the full and average map fractures at different shearing steps and different flow rates the following results were seen:

- When shearing increased the average aperture, a decrease of the corresponding pressure drops and average flow velocities were observed.
- Good agreement was observed between the results of the LCL model and Navier Stokes simulations for the average map fractures.
- The LCL model predicted slightly larger pressure drops across the fracture when compared to the Navier Stokes simulations for the full map fractures.
- The lower pressure drops for the average map fractures, compared to those of the full map fractures, illustrated the important effects of small scale surface roughness on increasing the fracture pressure drops. This was particularly true at higher flow rates.
- Agreement between the simple cubic law data and the more complex numerical simulations was obtained using the proposed h_{eq} and the coarser resolution averaged aperture maps.
- Deviation between the simple cubic law data using h_{eq} and the detailed simulations for the full map fractures, especially for higher flow rates, showed that nonlinear losses are significant in these fractures when small scale features are captured.

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References

ANSYS® FLUENT. Release 16.1

Bear, J., Braester, C.: On the Flow of Two Immiscible Fluids in Fractured Porous Media. *Developments in Soil Science* **2**, 177-202 (1972)

Bertels, S.P., DiCarlo, D.A., Blunt, M.J.: Measurement of aperture distribution, capillary pressure, relative permeability, and in situ saturation in a rock fracture using computed tomography scanning. *Water Resources Research* **37**(3), 649-662 (2001)

Brown, S.R.: Fluid flow through rock joints: the effect of surface roughness, vol. 92. *Journal of Geophysical Research: Solid Earth*, vol. B2(1987)

Brown, S.R.: Simple mathematical model of a rough fracture. *Journal of Geophysical Research: Solid Earth* **100**(B4), 5941-5952 (1995)

Brown, S.R., Kranz, R.L., Bonner, B.P.: Correlation between the surfaces of natural rock joints. *Geophysical Research Letters* **13**(13), 1430-1433 (1986)

Brush, D.J., Thomson, N.R.: Fluid flow in synthetic rough-walled fractures: Navier-Stokes, Stokes, and local cubic law simulations. *Water Resources Research* **39**(4) (2003)

Cnudde, V., Boone, M.N.: High-resolution X-ray computed tomography in geosciences: A review of the current technology and applications. *Earth-Science Reviews* **123**, 1-17 (2013)

Crandall, D.: Two-phase flow in porous media and fractures. Clarkson University (2007)

Crandall, D., Bromhal, G., Karpyn, Z.T.: Numerical simulations examining the relationship between wall-roughness and fluid flow in rock fractures. *International Journal of Rock Mechanics and Mining Sciences* **47**(5), 784-796 (2010a)

Crandall, D., Bromhal, G., McIntyre, D.: Evaluating the Influence of Wall-Roughness on Fracture Transmissivity with CT Scanning and Flow Simulations. *Advances in Computed Tomography for Geomaterials: GeoX 2010*, 270-278 (2010b)

Crandall, D., Moore, J., Gill, M., Stadelman, M.: Hydrodynamic response of sheared fractures. Submitted to the *International Journal of Rock Mechanics and Mining Sciences* (2016)

Ferer, M., Crandall, D., Ahmadi, G., Smith, D.H.: Two-phase flow in a rough fracture: Experiment and modeling. *Physical Review E* **84**(1), 016316 (2011)

Gangi, A.F.: Variation of whole and fractured porous rock permeability with confining pressure. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* **15**(5), 249-257 (1978)

Hammack, R., Harbert, W., Sharma, S., Stewart, B., Capo, R., Wall, A.: An evaluation of fracture growth and gas/fluid migration as horizontal Marcellus Shale gas wells are hydraulically fractured in Greene County, Pennsylvania. National Energy Technology Laboratory: NETL-TRS-3-2014.

https://www.netl.doe.gov/File%20Library/Research/onsite%20research/publications/NETL-TRS-3-2014_Greene-County-Site_20140915_1_1.pdf (2014). Accessed 1.25.2017

Hans, J., Boulon, M.: A new device for investigating the hydro-mechanical properties of rock joints. *International journal for numerical and analytical methods in geomechanics* **27**(6), 513-548 (2003)

- Karpyn, Z., Grader, A., Halleck, P.: Visualization of fluid occupancy in a rough fracture using micro-tomography. *Journal of colloid and interface science* **307**(1), 181-187 (2007)
- Karpyn, Z.T., Piri, M.: Prediction of fluid occupancy in fractures using network modeling and x-ray microtomography. I: Data conditioning and model description. *Physical Review E* **76**(1), 016315 (2007)
- Konzuk, J.S., Kueper, B.H.: Evaluation of cubic law based models describing single-phase flow through a rough-walled fracture. *Water Resources Research* **40**(2) (2004)
- Kutchko, B., Crandall, D., Gill, M., McIntyre, D., Spaulding, R., Strazisar, B., Rosenbaum, E., Haljasmaa, I., Benge, G., Cunningham, E.: Computed Tomography and Statistical Analysis of Bubble Size Distributions in Atmospheric-Generated Foamed Cement. Pittsburgh: DOE-NETL internal Publication (2013)
- Makedonska, N., Painter, S.L., Bui, Q.M., Gable, C.W., Karra, S.: Particle tracking approach for transport in three-dimensional discrete fracture networks. *Computational Geosciences* **19**(5), 1123-1137 (2015)
- McKoy, M.L., Sams, W.N.: Tight gas reservoir simulation: Modeling discrete irregular strata-bound fracture networks and network flow, including dynamic recharge from the matrix. In: *Proceedings of the Natural Gas Conference Emerging Technologies for the Natural Gas Industry*. Washington, DC: US Department of Energy's Federal Energy Technology Center Publication 1997
- Montemagno, C.D., Pyrak-Nolte, L.J.: Porosity of natural fracture networks. *Geophysical Research Letters* **22**(11), 1397-1400 (1995)
- Moore, J., Crandall, D., Gill, M.: Physical and Hydraulic Aperture Evaluation of Shale Fractures using Computed Tomography. Paper presented at the Shales of All Scales: Exploring Coupled Processes, Santa Fe NM, June 9-11, 2015
- Myshakin, E., Siriwardane, H., Hulcher, C., Lindner, E., Sams, N., King, S., McKoy, M.: Numerical simulations of vertical growth of hydraulic fractures and brine migration in geological formations above the Marcellus shale. *Journal of Natural Gas Science and Engineering* **27**, 531-544 (2015)
- Nazridoust, K., Ahmadi, G., Smith, D.H.: A new friction factor correlation for laminar, single-phase flows through rock fractures. *Journal of Hydrology* **329**(1), 315-328 (2006)
- Oron, A.P., Berkowitz, B.: Flow in rock fractures: The local cubic law assumption reexamined. *Water Resources Research* **34**(11), 2811-2825 (1998)
- Petchsingto, T., Karpyn, Z.T.: Simulation of fluid percolation in a rough-walled rock fracture. *Hydrogeology journal* **18**(7), 1583-1589 (2010)
- Piri, M., Karpyn, Z.T.: Prediction of fluid occupancy in fractures using network modeling and X-ray microtomography. II: Results. *Physical Review E* **76**(1), 016316 (2007)
- Pruess, K., Oldenburg, C., Moridis, G.: TOUGH2 user's guide version 2. Lawrence Berkeley National Laboratory (1999)
- Pyrak-Nolte, L.J., Myer, L.R., Cook, N.G., Witherspoon, P.A.: Hydraulic and mechanical properties of natural fractures in low permeability rock. Paper presented at the 6th ISRM Congress, Montreal, Canada, 30 August-3 September, 1987
- Pyrak-Nolte, L.J., Cook, N.G., Nolte, D.D.: Fluid percolation through single fractures. *Geophysical Research Letters* **15**(11), 1247-1250 (1988)
- Rasband, W.S.: ImageJ. U. S. National Institutes of Health, Bethesda, Maryland, USA. <http://imagej.nih.gov/ij/> (1997-2016).

- SubTER AGU Townhall TH25I. Paper presented at the American Geophysical Union Annual Fall Meeting, San Francisco, December 15-19, 2015
- Tsang, Y.: The effect of tortuosity on fluid flow through a single fracture. *Water Resources Research* **20**(9), 1209-1215 (1984)
- Tse, R., Cruden, D.: Estimating joint roughness coefficients. *International journal of rock mechanics and mining sciences & geomechanics abstracts* **16**(5), 303-307 (1979)
- Unsal, E., Matthäi, S.K., Blunt, M.J.: Simulation of multiphase flow in fractured reservoirs using a fracture-only model with transfer functions. *Computational Geosciences* **14**(4), 527-538 (2010)
- Witherspoon, P.A., Wang, J.S., Iwai, K., Gale, J.E.: Validity of cubic law for fluid flow in a deformable rock fracture. *Water resources research* **16**(6), 1016-1024 (1980)
- Zimmerman, R.W., Yeo, I.W.: Fluid Flow in Rock Fractures: From the Navier-Stokes Equations to the Cubic Law. *Dynamics of fluids in fractured rock*, 213-224 (2000)